Ecole Doctorale des Sciences Economiques, Juridiques, Politiques et de gestion
Centre d'Etudes et de Recherche sur le Développement International (CERDI)

Université Clermont Auvergne, CNRS, IRD, CERDI, F-63000 Clermont-Ferrand, France

CONNECTING ENERGY SYSTEM MODELLING WITH SUSTAINABLE ENERGY SYSTEM NARRATIVES ON A GLOBAL SCALE

Thèse présentée et soutenue publiquement le 3 décembre 2019 pour l'obtention du titre de Docteur en Sciences Economiques par

GANNA GLADKYKH

sous la direction de ARNAUD DIEMER, SONIA SCHWARTZ et BRYNHILDUR DAVÍÐSDÓTTIR

Membres du Jury

Prof. Robert Costanza	The Australian National University	Président
Dr. Kirsten Jenkins	University of Edinburgh	Suffragant
Dr. Darren McCauley	St Andrews Sustainability Institute	Suffragant
Dr. Sandrine Mathy	CNRS - Université Grenoble Alpes	Rapporteur
Prof. Valeria Jana Schwanitz	Western Norway University of Applied Sciences	Rapporteur
Prof. Arnaud Diemer	CERDI, UCA	Directeur
Prof. Sonia Schwartz	CERDI, UCA	Co-directeur
Prof. Brynhildur Davíðsdóttir	Université d'Islande	Co-directeur

PLEDGE

I hereby certify this document to be the original and authentic output of the author's research work. All sources and references are duly listed, and consist mostly of published scientific articles and papers, technical books, database sets from applied research institutes and official reports from international agencies or governmental organizations.

Ganna Gladkykh
Clermont-Ferrand, France
December 3rd, 2019

SUPERVISORS

Prof. Doctor Arnaud DIEMER (arnaud.diemer@uca.fr)
Université Clermont Auvergne (UCA), CERDI

Prof. Doctor Brynhildur DAVÍÐSDÓTTIR (bdavids@hi.is) *University of Iceland (HI),*
Department of Life and Environmental Sciences

Prof. Sonia SCHWARTZ (sonia.schwartz@uca.fr), *Université Clermont Auvergne (UCA), CERDI*

RESEARCH COMMITTEE

Dr. Sandrine MATHY (sandrine.mathy@univ-grenoble-alpes.fr)
CNRS Research Director - Université Grenoble Alpes

Ulrich GOLUKE (goluke@blue-way.net)
Blue Way consultancy, Business School Lausanne

PREFACE

This PhD thesis was developed under the AdaptEconII project funded by the European Commission's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Innovative Training Networks (ITN)research grant agreement No 675153.

AdaprEconII is a transdisciplinary program interlinking system science, ethics for an interdependent world, natural science, and observation-based political science with biophysical economics that includes expertise from academia and Civil Society Organisations.

In the AdaptEcon ITN twelve Early Stage Researchers (ESRs) are trained for a PhD at the University of Iceland (Reykjavik, Iceland), University of Clermont Auvergne (Clermont-Ferrand, France), Stockholm University (Stockholm, Sweden), Stockholm Resilience Center (Stockholm, Sweden).

The primary and the secondary universities for this PhD project are the University of Clermont Auvergne and the University of Iceland. Stockholm Environment Institute (SEI) in Sweden is a partner organization affiliated with this PhD project. In cooperation with them, a part of the research within this PhD thesis was conducted.

European Commission | Horizon 2020 European Union funding for Research & Innovation

MARIE CURIE ACTIONS

UNIVERSITATIS ISLANDIAE SIGILLUM

SEI Stockholm Environment Institute

ABSTRACT

In my PhD thesis, I explore 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. I started my PhD with exploring the current energy systems modelling practice as well as social science contribution in the sustainable energy research. I discovered several main research gaps related to the topic of this thesis: (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. This thesis has become an attempt to close the identified research gaps in order to answer the main research questions. System dynamics, steady-state economy and energy justice theory are the main methodological and conceptual components of the thesis' research design. The main results of my research are: (1) The list of questions defining the current energy paradigm which can be used as a guidance for a sustainable energy system modelling; (2) The 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; (2) The list of requirements for a socially sustainable energy provision based on the energy justice principles which can be used as guidelines for a sustainable energy policy assessment and design; (3) The system dynamics model of electricity access provision in Sub-Saharan Africa which demonstrates an example of how energy system modelling can be combined with sustainable energy system narratives for addressing methodological and disciplinary gaps in the energy system research and for contributing 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

RÉSUMÉ EN FRANÇAIS

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

TABLE OF CONTENTS

1. INTRODUCTION

A well-functioning energy system is a requirement of 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 reaching sustainable energy system state (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.

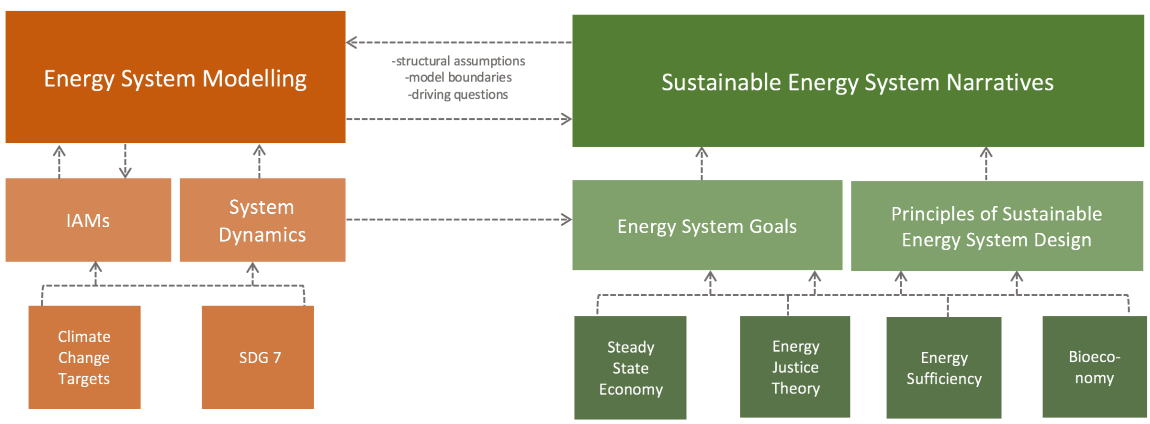
Energy system includes all "all components related to the production, conversion, delivery, and use of energy" (Bruckner et al., 2014). Despite this straightforward definition, the boundaries of the energy system are constantly changing. With the improved understanding of how the energy system is embedded in the economic, social and environmental systems, energy system problems are no longer perceived as predominantly technological, 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 problems, 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 the energy system research are changing along with recognizing energy system's higher complexity. Today, there are two main trends in the energy literature. On the one hand, social science research in the energy field is advancing. During the last decade, in the energy literature, despite still dominating engineering approach in the energy research, the number of the studies related to a social science domain has increased significantly (Sovacool, 2014; Ramazan *et al.*, 2017). On the other hand, energy system modelling field is advancing. Energy models gain increasing attention as the tools for informing decision-making (Hitch et al., 1977; Evans and Hausfather, 2018)

In this PhD project, I explore the energy system on a global scale. By connecting energy system modelling with the social science advancement in the energy research, I am trying to answer the following questions: *What is the energy system on a global scale that can be considered sustainable?* and *What methods and tools can help sustainable energy policy design and assessment?*

In the fig. 1, there is an overview of my PhD project, which includes all the main structural components present my research.

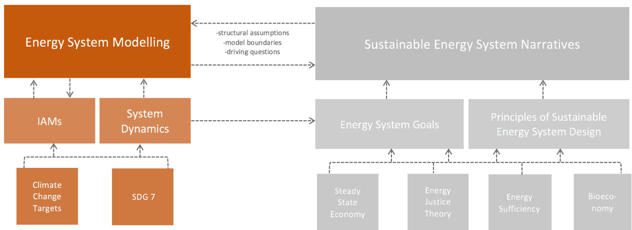
Fig. 1*. An overview of the PhD Thesis*



Energy system modelling and 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. There are seven papers included in this cumulative thesis. Each paper addresses some of the PhD thesis components depending on the specific research questions. In the Table 1, the full list of papers is provided. It includes the main research questions associated with each paper and a navigation scheme that helps to understand where each paper is placed in the full PhD thesis overview picture.

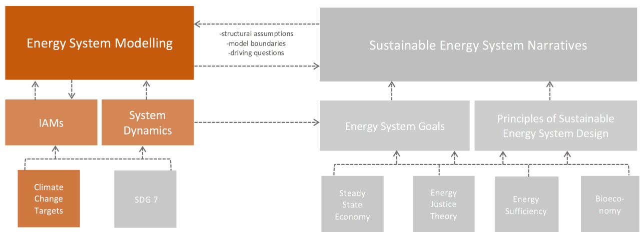
Table 1: *A full list of publications included in the PhD thesis*

<table>
<tr><td>Paper 1.

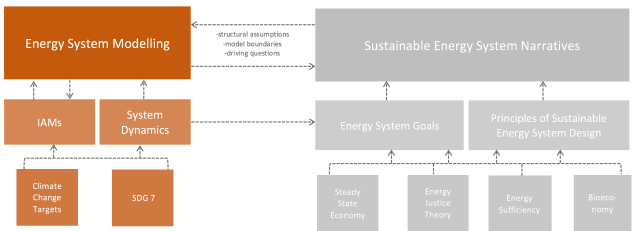
Understanding the current energy paradigm and energy system models for more sustainable energy system development</td><td>N. Spittler, G. Gladkykh, A. Diemer and B. Davíðsdóttir
Journal paper (Energies)
Link to the publication</td></tr>
<tr><td>
</td><td>→ How can the current energy paradigm be formulated?

→ To what extent do existing modelling tools correspond to the energy policy agenda and whether 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?</td></tr>
<tr><td>Paper 2.

Renewable energy characteristics and representation in macroeconomic energy-climate models</td><td>G. Gladkykh, N. Spittler, F. Dierickx
Book chapter (European Union and Sustainable development: challenges and prospects)
Link to the publication</td></tr>
<tr><td>
</td><td>→ 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?</td></tr>
<tr><td>Paper 3.

Integrated Assessment Models (IAM): How to integrate Energy, Climate and Economics?</td><td>B. Diemer, G. Gladkykh, N. Spittler, A. Ndiaye, D. Collste, F. Dierickx
Journal paper submitted, Oeconomia, under review</td></tr>
<tr><td>
</td><td>→ What are the main structural components, goals and assumptions on the policy drivers of the IAMs used for informing climate policy?

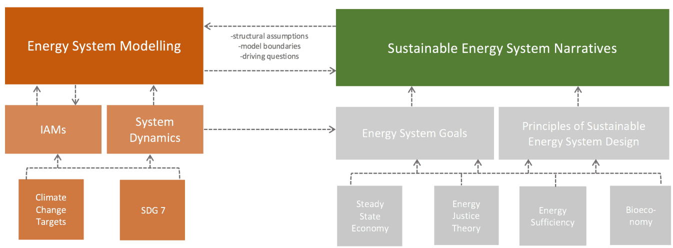
→ What are the main problems associated with the current generation of IAMs?</td></tr>
</table>

→ 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?

Paper 4.

Grounding social foundations for Integrated Assessment Models of climate change: Policy-makers need models with social assessment for developing efficient climate policies

J.-D. Mathias, M. Debeljak, G. Deffuant, A. Diemer, F. Dierickx, J. Donges, G. Gladkykh, J. Heitzig, G. Holtz, W. Obergassel, F. Pellaud, A. Sánchez, A. Trajanov, N. Videira
Journal paper submitted, under review



→ Why is it important to integrate the social dynamics in the IAMs?

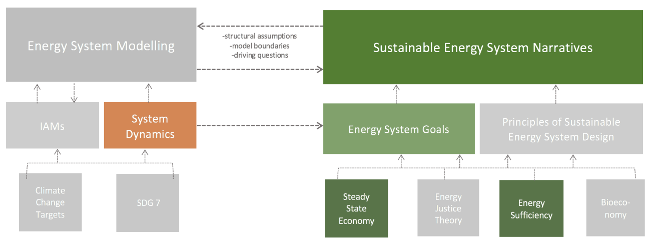
→ What are the ways of integrating social system dynamics in the IAMs?

→ How can the social drivers of and social impacts on climate change be addressed in the IAMs?

Paper 5.

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

G.Gladkykh, N. Spittler, B. Davíðsdóttir, A. Diemer
Journal paper (Energy Policy)
[Link to the publication]



→ To what extent can a steady state economy theory help to conceptualize a sustainable energy system?

→ What leverage points can be identified to achieve a sustainable energy system?

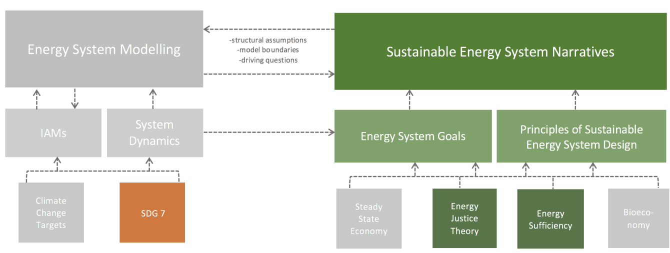
→ What are the implications of using a steady state economy concept for a sustainable energy system development on a global and national policy levels?

→ How feasible is the goal of a long-term energy system growth?

Paper 6.

Designing a socially sustainable energy system narrative based on the energy justice principles

G. Gladkykh, B. Davíðsdóttir, A. Diemer
Journal paper/Submission in process

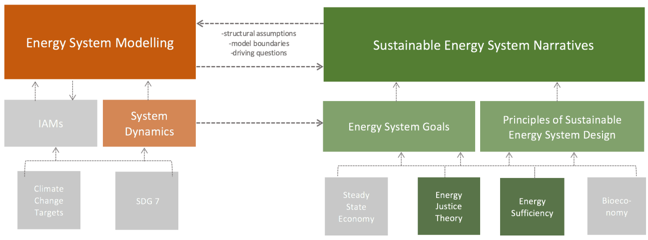
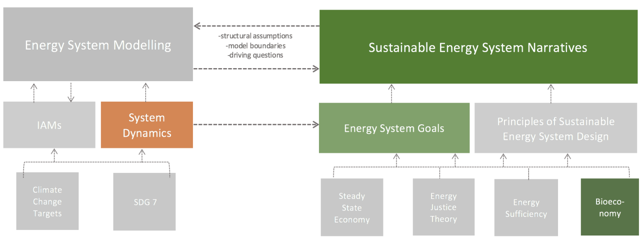


→ What are the principles of socially sustainable energy system design on a global scale?

→ What energy system goals on a global scale are compatible with the socially sustainable energy system?

→ What are the principles of energy access provision that can be considered socially sustainable?

→ How can energy justice theory be operationalized to formulate the

	principles of socially sustainable energy system?
Paper 7. ***A case of electricity sufficiency for Sub-Saharan Africa: combining system dynamics modelling with a socially sustainable energy system narrative***	G. Gladkykh, A. Diemer, B. Davíðsdóttir Journal paper/Submission in process
	→ How can energy system modelling be combined with the theoretical advancement in the energy systems research? → How a combination of theoretical work with modelling can help creating the tools for socially sustainable energy system policy assessment and design? → How can system dynamics modelling and energy justice theory be connected for a better understanding of cost and benefits associated with different ways of energy access provision?
Paper 8. ***Developing an analytical toolkit for a participatory design of bioeconomy visions***	G. Gladkykh, F.X. Johnson (based on collaborative work with Stockholm Environment Institute) Journal paper/Submission in process
	→ What are the available visions of bioeconomy development by 2050 in the Global North and the Global South context? → What role does energy system development play in different bioeconomy visions? → How do the goals of bioeconomy correspond to the goals of sustainable energy system? → What are the social justice implications of a biomass use in the context of sustainable bioeconomy visions on a global scale?

1.1. Energy system modelling

A part of this PhD project 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. In Paper 1 (table 1), I explored how different types of energy system models correspond to the overall sustainability agenda and presented a list of questions incorporating the most important components which need to be addressed in the current generation of energy system models. These questions constitute a so-called current energy paradigm. 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.

By comparing selected energy models with the formulated energy paradigm, I conclude that there are some assumptions about biophysical and social reality that are missing in the majority of energy models and emphasize the importance of developing the new modelling approaches and tools. Being aware of the fact that each model serves a specific purpose and is not supposed to answer all the questions, I came up with the categorization of different types of energy 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.

Integrated Assessment Models (IAMs) were analyzed in the context of the current energy paradigm, (Papers 2, 3 and 4 in the table 1). IAMs play an important role in the energy and climate policy-making, and aim to address interactions between the economy and climate impacts. In Paper 2, I reviewed several energy-climate IAMs used for informing climate policies. Considering that renewable energy transition is the highest priority in the global climate change mitigation agenda, the main research interest was directed at exploring the assumptions of modelling renewable energy sources in those models. 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. I discovered that in most IAMs, there are no connections between the stocks of non-renewable natural resources and renewable energy production. Acknowledging this limitation in the way renewables are modelled in the IAMs 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.

In Paper 3 which is also dedicated to the review of IAMs, I compare the way climate-energy-economy nexus is addressed in the integrated models. I explore how the core modelling structures across different generations of IAMs have changed historically. The analysis revealed that current generation of IAMs, due to advancement in research and increased capacities of the modelling tools, address 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 the new research methods and tools that can challenge established IAMs modelling practice (Gambhir et al., 2019). In Paper 4, the gaps in the current IAMs related to the social dynamics structural assumptions as well as suggestions on methodological suggestions on closing those gaps are discussed in more detail.

1.2. Sustainable energy system narratives

The second thematic part of this PhD thesis is related to exploring 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.

There are two building blocks of the sustainable energy system narratives that I explore in this thesis (fig. 1): (i) energy system goals and (ii) the principles of a sustainable energy system design.

The importance of the energy system goal-setting is discussed in Paper 6 and 7 (table 1). System dynamics is applied in this study as the main approach used for defining and conceptualizing energy system goals.

System dynamics is based on systems thinking principles. It is an approach to understanding causal linkages, feedback loops, rates and levels, 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 qualitative (Causal Loop Diagrams or CLDs) and quantitative System Dynamics modelling tools (Stock and Flow Diagrams or SFDs) (Sterman, 2000). Both of these tools are used in paper 6 at the model's conceptualization and simulation stages.

In Paper 6, I argue that the way energy system goals are formulated in the SDG7 (United Nations, 2015) provides only fragmented understanding of the targets to be met in the future and does not contain a vision of the globally sustainable energy system. Besides, SDG7 is based on the implicit assumption of the long-term energy system growth, which looks controversial considering that absolute decoupling is impossible (Parrique et al., 2019). Taking all this into account, I argue 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 the sustainability principles.

In Paper 5, I explore a sustainable energy system narrative from a biophysical perspective. In this paper, I depart from Daly's concept of a steady-state economy (Daly, 1974). I look at the energy system in a holistic manner aiming to understand underlying biophysical dynamics of the energy system development over time. As a result of this theoretical analysis, I introduce the Steady State of Energy concept, where energy sufficiency is defined as a universal sustainable energy system goal on a global scale. Having conducted a conceptual analysis of the energy system leverage points, I 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. I argue 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 based on the Meadows' framework (1997). Using this framework, I classified global energy policies according to the level of their systemic impact. Transition to the renewables as well as energy efficiency increase were, among other energy policies, which are on the top of the current energy policy agenda, were 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 the natural resources, which is incompatible with the 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).

In Paper 6 (table 1), I elaborate the concept of energy sufficiency as a universal energy system goal further by exploring it from a social sustainability perspective. In this study, I design a socially sustainable energy system narrative, which includes universal energy sufficiency as a socially desirable energy system goal, with the set minimum and maximum levels of energy services per capita. In this paper, I also define energy transition and energy access provision as the energy sufficiency sub-goals.

In that context, energy transition is the goal associated with the Global North, where transition from a fossil-fuel-based energy system to a renewable-energy-based one is the main focus. Energy access provision, in turn, is primarily applicable in the Global South, where more energy infrastructure is yet to be built and more energy services are to be provided.

As it was stated in fig. 1, the second component of a socially sustainable energy system narrative is the principles of a socially sustainable energy provision. In Paper 6, such principles are formulated based on the energy justice concept (Jenkins *et al.*, 2016; Ramazan *et al.*, 2017; Biros *et al.*, 2018).

In the modern energy literature, energy justice is the best elaborated normative theory that brings social justice principles into the energy system research. Energy justice positions itself 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). For the purpose of designing the principles of a socially sustainable energy provision, I operationalized the three main energy justice pillars (i.e. procedural, distributional and recognition justice) (Jenkins et al., 2016) 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). 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. In Paper 6, I conclude that these energy provision principles, together with the energy sufficiency goal, comprise a socially sustainable energy system narrative on a global scale.

1.3. Connecting energy system modelling with a sustainable energy system narrative

The two main research threads – energy system modelling and sustainable energy system narratives – are connected together in Paper 7 (table 1). In this paper, I combine system dynamics modelling with the formulated in Paper 7 narrative of a socially sustainable energy system, aiming to provide a methodological example of how energy system modelling and sustainable energy system narratives can be combined.

In the modelling exercise, the principles of a socially sustainable energy provision and the energy sufficiency goal are combined with system dynamics to simulate the case of providing access to a sufficient amount of electricity for rural and urban households in Sub-Saharan Africa. This case is aimed at being 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, I compared a default simulation run with the two normative scenarios. The normative scenarios excluded from an electricity generation mix those types of technologies that did not correspond to the socially sustainable energy provision principles formulated in Paper 7. A comparison between the default model run and the two normative scenarios allowed to identify controversies and trade-offs between types of energy access provision. Particularly, the analysis showed how compatible different renewables-based and fossil-fuel-based energy technologies, as well centralized and decentralized types of energy generation, with the designed principles of a socially sustainable energy provision.

I see this modelling exercise being a contribution to the interdisciplinary energy system literature, since it demonstrates how the theoretical assumptions about the energy system structure can be connected to the energy system modelling and become more instrumental for a sustainable energy policy design and assessment.

1.4. Bioeconomy as an example of a sustainable economy narrative

A part of this PhD thesis project (Paper 8) diverges from purely discussing energy systems and is related to exploring bioeconomy narratives. In collaboration with the Stockholm Environment Institute (SEI, 2018), I conducted a study on exploring bioeconomy visions in Thailand and compared them to the visions in the bioeconomy literature from different Global North and Global South countries. The data for this study was collected during a participatory workshop and was analyzed using the CLDs – the above-mentioned system dynamics tool for a qualitative systemic analysis. The fact that the scale of a bioeconomy is bigger than a scale of energy system allowed to raise the questions on what is the role of the energy system in designing sustainable economy futures, and how energy system goals correspond to the general goals of sustainable economic development, on the example of a sustainable bioeconomy narrative.

Overall, with this PhD project, I aimed to contribute to the interdisciplinary energy system research and to provide a specific theoretical contribution into the energy justice theory.

energies

MDPI

Review

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

Nathalie Spittler [1,2,*], Ganna Gladkykh [1,2], Arnaud Diemer [2] and Brynhildur Davidsdottir [1]

1 Department of Life and Environmental Sciences, University of Iceland, Reykjavik 101, Iceland, Sæmundargata 2, 101 Reykjavík, Iceland; ganna.gladkykh@uca.fr (G.G.); bdavids@hi.is (B.D.)
2 Department of Economics, University of Clermont Auvergne, 63000 Clermont Ferrand, France, diemera@aol.com
* Correspondence: nas14@hi.is; Tel.: +43-650-790-8353

Received: 26 March 2019; Accepted: 17 April 2019; Published: 25 April 2019

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).

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	Energy is central for sustainable development Link between energy and socio-economic development (incl. energy relation to poverty, urbanization, population dynamics)	IAEA, IEA, UNDESA, Eurostat and EEA indicator set World Energy Assessment - Energy and the Challenge of Sustainability by UNDP

	Kyoto protocol Creation of EU ETS	Cross-scale energy systems impacts (national/regional impact on global and vice versa)	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

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 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.

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 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.

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.

Author Contributions: Conceptualization, G.G. and N.S.; methodology, N.S.; formal analysis, N.S. and G.G.; writing—original draft preparation, G.G. and N.S.; writing—review and editing, N.S. and G.G.; supervision, A.D. and B.D.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675153.

Conflicts of Interest: The authors declare no conflict of interest.

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

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

Ganna GLADKYKH, Nathalie SPITTLER, Florian DIERICKX

University Clermont Auvergne, CERDI-OR2D, University of Iceland, AdaptEcon II

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.).

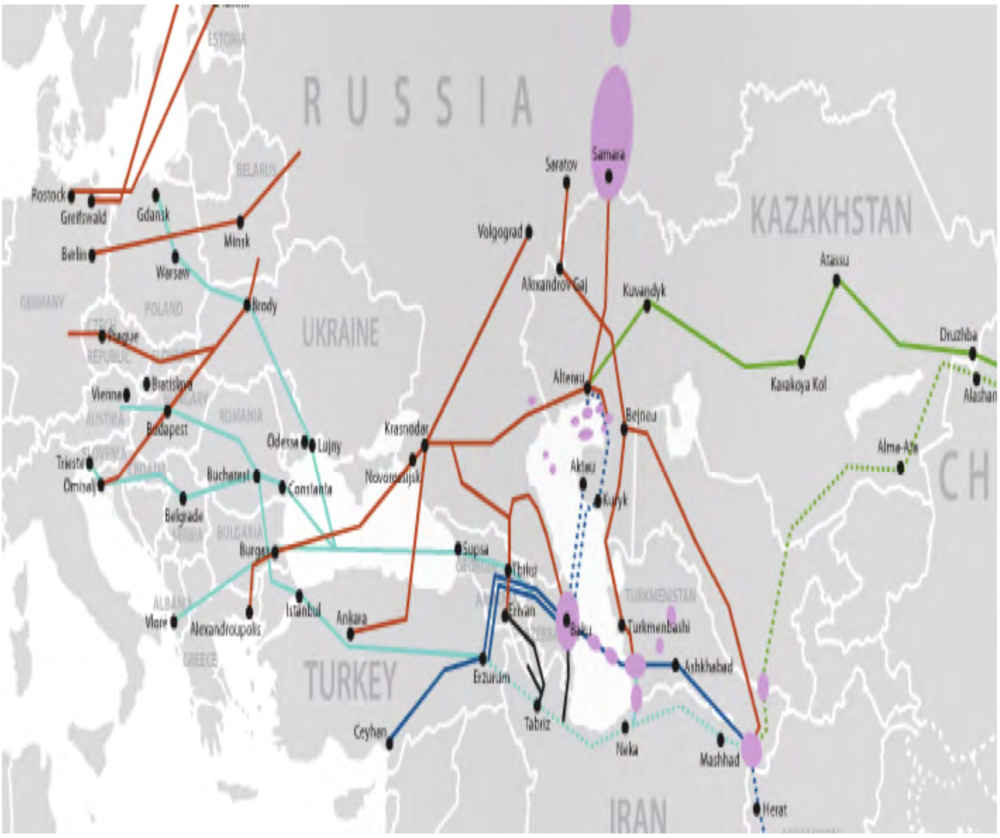
It can be interesting to know, to which extent institutions reflect on whether the values associated with large-scale renewable energy projects around the world are compatible with the values it defends on its territory. In the EU context, an example of a large-scale deployment of renewable energy is 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.

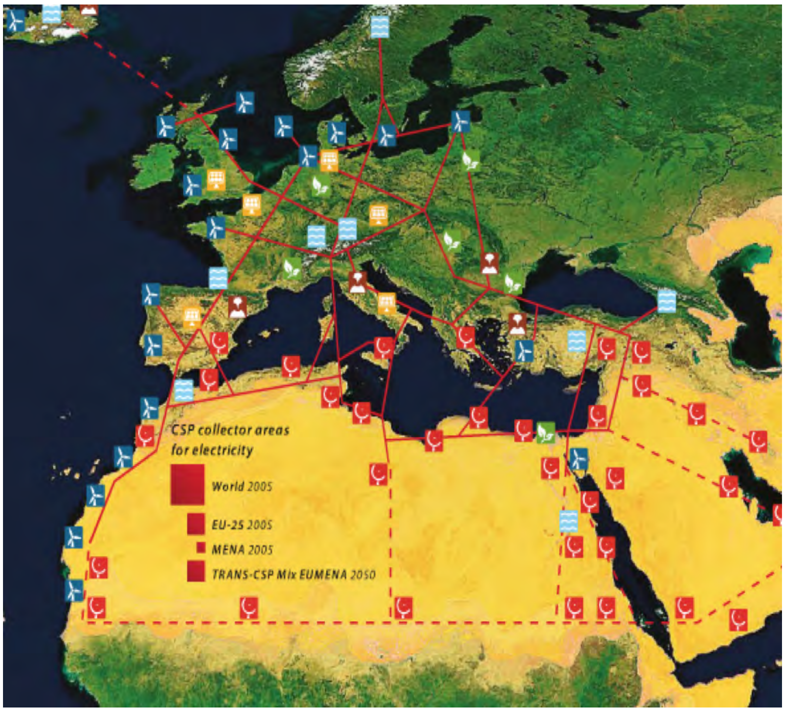
Social and geopolitical aspects discussed here, despite being very important, are not usually taken into account in macroeconomic energy-climate models. To ensure feasible modelling results, those aspects are to be discussed in the models' assumptions.

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).

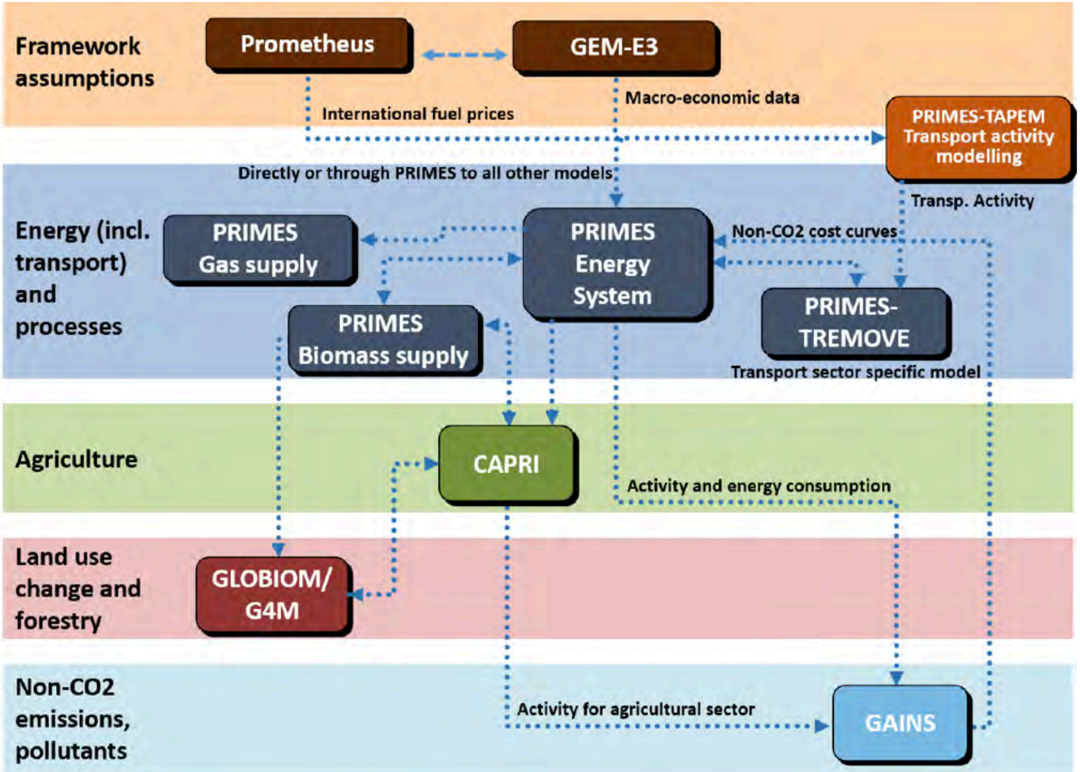
Originally GEM-E3 and PRIMES were designed as stand-alone models used for analysing the global economy and EU energy markets. For the purpose of addressing the needs for climate and energy policy making at the EU level these two models were coupled into the one hybrid structure. The intention of coupling 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.

Integrated Assessment Models (IAM)

How to integrate Energy, Climate and Economics?

Arnaud DIEMER, Ganna GLADKYKH, Nathalie SPITTLER
Abdourakhmane NDIAYE, David COLLSTE, Florian DIERICKX
Université Clermont Auvergne, CNRS, IRD, CERDI, F-63000 Clermont-Ferrand, France.

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.

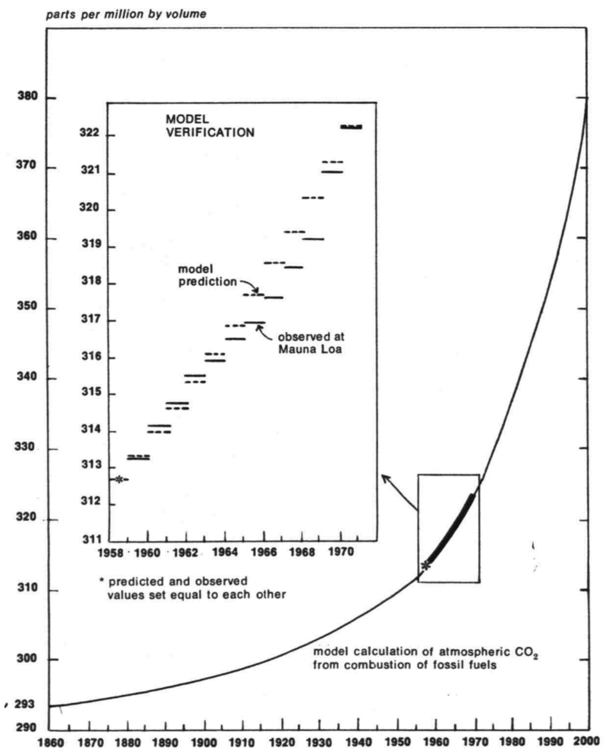
They include deterministic projection models in which each input and output takes a single value, and stochastic projection models in which at least some inputs and outputs take a range of values. Policy evaluation models take actions by agents and governments as given, provided by policy proposals,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

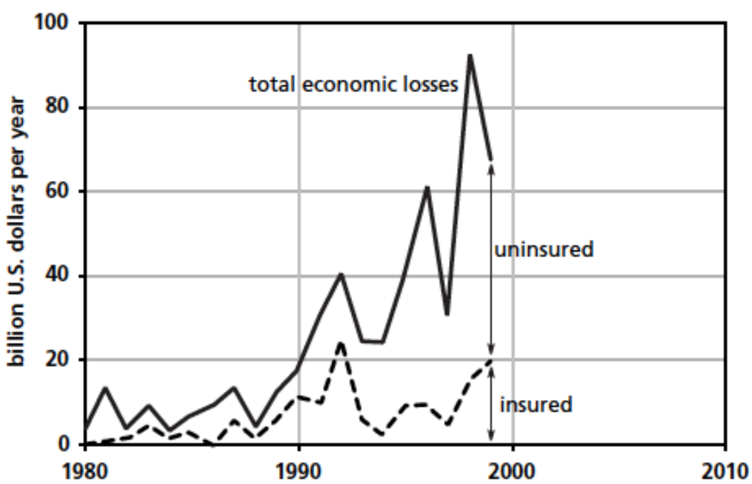


Source : Meadows et al. (1972, p. 72)

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).

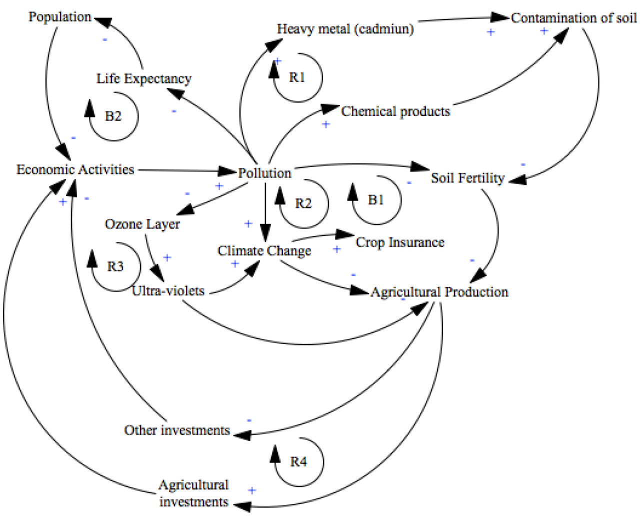
Figure 2: Worldwide Economic Losses from Weather Related Disasters



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…*

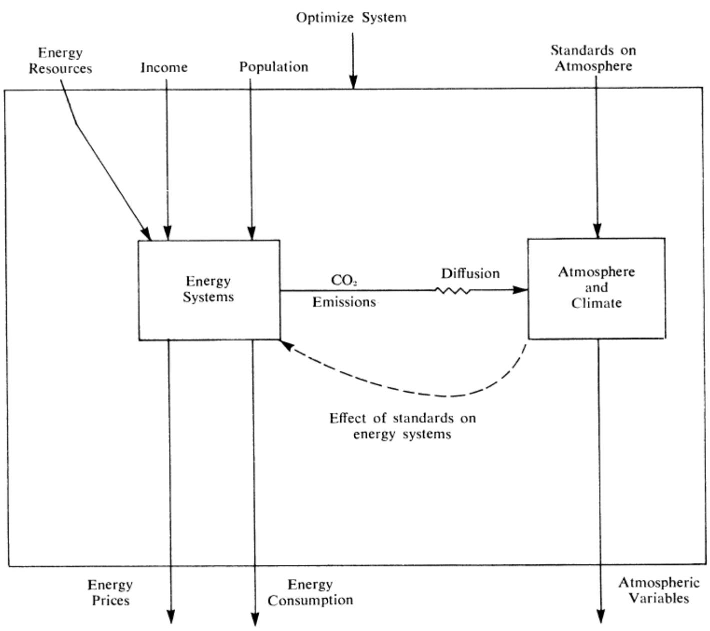
Fourth, the methodology of modelling in World Dynamics differs significantly from other studies of economic systems…Fifth, the predictions of the world's future are highly sensitive to the specification of the model… Sixth, there is a lack of humility toward predicting the future" (1973, p. 1183).

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.

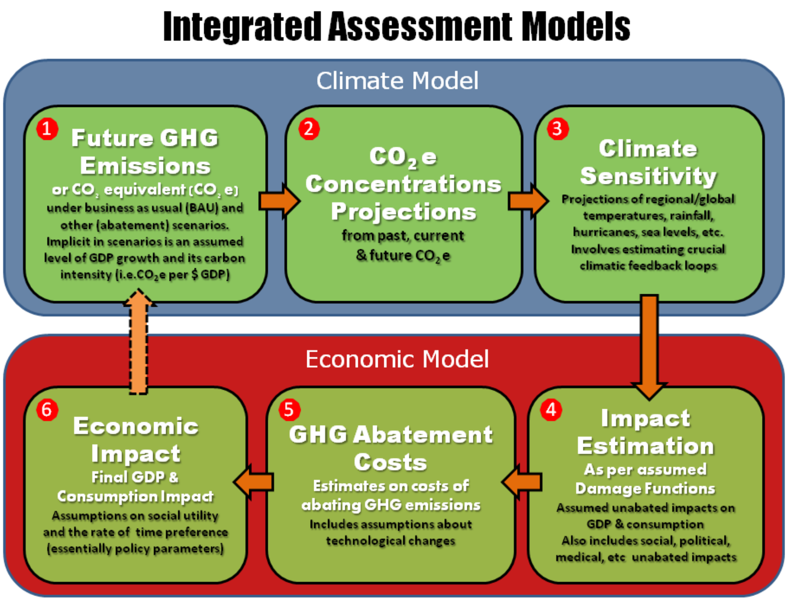
It was not until the 1990s that the DICE (Dynamic Integrated Model of Climate and the Economy) and RICE (Regional Integrated Model of Climate and the Economy) family of models was born (Nordhaus, 1992, 1994). The DICE model is a dynamic optimization model (Ramsey, 1920) which seeks to estimate the optimal 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

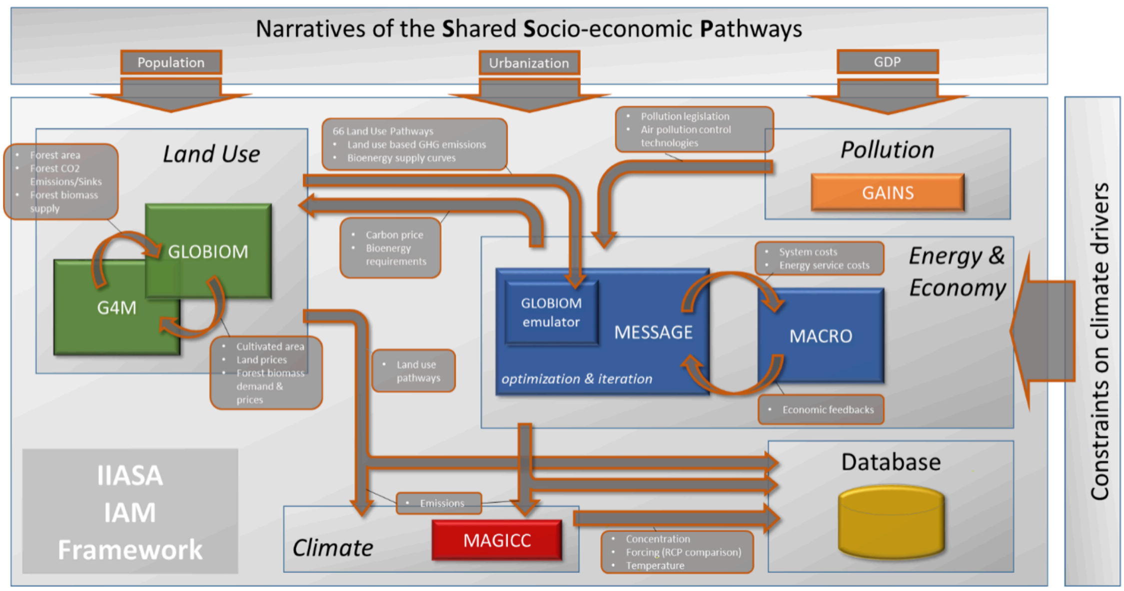
Source: O'Neill et al (2014, p. 391; 2015, p. 2)

[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.

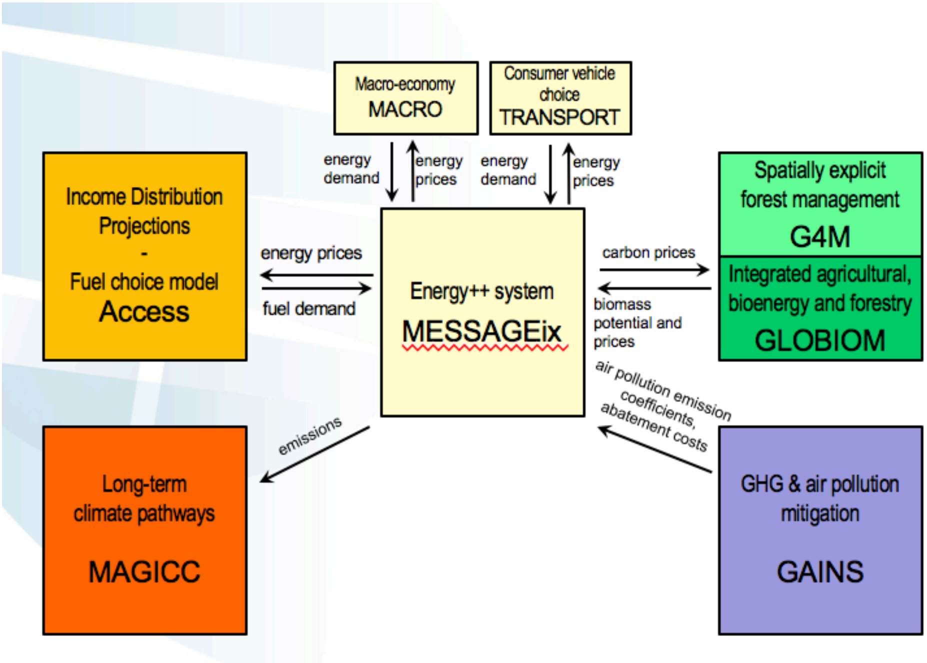
(iii) Linkages to models such as the agricultural model GLOBIOM (Global BIOsphere Management) and the air pollution one GAINS (Greenhouse gas – Air pollution Interactions and Synergies) permit the assessment of other possible effects of energy system developments in other relevant fields. GLOBIOM is 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.

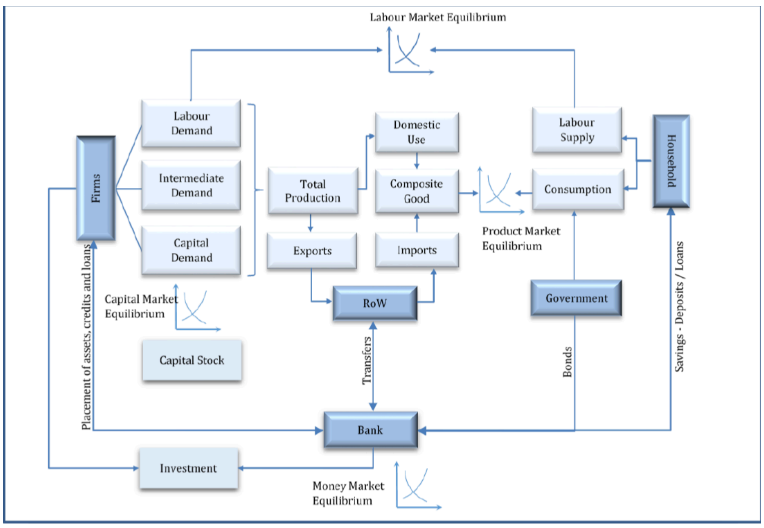
The model calculates the equilibrium prices of goods, services, labor, and capital which simultaneously clear all markets under the Walras Law (Capros, Van Regemorter, Paroussos, Karkatsoulis, 2015). The model follows a computable general equilibrium approach[6].

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

- Demand for finance: Each agent (in deficit) can receive a loan from domestic capital markets that needs to repaid in a given time period at a market clearing interest rate
- Supply of finance: Each agent (in surplus) owns a portfolio of financial products with different returns and risks.

without financial sector	with financial sector
Debt accumulation does not have an impact on the real economy and/or interest rates Depending on the closure rule the financing of an investment project takes place in one period (at the period where the investment products are constructed) and can be financed from the sector, country or abroad. In a given year/period alternative investment projects compete for the same capital resources (crowding out effect)	Agents financing is subject to their financial position (surplus – deficit). Detailed representation of financial products and detailed accounting of the financial position of each economic agent. Book keeping of stock/flow relationships on debt accounting (domestic and external Private and Public debt) Endogenous computation of interest rates for alternative uses of financial resources (deposits, bonds etc.) Use of the endogenous interest rates for rationing financing decisions The option to create payback schedules that span over many periods moderates considerably the crowding out effect

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)

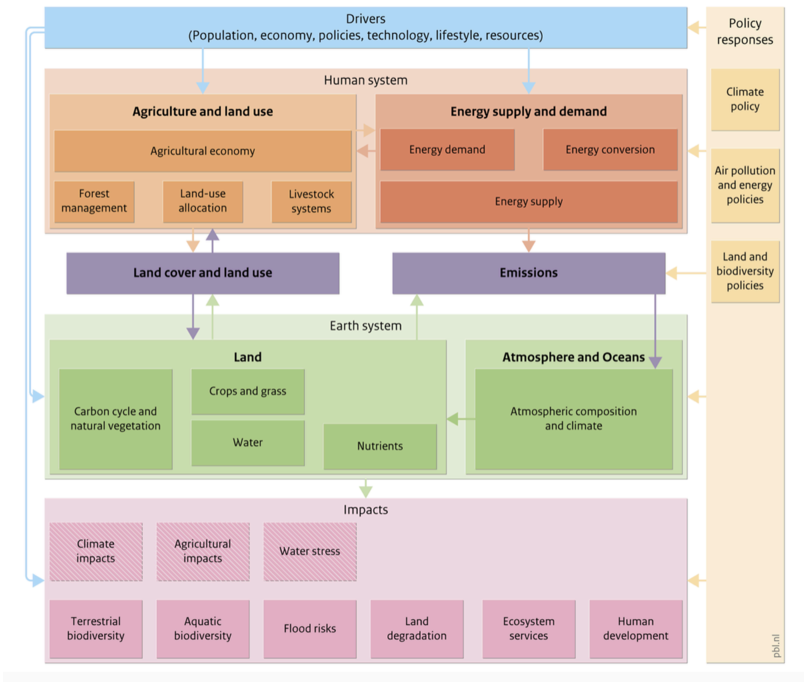
- it includes projections of the Input/Output Table (IOT) for country national accounts, employment, capital, monetary and financial flows, etc based on Eurostat data.

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.

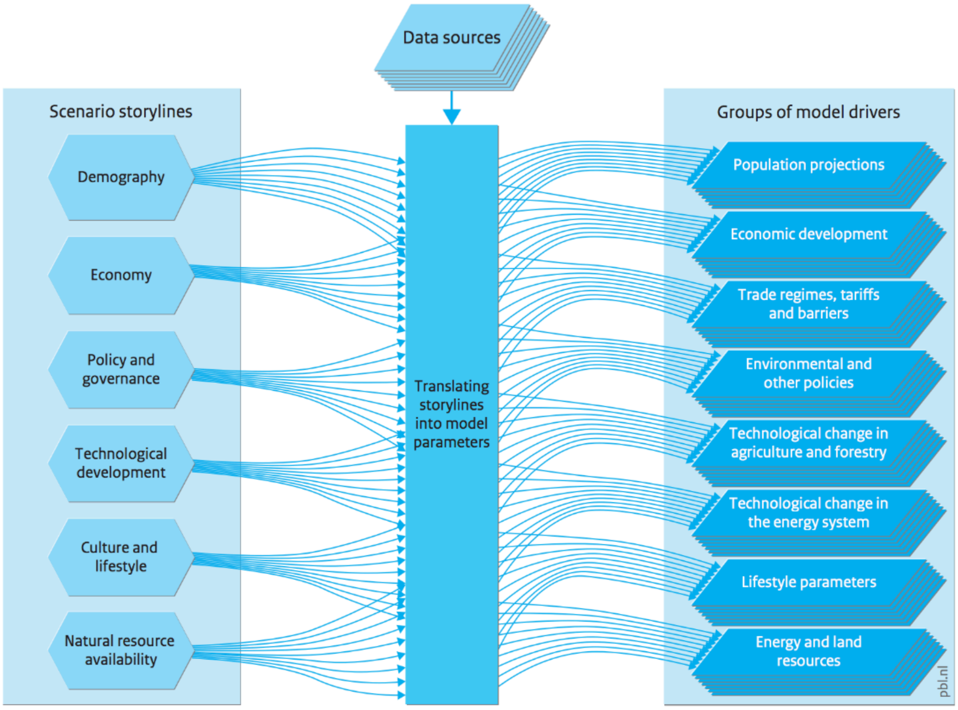
Within the family of the IAMs, IMAGE developers classify the model within the IAM typology as a *Process-oriented energy/land IAM framework*. The models of this type are of an intermediate complexity for the human and the earth systems (van Vuuren et al, 2015).

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)

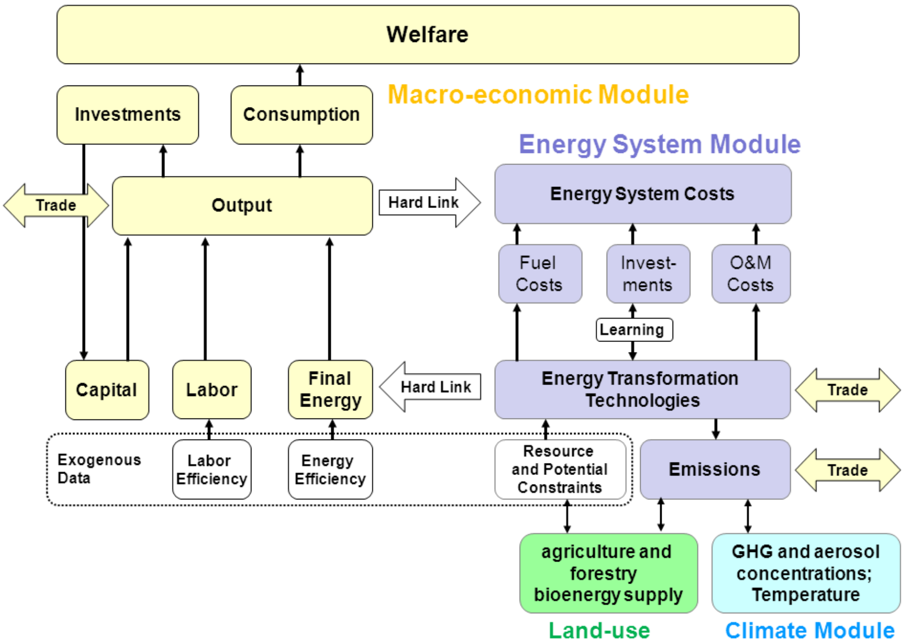
IMAGE is aimed at providing an Integrated Environmental Assessment and at being used for policy analysis. The main clients of IMAGE include the Dutch Government, the European Commission, international organizations, such as IPCC, UNEP and OECD, and the research community. In the future, efforts will 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.

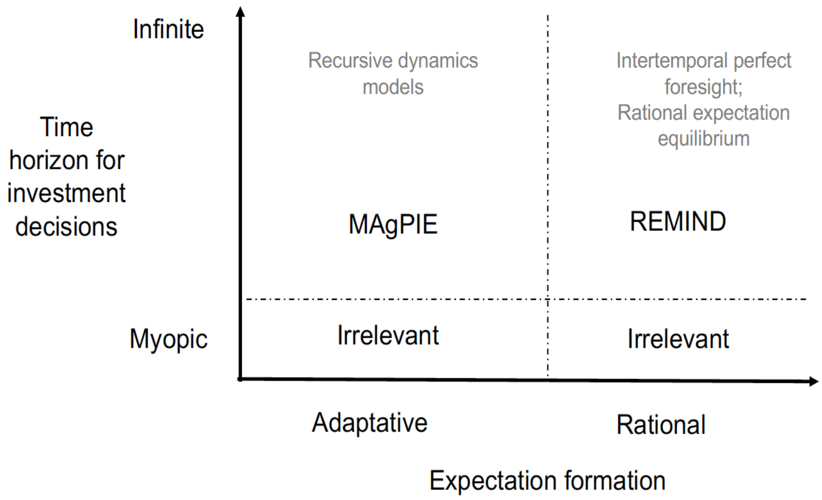
Table 1: Main characteristics of REMIND-R

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.

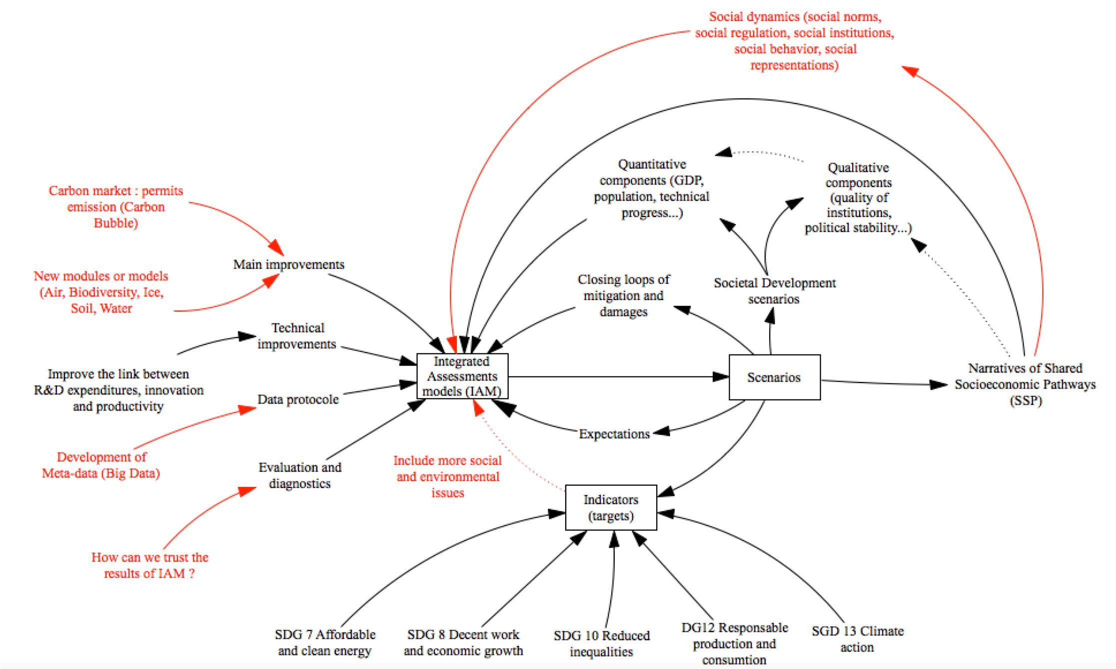
IAM	DICE	MESSAGE	IMAGE	GEM-3E	REMIND
Macroeconomic core of the model	Dynamic Optimization Model (Ramsey, 1920)	None but soft-linked to general equilibrium model MACRO	The economy is represented separately by different model components. The model is not suitable to assess detailed economic impacts, such 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.

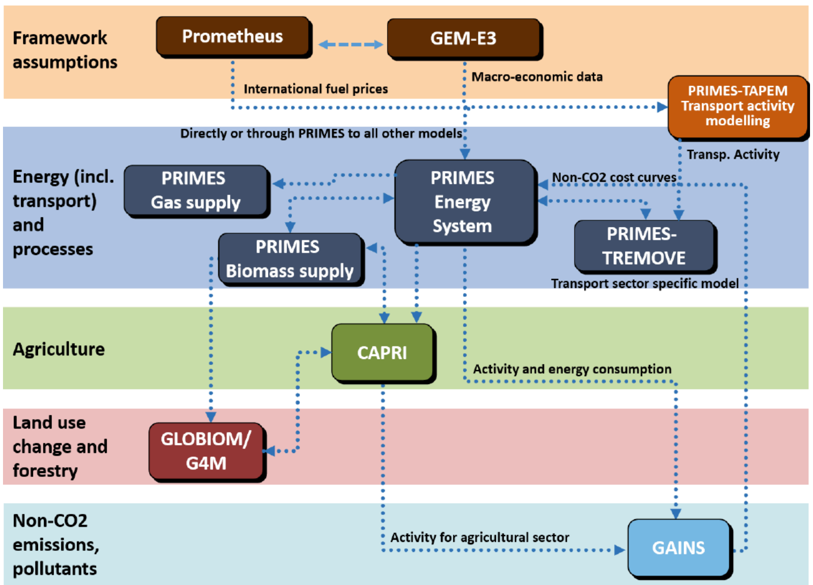
Indicators, like targets, can help to introduce more social and environmental issues - Stakeholders would fix the targets they want to reach; national policies could explain the gap between expectations and results.

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.

Grounding social foundations for Integrated Assessment Models of climate change

Policy-makers need models with social assessment for developing efficient climate policies.

Jean-Denis Mathias[1], Marko Debeljak[2], Guillaume Deffuant[1], Arnaud Diemer[3], Florian Dierickx[3], Jonathan Donges[4], Ganna Gladkykh[3], Jobst Heitzig[5], Georg Holtz[6], Wolfgang Obergassel[6], Francine Pellaud[7], Angel Sánchez[8,9], Aneta Trajanov[2], Nuno Videira[10]

[1]Université Clermont Auvergne, Irstea, UR LISC, Centre de Clermont-Ferrand, 9 avenue Blaise Pascal CS 20085, F-63178 Aubière, France

[2]Department of Knowledge Technologies, Jozef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia

[3]Université Clermont Auvergne, CERDI, ERASME (Jean Monnet Excellence Center on Sustainability), 2 avenue Blaise Pascal, 63178 Aubière, France

[4]FutureLab on Earth Resilience in the Anthropocene, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany

[5]FutureLab on Game Theory and Networks of Interacting Agents, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany

[6]Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany

[7]Haute école pédagogique de Fribourg, CH-1700 Fribourg, Switzerland

[8]BIFI, Universidad de Zaragoza, c/ Mariano Esquillor (Edificio I+D), 50018 Zaragoza, Spain

[9]GISC / UMICCS / IBiDat, Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911 Leganés, Spain

[10]CENSE – Center for Environmental and Sustainability Research, NOVA School of Science and Technology, NOVA University Lisbon, Campus da Caparica, 2829-516 Caparica, Portugal

The progress in reaching climate policy goals so far has been much slower than needed to avoid catastrophic consequences. Achieving the goals of the Paris Agreement on climate change requires a fundamental transition of the economy and society that is comparable in scale to the industrial revolution or the Neolithic revolution. Such fundamental transitions are "*the result of a co-evolution of economic, cultural, technological, ecological and institutional developments at different scale-levels*" (*1*). To design feasible and viable transition pathways, we need decision-support tools that incorporate the complexity and interdisciplinary associated with such a multi-dimensional transition. Integrated Assessment Models (IAMs) are famous for being decision-making support tools for designing climate policy solutions and have been used for informing climate policy for several decades. However, the structures of currently existing IAMs are mostly oriented at understanding interactions between economics and biophysical systems, while the principles of the social system functioning and the behavior of actors involved are addressed in the models to a limited extent. Being convinced that IAMs will and should remain key tools for informing decision-making in the climate policy domain, we argue that IAMs need to be transformed on the level of the models' structure in order to help reaching the Paris Agreement goals as soon as possible.

IAM development has generally moved from a narrow, disciplinary orientation to more complex and integrated structures. While the earlier generation of IAMs aimed at answering quite specific research questions (e.g. DICE (*2*)), the new generation of IAMs (see e.g. latest versions of IMAGE (*3*)) focuses on a much wider range of research questions and on multidisciplinary and integrated approaches. However, despite a higher level of integration of different domains in the IAMs' structures, social complexity is rarely portrayed there beyond purely economic behavior. Indeed, in terms of social dynamics, existing IAMs typically consider the whole world (or a small number of world regions for the RICE model) as just one or a small number of rational and farsighted agents with "rational expectations" (i.e. correct beliefs about the future) who make decisions that optimize social welfare (measured in economic terms) over the analysed time period. The goal of this approach is the identification of cost optimal pathways for climate change mitigation from a technological and economic point of view. Questions of implementation of the identified pathways in a complex social world and mitigation of social impacts are left to subsequent considerations. We argue that the identification of optimal pathways has merit by providing a benchmark for action, but that those IAMs provide limited guidance for the design of effective climate mitigation policies. In particular, such IAMs are designed to be blind to social drivers, impacts and complexity.

When it comes to better understanding what the role of the "social" is in this context, we argue that it is important to distinguish between social dynamics that *drive* climate change from those that are *impacted* by climate change. Finally, it is essential to understand whether and how actions of different parties are mutually dependent, and how they unfold synergies or counteract each other because of social complexity. On the impact side of social dynamics, the concept of social cost of carbon (*4*) currently dominates climate policy discourse, addressing such issues as climate change effect on agricultural productivity, human health, or property damages for instance (*5*). Therefore, for better accounting of social cost, it has become increasingly important to address in IAMs such social system aspects as equality, welfare distribution, ethical or justice issues (*6*). Increased accuracy of climate damages accounting will be beneficial for understanding both the underestimated and the overestimated share of social costs (*6*).

Building climate transition pathways on social foundations

IPCC – as well as a large part of the scientific community – favors transition pathways that include social aspects such as motivational factors, institutional feasibility or behavioral changes. However, we have to move forward from these intentions to operational tools for policy-makers. For developing such operational tools, we suggest a "paradigm shift" in IAM development. In particular, the above outlined social drivers are neglected in IAMs and their use, so far. However, they are crucial for understanding actual dynamics of climate change mitigation action. Moreover, including them in models becomes all the more important as soon as social impacts of climate change begin to affect social drivers – leading to a feedback loop that may drive non-linear dynamics which traditional IAMs are not able to capture. As a starting point, we argue that IAMs should progressively include the results that connect economics with social sciences as IAMs currently connect economics with climate. More specifically, IAMs are mainly founded in neoclassical economics while several other branches of economics consider social aspects. Among them, we point out three branches of economics from which social processes may be considered and formalized for tackling climate issues: behavioral economics, welfare economics and political economics.

First, behavioral economics may overcome the limitation of rational choice theory by formalizing psychological processes involved in climate-economics interactions. Indeed, while most IAMs focus on economic decisions by a hypothetical rational social planner, actual technological and behavioral change comes from many boundedly rational players at different societal levels, interacting not only via price signals but also through non-economic processes such as social norms, spreading information or preferences with non-monetary components. For instance, a recent study in North Carolina (USA) shows the impact of intergenerational learning on the perception of climate change (*7*). This study shows how education of children may affect the behavior of parents without any economic incentives. The emerging fields of social simulation and complexity economics suggest that such behavioral effects can cause much more nonlinear trajectories than represented in close-to-equilibrium economic models, containing tipping behavior highly relevant for the transitions that IAMs are meant to study (*8*).

Second, formalizing components of welfare economics in IAMs may evaluate inequity and distributional impacts that affect the feasibility of climate policies (*9*) as shown, for instance, by the "yellow jacket" crisis in France. The fuel tax implemented by the French government created distributional effects (especially between rural and urban populations) yielding weekly protestations whereas the same people support actions against climate change. Existing IAMs analyze measures based on their consequences on the whole economy (GDP) and on CO_2 emissions. However, such measures also have distributional effects within the economy (i.e. *who "wins" and who "loses"*) that may affect population's welfare. A truly "integrated assessment" of climate protection measures should include an assessment of such distributional side-effects, because those side-effects are the most important in the feasibility of measures. The current approach of IAMs to inequality is to disregard it or at best include it in some inequality-averse welfare measure that is then used as the optimization target. This ignores however the feedback effects of inequality on economic pathways and on the feasibility of policy measures. Welfare economics can therefore provide operational tools (*10*) in order not to reinforce potential inequalities that may emerge from climate policies. Since agents' perceptions of what a just climate policy regime is not only depend on issues such as inequality but also strongly on various notions of historical responsibility, the design of welfare measures for use in IAMs should also make use of tools from the emerging field of formal ethics (*11*).

Third, political economics would highlight resistance or support dynamics on climate policies emerging from the effects of political power and lobbying. These political processes are neglected in IAMs whereas measures have to be decided within a socio-political context that renders some measures unfeasible while others may receive more support from influential actor groups. Political leaders typically seek compromise with important stakeholder groups beforehand. For instance, in the case of the Waxman-Markey bill in USA which would have set a limit on the emission of greenhouse gases, the role of political lobbying over climate policy has been estimated to US$60 billion in terms of social costs (*12*). In this latter case, the effect of lobbying has been neglected whereas it significantly downsizes the expected results. Such socio-political factors contributing to the lack of climate ambition are not taken into account in IAMs so far despite of their well-established impacts (*12*).

Integrating these three main social strands in IAMs requires not only the inclusion of state-of-the-art and cutting-edge model components but also the acquisition of social data for driving and validating the models. Either such data are readily available (e.g. input-output tables, data from social networks) or data have to be elicited and assessed. Eliciting and assessing new social data may be done through a variety of participatory modelling approaches to collect perceptions of large participant groups, focusing on social climate change issues connecting to geographical locations. Such massive data may be collected through qualitative surveys and expertise using participatory face-to-face or online approaches. Once data are collected, analysis becomes challenging due to its volume and heterogeneity. Artificial intelligence – based on data mining – is a natural way for addressing the issue of quantity and heterogeneity of data for extracting social patterns. Methods for social media mining (*13*) such as sentiment analysis, relational data mining and predictive modeling can represent powerful tools for discovering social patterns in data, which enriches the existing process- or cost-based IAMs with an additional social component (Figure 1).

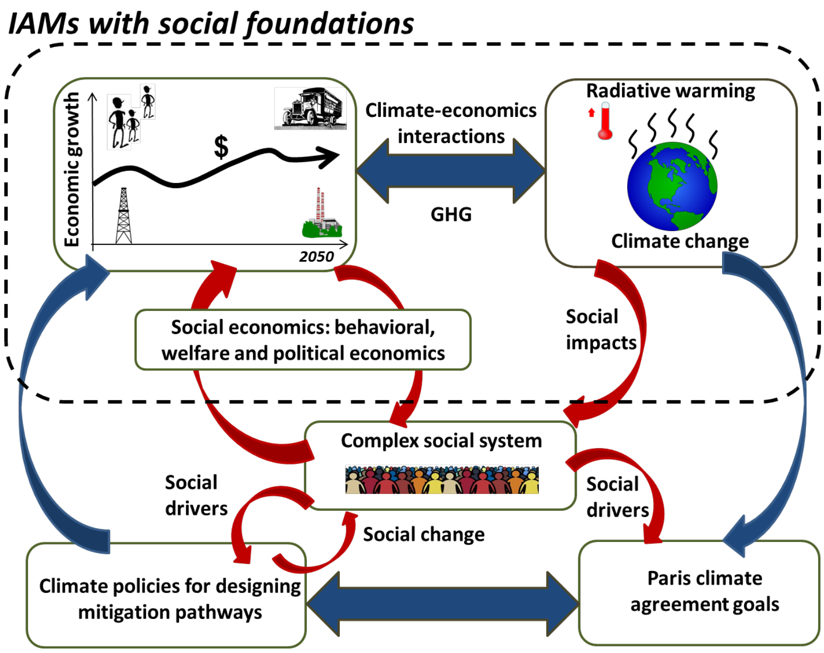


Figure 1: the role of complex social system on climate dynamics. IAMs should progressively include complex social dynamics through social branches of economics (e.g. behavioral, welfare or political economics) that are natural connections between social and economics processes already used in IAMs.

Implementing the global response through the lens of social change

At a glance, developing efficient climate policy means to introduce a coherent methodological perspective by extending IAMs' structure towards economics that takes into account social aspects, such as behavioral, welfare or political economics. These branches of economics will foster the integration of social processes in the existing modeling of economics-climate interactions. Besides, the social branches of economics also require fundamental efforts in the different fields of social sciences as sociology, psychology, political sciences, cultural multi-scalar structure and so on. However, we argue that considering these domains as a bridge between social foundations and IAMs is required for moving from intentions to actions. Once these social foundations are built up IAMs, they will open up new perspectives for climate actors in terms of mitigation pathways. More specifically, one key-outcome of considering social aspects in IAMs – and therefore in climate policies – may be a greater attention to social dynamics for coping with climate change. This transformation may be driven by different social approaches based on the nudge theory or social innovations (*14*). For instance, social innovations refer to new ways of meeting social needs or delivering social benefits to communities. Their implementation is sought to improve human rights, tackle poverty and social exclusion (*14*). The integration of social processes in IAMs can lead to complementary bottom-up approaches, where the impact of households on climate through, for example, mobility and consumption choices, can be understood and acted upon via social change interventions. This fills the gap between how household perceive their role in climate change mitigation and the input received from climate policies (*15*). IAMs with embedded social processes may provide crucial information to address this mismatch. Such approaches may build environmental-friendly solutions based on a better understanding of interactions between social, economic and climate dynamics. Ultimately, this may lead to better consumption attitudes such as extensive consumption, less waste, and more cooperation through exchange of goods for reuse or services. In the long-term, integrating social foundations in IAMs will foster such social change towards a low carbon and just society.

Energy Policy 120 (2018) 121–131

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

Ganna Gladkykh[a,b,*], Nathalie Spittler[a,b], Brynhildur Davíðsdóttir[b], Arnaud Diemer[a]

[a] University of Clermont Auvergne, Clermont-Ferrand, France
[b] University of Iceland, Reykjavik, Iceland

ARTICLE INFO

Keywords:
Steady state
Sustainable energy system
Sustainability
Leverage points
Herman Daly
Donella Meadows

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

* Corresponding author. Postal address: 50 Avenue Pasteur, Chamalieres 63400, France.
E-mail addresses: ganna.gladkykh@uca.fr, ganna.gladkykh@gmail.com (G. Gladkykh).

https://doi.org/10.1016/j.enpol.2018.04.070
Received 30 December 2017; Received in revised form 27 April 2018; Accepted 29 April 2018

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

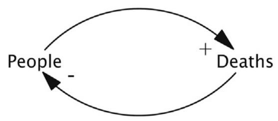


Fig. 1. Example of a CLD.

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

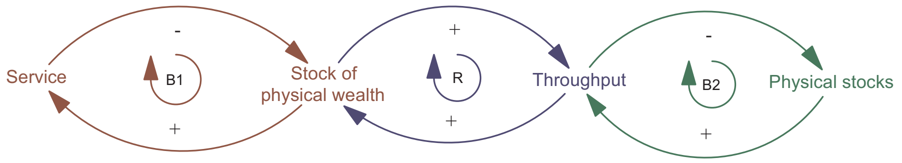


Fig. 2. CLD of Daly's equation.

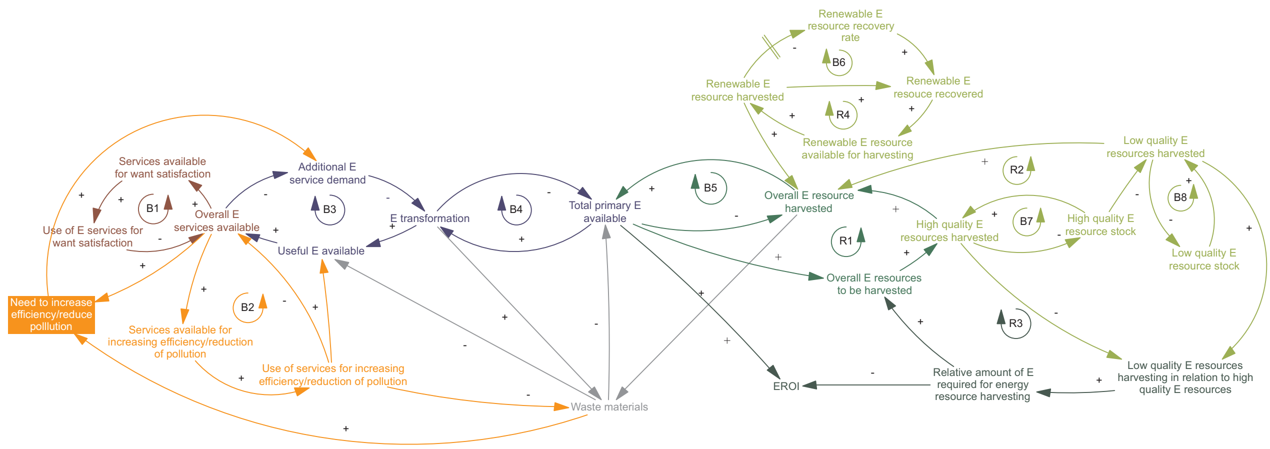


Fig. 3. CLD of steady state of energy based on Daly's equation.

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

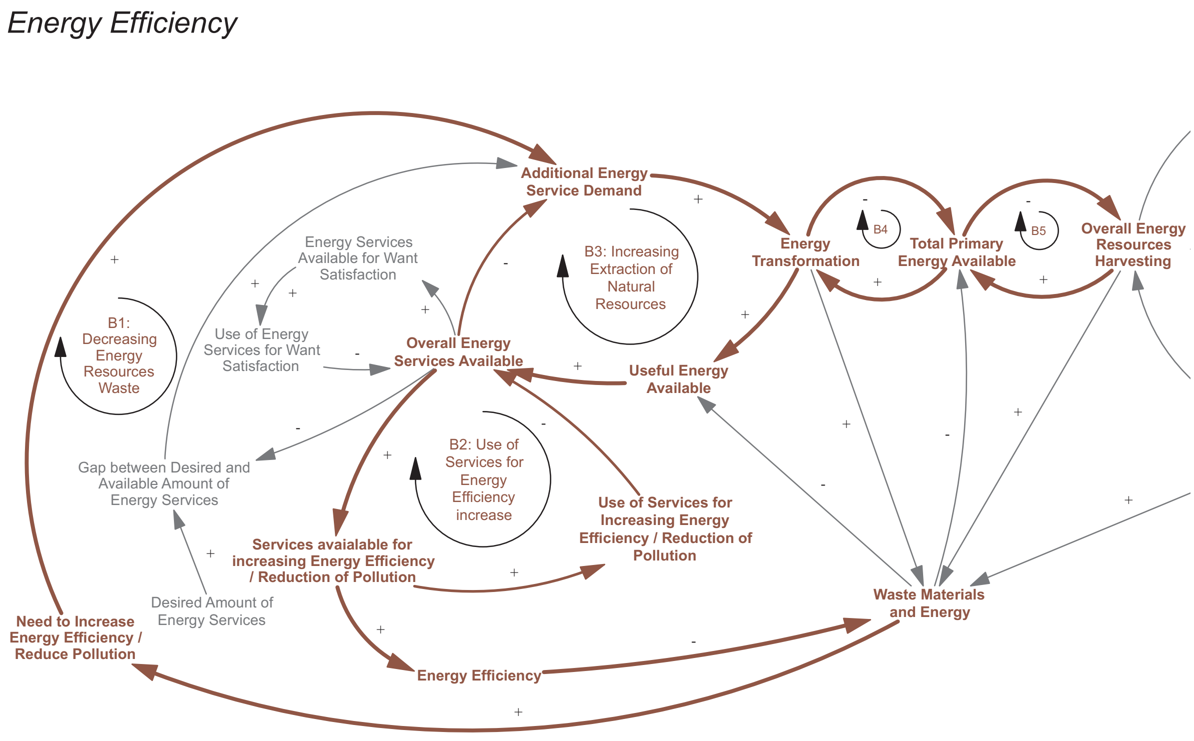


Fig. 4. Energy efficiency leverage point.

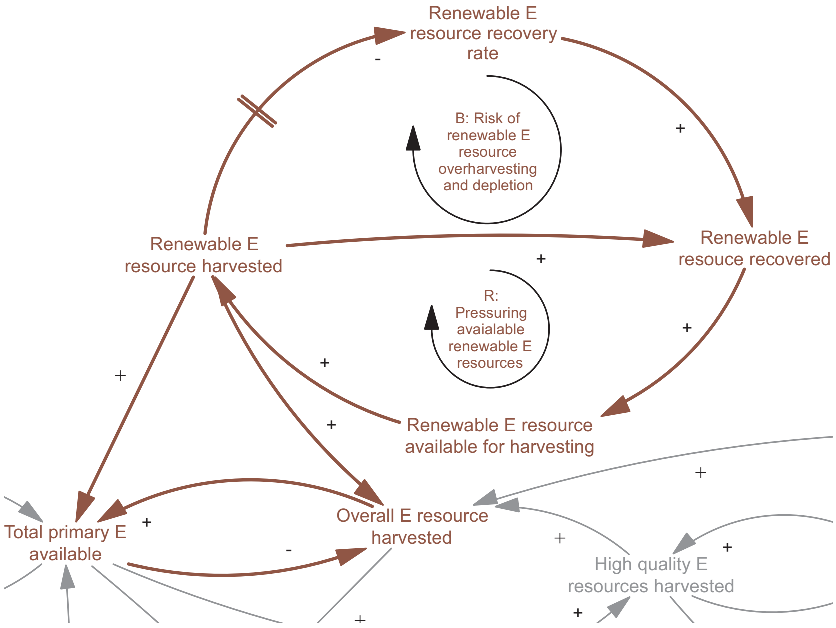


Fig. 5. Shifting to renewable energy sources leverage point.

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.

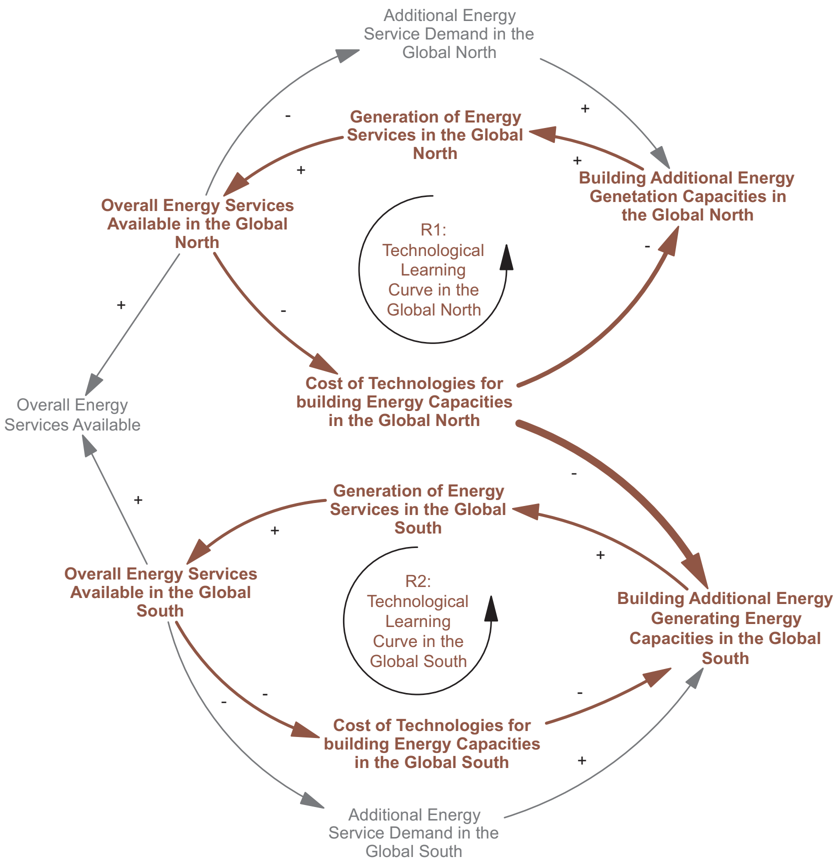


Fig. 6. Technological transfer leverage point.

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).

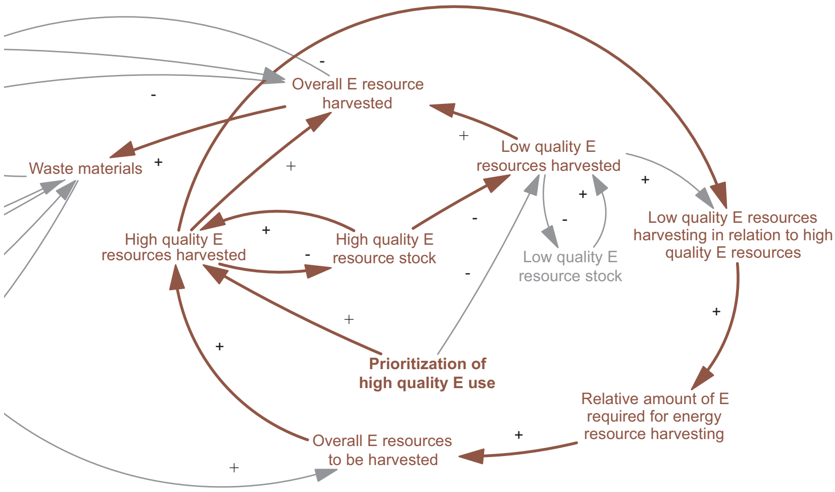


Fig. 7. Shifting to high quality energy leverage point.

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

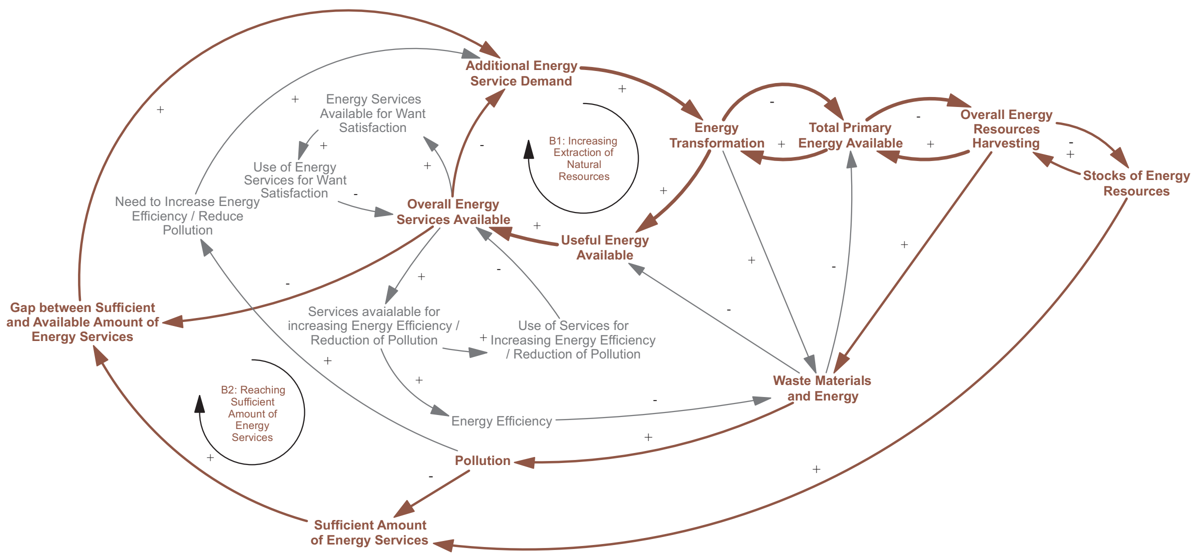


Fig. 8. Energy sufficiency leverage point.

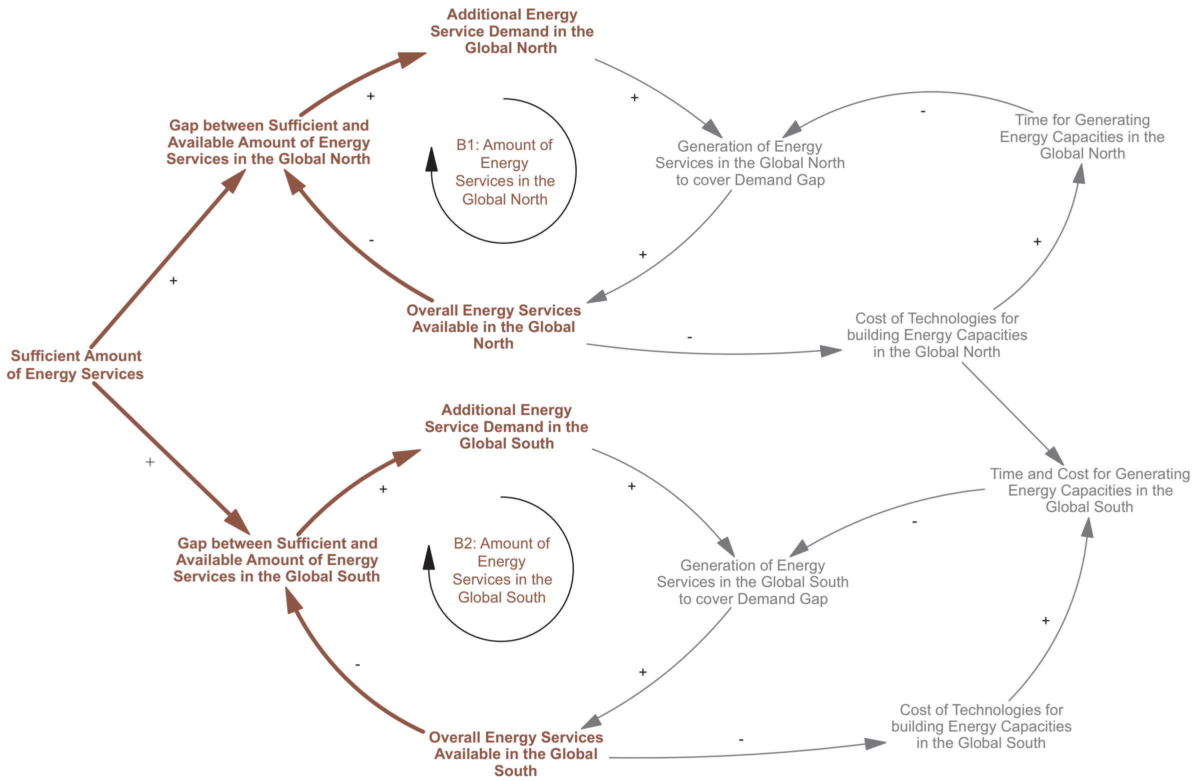


Fig. 9. Energy justice leverage point.

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.

Funding

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No 675153.

.

Designing a Socially Sustainable Energy System Narrative Based on the Energy Justice Principles

Ganna Gladkykh[1,2], Arnaud Diemer[1], Brynhildur Davíðsdóttir[2]

[1] Department of Economics, University of Clermont Auvergne, 63000 Clermont Ferrand, France

[2] Department of Life and Environmental Sciences, University of Iceland, Reykjavik 101, Iceland, Sæmundargata 2, 101 Reykjavík, Iceland

Abstract

Providing energy services for satisfying basic human needs is a fundamental purpose of the energy system. Sustainable energy system visions should incorporate this purpose by explicitly addressing it in the energy system goals a well as by prioritizing it when designing technological solutions for energy provision. In this study, we developed a socially sustainable energy system narrative. We define energy sufficiency with the minimum and maximum desired limits of the energy consumption per capita as a universal energy system goal on a global scale. Additionally, we bring energy justice theory as the framework helping to define the criteria for socially sustainable energy provision technologies. The results of this study contribute to the alternative-to-growth energy system narratives and provide a conceptual tool for socially sustainable energy policy design and assessment.

1. Introduction

Today's global energy system is in crisis. Some parts of the words suffer from the lack of energy access provision to meet human needs. At the same time, other regions experience excessive energy consumption. A long list of problems associated with the global energy system design include unaffordable energy for consumers, environmental pollution, economic and political inequalities. All of this allows to define the current state of things in the energy system as crisis (IPCC, 2014; IEA, 2018).

Current energy system research agenda includes the questions of what is a desirable sustainable energy system state as well as how it can be reached. Dealing with these questions is complex and calls for interdisciplinary methodological approaches. Solving energy system crisis is not any longer seen as a predominantly technological, engineering challenge. Today, with an increased understanding of energy system complexity, there is recognized need in the interdisciplinary approaches and multi-directional efforts to transform existing energy system (Sovacool *et al.*, 2018; Xu *et al.*, 2016). In order to have a holistic understanding of what a desired sustainable energy system is, it is important to explore all sustainability aspects of the energy system, including its biophysical, economic and social sustainability parts. In the current energy systems literature, social sustainability component of the energy system is the least elaborated one. It has historically received lack of research attention, since energy research has been dominated by the research questions related to the technical advancements of the energy system organization and to the cost-minimization objectives (Spittler et al., 2019). Therefore, social science contribution in a sustainable energy system research agenda, that has been happening in the recent years, is very relevant for defining what socially sustainable energy systems means (Sovacool *et al.*, 2015; Sovacool *et al.*, 2018).

Discussion about the principles of a sustainable energy system design goes in line with understanding energy system goals – a general direction of the energy system development.

Currently, most of intellectual and political effort in energy system research is focused on designing solutions for reaching a sustainable state of the energy system without clearly communicating the long-term energy system goals. It would be, however, unfair to claim that a concept of energy system goals is totally absent from the energy policy discourse, especially considering that at the international level. There is a sustainable development goal (SGD7) which directly states the objectives of sustainable energy system development. At the same time, despite mentioning the targets and indicators for the energy system development by 2030, despite being specific about aspects of a desirable energy system design (e.g. prioritizing energy efficiency, maximizing use of renewable energy sources, minimizing GHG emissions) (UNDP, 2015), SDG7 does not provide understanding of the fundamental principles of a desirable energy system design on the global scale. These principles are defined in this study as the energy system goals. We argue that what is classified as sustainable energy system goals in the SDG7 is, in fact, a set of parameters separated from the general vision of a sustainable energy system. Using the systems thinking language (Meadows, 1999), we can say that meeting the SDG7 targets could mean achieving some adjustments in the energy system parameters, but it would not guarantee that a fundamental energy system structure would be transformed and the undesired energy system behavior would be changed. For example, the indicators and targets of the SDG7 cannot do not give any insights for answering the questions like: Do we want continuous increase of energy consumption and production globally after a minimum required amount of high quality energy for everyone is provided globally? Would that continuous growth of the energy system be feasible considering that absolute decoupling is impossible (Parrique et al., 2019)? Can potential shift to a 100% renewable energy (WWF, 2014; Moriarty and Honnery, 2016) allow for solving all the main energy system problems? In this study we aim to define energy system goals on the global scale. We believe that having energy system goals clearly defined and the principles of sustainable energy system design formulated would allow guiding energy policies into a more sustainable direction allowing to minimize potential undesired long-term consequences of the energy policies.

With an overarching objective to contribute to designing sustainable energy system narratives (Moezzi et al., 2017), with the focus on the social sustainability aspects of the energy system development, this study aims to answer the following research questions:

- What are the principles of socially sustainable energy system design on the global scale?
- What energy system goals on the global scale are compatible with the socially sustainable energy system?

Systems thinking approach (Meadows, 1999) and energy justice theory (Sovacool *et al.*, 2017; Jenkins *et al.*, 2016) are the main conceptual instruments applied in this study. Systems thinking categories are applied in the part that talks about energy system goals. As for the energy justice theory, it is used in this study as the core operational framework for formulating the principles of a socially sustainable energy system and for formulating the principles of the technological energy provision compatible with the social sustainability principles.

2. Theoretical framework

This section aims at setting up a theoretical ground for what are the principles of a socially sustainable energy system design and how these principles relate to the energy system goals.

2.1. Systems goal-setting. Defining Energy System through the human needs lens

From a systems thinking perspective, goal-setting is a fundamental part of decision-making in a well-functioning social system regardless the scale and a complexity of the decisions to be made. Energy system is one of the fundamental socio-technical structures in a modern society, and it is important to have a clear energy goal-setting for the energy system to deliver its societal value. Energy systems exist at different scales and the question of defining their boundaries depends on the research or policy purposes. In this study, energy system and the concept of energy system goals are discussed on the global scale with the aim to understand the universal principles and underlying dynamics of energy system design towards social sustainability.

Together with discussing energy system goals, it is important to clearly articulate what the energy system is. This study does not aim for a comprehensive analysis of energy system definitions. However, what is fundamental for understanding the further arguments developed in this paper, is that 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 (Jones, Sovacool and Sidortsov, 2015). Energy system, correspondingly, is a socio-technical structure designed to provide energy for meeting human needs. The way 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, energy system which main goal is to help meeting human needs would not necessarily exclude energy use beyond this purpose. However, in this case, energy use that exceeds direct and indirect amount of energy needed for meeting basic human needs would be considered a secondary priority.

In this study, we do not go deep into the theoretical details of energy system meeting basic human needs. Theoretical assumptions behind our arguments are based on the capability theory assumptions (Day, Walker and Simcock, 2016; Rao and Baer, 2012).

2.2. Energy sufficiency

In this paper, the concept of energy sufficiency is discussed in connection with the energy system goals.

Energy sufficiency as a term means possibility of having enough amount of energy (e.g. Steinberger and Roberts, 2010). However, there is no universal definition of energy sufficiency in the energy literature as well as no universal agreement on how much energy can be considered sufficient (De Deker, 2018).

In this study, for instrumental purposes we use the terms Global South and the Global North (Dados and Connell, 2012). This allows to distinguish between the regions with the energy provision below and above sufficiency level, correspondingly.

When 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 (e.g. Monyei *et al.*, 2018). It is usually implied that having a continuous growth of energy generation and energy consumption is desirable (see e.g. an energy access definition at (International Energy Agency, 2017)).

Being aware that there are inequalities existing not only between the more developed and the less developed world regions, but also within the Global North and the Global South (e.g. Alfani and Tadei, 2017; Arroyo Abad and Astorga Junquera, 2017), we, however, do not address them here, since it is beyond the aggregation level of this paper.

In the Global North context, energy sufficiency is associated not only with the minimum but also with maximum amount of energy to be consumed (e.g. Thomas *et al.*, 2015; Darby and Fawcett, 2018). In the energy sufficiency literature that focuses on the Global North, it is implied that sufficient amount of energy per capita is already available and thus for sustainability reasons there should be cap on individual energy consumption to avoid excessive energy use.

In this paper, we operate on the global scale and argue that for both the Global North and the Global South energy sufficiency should be associated with the minimum and maximum limits of a desirable amount of energy per capita. We argue that energy sufficiency, with both minimum and maximum limits of it, is desirable from a biophysical as well as from a social sustainability perspective. Biophysical part of the energy sufficiency is not discussed in detail in this study. In fact, the claim that having sufficient amount of energy as the energy system goal is desirable from a biophysical point of view, is based on the previous study that we conducted, where energy sufficiency was discussed in the context of the Steady State of Energy concept (Gladkykh et al., 2018). Based on the results of a conceptual analysis presented in that study, we defined energy sufficiency as a universal energy system goal which is compatible with a biophysically sustainable energy system development in the long term. Building on the results of the previous work, in this study, we focus on the energy sufficiency from a social sustainability point of view.

The argument of the energy sufficiency desirability from a social sustainability perspective is developed further in this part, where we discuss the energy justice theory in connection to the energy sufficiency.

By bringing social sustainability component to the argument of a sufficient amount of energy being an energy system goal, we claim that having both minimum and maximum limits for energy sufficiency is socially desirable regardless biophysical limits' pressure. 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. In this paper, we elaborate the arguments to support this statement and explain why reaching the goal of energy sufficiency globally can be qualified as reaching sustainable energy system goal.

2.3. Energy transition and energy access provision. Theory and connection to the energy system goals

In this paper, apart from developing the definition of the energy sufficiency as the system goal, we discuss the two sub-goals: the one of energy transition and the one of energy access provision. Energy transition, the way we define it here, is primarily associated with the Global North, where the system is already well developed and where the main policy focus is directed at shifting from the fossil-fuel-based energy technologies to the renewables-based ones (e.g. European Commission, 2016). Similarly, energy provision goal is mostly applicable in the Global South, where the energy system needs to expand and where more energy services need to be provided to reach a minimum required level. We believe that by incorporating these additional sub-goals, the difference in initial conditions of the energy system development in different world regions can be emphasized. We argue that bringing in these sub-goals could foster more effective and targeted energy policy design which would account for the differences in the initial conditions of the energy system development in different parts of the world. As a result, this could help designing sustainable energy system solutions that would not drive undesired energy system dynamics and lock-ins. This is especially relevant for the energy policy-making in the Global South, where it is important to avoid reproducing undesired energy system behaviors that are already present in the Global North (e.g. Unruh, 2000; Unruh and Carrillo-Hermosilla, 2006).

2.4. Energy sufficiency connection to the energy justice theory

Energy justice theory is the most elaborated up-to-date framework that aims at providing analytical and conceptual tools for designing energy systems according to the social justice principles (Sovacool *et al.*, 2017; Jenkins *et al.*, 2016). In this study, we apply energy justice theory to help understanding what are the energy system goals from a social sustainability perspective and what are the principles of reaching those goals from a social justice point of view. Additionally, we aim at contributing to a further theoretical development of the energy justice field. Particularly, we seek for better understanding how energy sufficiency and energy justice theory are connected on a conceptual level. In the energy justice literature, there has been already identified a gap in understanding how energy justice and energy sufficiency are connected, and attempts to bring the two concepts together have been made (Monyei *et al.*, 2018; Todd *et al.*, 2019). Aiming to contribute to that discourse, we explore the connection between energy sufficiency and energy justice by asking (i) how energy justice principles can act as a theoretical foundation for justifying energy sufficiency as a universal energy system goal and (ii) how energy justice theory can act as a framework to define the principles to reach this goal.

In this part, energy sufficiency (with its minimum and maximum limits as it was described in 2.2), is discussed through the lens of the energy justice principles. Minimum amount of energy for satisfying basic human needs is connected to every human's entitlement to the minimum amount of energy (Jones et al., 2015a). This statement is grounded on the prohibitive and affirmative energy justice principles which derive from the assumption that everyone is entitled to the basic goods to develop their human capacities. In those cases, when basic goods cannot be produced without energy, everyone automatically becomes entitled to the amount of energy required for the basic goods' production. This way, prohibitive and affirmative energy justice principles clarify the meaning of energy system having an instrumental value to help meeting human needs and justify why having the minimum limits of a sufficient amount of energy is essential. However, the need for a maximum limit of a sufficient amount of energy cannot be directly derived from the prohibitive and affirmative justice principles. This aspect is addressed later in this study.

Apart from using energy justice principles to justify energy sufficiency goal, in this section, we aim to understand how energy justice principles can be instrumental for setting the principles for this goal to be achieved. Specifically, energy justice theory acts here as a framework for defining who the main beneficiaries of the energy system are and what the ways of providing to them with energy should be from a social justice point of view.

Energy justice literature defines four pillars of energy justice: cosmopolitan, recognition, distributional and procedural justice (Jones, Sovacool and Sidortsov, 2015; Mccauley, Heffron and Jenkins, 2013). Below, each of these pillars are discussed in more detail and in connection to the energy sufficiency.

Cosmopolitan justice pillar sets a requirement for the energy system to be designed in a way that would allow everyone having equal access to energy system's benefits. This pillar is especially relevant in the context of energy sufficiency being seen as a universal energy system goal. From a more applied perspective, cosmopolitan justice would mean that the principles of a sustainable energy system and energy policy design should be the same for any region in the world, the same for the Global North and the Global South.

Recognition justice pillar's main role is defining who must be the priority beneficiaries to receive energy services (Jenkins *et al.*, 2016). In the context of this study, it would define priority beneficiaries to be provided with the sufficient amount of energy. Since the way energy sufficiency discussed in this study emphases meeting human needs as the main reason energy system is needed in society, individuals and households naturally become the principal beneficiaries of the energy services. Additionally, recognition justice emphasizes the importance of providing with energy services 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 the energy justice perspective, energy access provision for the Global South should be considered a higher priority for the global energy policy than energy transition in the Global North. As for the households from the Global North (most of whom already have access to a sufficient amount of energy (International Energy Agency, 2017), as well as industrial and non-household energy consumers worldwide, they would be placed lower in a hierarchy of energy service beneficiaries, especially those of them whose activity is not related to producing goods and services that help satisfying basic human needs. It is worth mentioning that in this context the recognition justice principles are formulated based on the highly aggregated dynamics in the Global North and the Global South which does not take into account local contexts. For example, the households in the Global North that are not provided with the sufficient amount of energy will still be equally prioritized as the households in the Global South.

Procedural justice pillar has to do with understanding how decisions about energy system design are made and how fair are the procedures related to the energy production and consumption are (Jenkins *et al.*, 2016). 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 a full decision-making autonomy on the local levels. The idea of a universal energy sufficiency implies that there is a universal normative amount of energy per capita defined 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 sufficient amount of energy is supposed to be the result of a democratic 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 the biophysical limits. In this context, energy justice theory contradicts with the principle of energy sufficiency as a universal energy system goal. In fact, the contradiction between energy sufficiency and procedural energy justice pillar originates from a contradiction between the notion of universal basic human needs and procedural justice. An idea of a universal energy sufficiency derives from the premise of the universal basic human needs. Therefore solving the dilemma between the universal energy sufficiency and a procedural energy justice pillar requires an elaborated discussion on the procedural aspects of decision-making related to the universal basic human needs. Such discussion, however, is beyond the boundaries of this study.

Distributional justice pillar is related to ensuring an equal distribution of cost and benefits in the energy system (Jenkins *et al.*, 2016). In the context of a universal energy sufficiency for the Global North and the Global South, distributional energy justice principle would act as a guidance to monitor what are the balances of the resource and technological exchanges connected to energy access provision and energy transition policies. In particular, distributional justice would aim to prevent imbalance between energy system cost and benefits associated with the choice of energy resources, technological solutions, financial mechanisms on local, regional and international scales.

In the results and discussion part of the paper, the principles of energy justice in relation to the sufficiency goal are elaborated in detail and are connected to different technological solutions for energy y provision.

Aiming to understand connections between universal energy sufficiency and the energy justice pillars, we discovered that the minimum amount of a sufficient energy can be justified by a prohibitive and affirmative social justice principles which are related to the concept of basic human needs. At the same time, the concept of universal basic human needs manifested in the idea of energy sufficiency contradicts procedural energy justice principles. This contradiction is addressed in this study very briefly and further research can provide more insights related to it. Regarding the argument that having a maximum limit of a sufficient amount of energy is socially desirable, energy justice theory does not provide theoretical ground to justify this. In fact, in the current energy justice discourse, there is no discussion related to a desirability of a continuous growth of energy production and consumption. This type of discussion could potentially provide the arguments for or against the maximum limits of the universal energy sufficiency. We, therefore, call for the further research on connecting energy justice theory with the concept of energy sufficiency as it is defined in this study, as well as on critically discussing energy justice principles in connection to the energy system growth. We believe that better understanding of this could provide new understanding of what are the social justice principles for a sustainable energy system development. Connecting energy justice pillars to the energy sufficiency goal can lead to the new research questions in the energy justice field, particularly, related to understanding the role of the universal energy sufficiency for achieving social and environmental justice globally and locally.

There is no strong theoretical ground which can help justifying the arguments of a social desirability of a maximum limit for a sufficient amount of energy. Partly this argument is inspired by Illich (1973). In his work, Illich associates a continuous the growth in per capita energy consumption with inevitable increase of power imbalance in society and rise of inequality. The argumentation provided by the author is built on the societal organization and available technologies that were available in the 1970s.

However, despite today's increased variety of the technological options for the energy provision in comparison to 1970s, we argue that growth mindset dominating energy systems design is socially unsustainable and even a shift to fully renewables-based energy provision would not help preventing undesired social dynamics. We argue that having energy sufficiency as the energy system goal would shape the vision of the energy system design and of the preferable technological solutions that would lead to a more democratic and fair energy system design. In the next part, we elaborate this argument further through operationalizing energy justice pillars for understanding what energy provision solutions would be the most compatible with the socially sustainable energy system in the context of the energy sufficiency goal.

2.5. Energy sufficiency in the context of sufficiency economy narratives

Being focused on the energy sufficiency as a universal energy system goal and on the socially sustainable principles of energy system design, this study, in a way, contributes to creating alternative energy system narratives. However, the narrative being created in this study would be incomplete, if it is discussed without taking into account general economic development context. Understanding and meeting basic human needs, which is a departure point for the energy sufficiency vision, belong to the economic domain. Discussing assumptions behind the human needs is beyond the scope of the energy system and outside the limits of this study. However, it is important to have elaborated alternative economies narratives that would be focused on human needs and that would be compatible with the particular energy sufficiency narrative explored in this study. Without a broader economic context, this energy narrative will exist in a vacuum and its applied value will be very limited. In this paper, we do not discuss any alternative economic narratives. We believe, however, that the results of this study can be particularly interesting for those exploring sufficiency economies narratives (e.g. Alexander, 2015; Ingleby and Randalls, 2019), especially in the part that deals with understanding how energy system within those narratives should be designed.

In the alternative-to-growth economic studies, re-thinking production of goods and services is one of the main focuses. Alexander (2015) argues that in a sufficiency economy a process of production will still take place, but the values of it will be different and will prioritize the provision of basic needs, such as food, clothing, shelter, tools, and medicine. With this regard, re-thinking energy system in the context of energy sufficiency and with applying social justice principles presented in this paper can be insightful for re-designing goods and services production principles in the economy overall.

There are number of alternative-to-growth economy visions discussed in the literature (e.g. sufficiency economy, degrowth, post-growth etc.). However, when it comes to a geographical scale, very few of them go beyond the Global North region, explicitly or implicitly assuming that those types of narratives are not applicable in the Global South. With this regard, energy sufficiency concept, as a universal energy system goal applicable not only for the Global North but also for the Global South, can bring new perspectives to the sufficient economies narratives and can inspire new research on understanding what economic sufficiency in the Global North could mean for the Global South and the other way around. This particular study would gain a lot if there were elaborated sufficiency-oriented economy narratives operating on the global scale. Having sufficient economy narratives for the Global South would influence the design of socio-technical systems there, potentially leading to making technological choices that would not be made within the economic growth assumption (Kerschner et al., 2018).

Talking about currently available descriptions of the energy system within the existing alternative-to-growth economic narratives, they are very limited. Energy systems there are rarely described in more detail than being renewables-based and decentralized (Alexander and Gleeson, 2019). At the same time, it is emphasized in the sufficiency economy literature that meeting basic material needs should be done in ecologically sustainable, localized and socially equitable manner (Alexander, 2015). Logically, the same principles should to be applied to the energy system design that is instrumental for meeting those basic needs. Thus, it can be said that a gap in more elaborated energy sufficiency visions have been already indirectly acknowledged in the sufficiency economy literature.

3. Results and discussion

Applying energy sufficiency as energy system goal and energy justice pillars to define criteria for socially sustainable energy technologies

In this part, we operationalize the principles of energy justice to understand what should be the underlying principles for selecting technological solutions that could be the best for reaching the goal of energy sufficiency.

To reach the goal of a universal energy sufficiency, we need to make sure that policies for energy transition and associated with them technological solutions are chosen and designed in line with the biophysical and social sustainability principles. Understanding those principles is especially important for 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 provision solutions that would not lead to the undesired dynamics in the energy system similar to those in the Global North, lead to new potential energy system injustices (McCauley, 2018).

In this section, we provide a conceptual table (table 1), where energy justice pillars are connected to the principles of energy provision and to the energy provision technologies. Each of the principles presented in the table, is discussed below in more detail. The goal of the discussion in this part is concluding what types of energy provision are the most and the least compatible with the socially sustainable way of energy system design.

The types of energy provision technologies, the way they are presented in the table below, do not include the details on each particular energy resource or technology for energy provision. In the table 1, each of the three energy justice pillars (i.e. recognition, distributional, procedural justice) correspond to the certain energy provision principles. These principles are juxtaposed with the different types of energy provision technologies. These technologies are presented in the table on a rather highly aggregated level (i.e. small-scale fossil-fuels, small-scale renewables, large-scale fossil fuels, large scale renewables) and do not specify particular types of energy resources and technology used. However, we see such level of aggregation being enough to support the arguments of this study and to provide an instrumental tool for designing the solutions for designing socially sustainable energy systems. The tool which can the further used in more specific contexts, with more details related to the available energy provision technologies.

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

2.Distributional justice pillar	2.1. Technology allows for minimizing dependencies between the Global North and the Global South	+/-	+/-	-	-
	2.2. Technology can contribute to community self-sufficiency and can create community co-benefits	+/-	+	-	-
	2.3. Technology depends on energy resource that is geographically widely available	-	+	-	+
3.Procedural justice pillar	3.1. Technology can be compatible with the alternative-to-growth business models	+	+	-	-
	3.2. Technology allows for maximizing use of locally available resources, technologies, expertise	-	+	-	-
	3.3. Technology is associated with a low risk of creating power imbalances in the energy system	-	+	-	-
	3.4. There is a low risk of stranded assets associated with the technology	+	+	-	+/-
	3.5. Technology allows for relatively fast installation of generating capacities	+	+	-	+/-

Recognition justice pillar

This pillar prioritizes basic-needs-oriented energy provision for the individuals and households in the context of reaching energy sufficiency goal. Energy provision principles associated with the recognition justice pillar emphasize the importance of the 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 requiring higher energy demand (table 1: 1.1.). Energy provision within energy sufficiency goal would have different implications than energy provision within growth-driven assumptions. In the latter case, it is often implied that an increase of energy access for households and decrease of energy poverty are derivative from of industrial energy provision and economic growth driven by the following causal chain is assumed: energy access provision for industries – economic growth – household income increase – energy affordability for households – lack of energy poverty (McDonald, 2009). According to that logic, preferable criteria for choosing energy technologies would be rather big scale energy technologies based on the criteria of cost minimization, with no intermittencies in energy supply and with the possibilities to increase energy generation capacities in the future. In contrast, when 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 increase of generation capacities without intermittency being a major concern, because the patterns of energy supply for basic needs is less demanding in terms of uninterrupted energy supply than energy-dependent production processes.

Recognition of households as potential energy prosumers (not only as energy consumers but also as energy producers) another important component of this pillar. Energy prosuming would encourage local, community-based energy provision and local autonomy in decision-making related to the energy system design, together with other co-benefits on a community level (table 1: 1.2) (McCauley, 2018).

Additionally, technological solutions for energy provision also need to take into account 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 (International Energy Agency, 2017).

Distributional justice pillar

Aiming to prevent imbalance between energy system cost and benefits related to the choice of energy resources, technological solutions, financial mechanisms on local, regional and international scales, this pillar is primarily driven by the logic of fostering local/regional self-sufficiency. To discuss energy provision principles within this pillar, we employ the energy affordability and energy availability terms that are widely used in the energy policy context (UNDP, 2015) and re-interpret them. Here, energy is considered to be affordable if it is locally affordable and considered to be available if it is locally available. According to this logic, the most affordable energy provision options would be those that are 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, financial resources, etc. Such understating of energy affordability is in line with the one of McCauley (2018), who argues that affordability needs to account for a community capability for acquiring the technologies and knowledge needed.

Prioritizing regional self-sufficiency is also the way to avoid creating technological, monetary, resource, 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 embedded international knowledge and ecological flows embedded in technologies (Hornborg, 2012). However, aiming for maximizing 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 a distributional justice pillar, fossil fuels distribution is much more geographically concentrated than renewables. However, this is true for the physical resource part. As for the technologies, know-how, financial mechanisms behind different energy provision technologies etc., then the difference between renewables' and fossil fuels' distribution becomes more ambiguous. There is, in particular, a resource mining part related to the harvesting technologies for some of the renewables (e.g. JRC, 2013; WWF, 2014) that is often missing from a discussion on potential biophysical as well and social complexities associated with different renewable energy sources, but that can be a source of new energy system injustices within energy futures where most of energy provision is renewables-based (McGee and Greiner, 2019; McCauley, 2018).

Procedural justice pillar

This pillar deals with the procedures and overall principles of a socially sustainable energy system design. The procedures associated with the procedural justice pillar are important for creating conditions for activating recognition and distributional pillars. Avoiding creation of power imbalances in the energy system, as well as empowering 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 the ways that do not drive winners and losers dynamics between the actors in the energy system (table 1: 3.3). Within this pillar, we employ the term energy access. Similarly to re-interpreting energy availability and energy affordability, here, we re-interpret energy access. 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, technological ones (table 1: 3.2). In the context of energy sufficiency goal and in line with prioritizing community access provision, it is important to have access to the diverse business models and diverse forms of organizing energy production (table 1: 3.1). Ideally, these forms of organization need to be inclusive, help preventing power imbalances and serving a higher-level purpose of democratic community transformations (Hiteva and Sovacool, 2017). Questioning an assumption of energy system growth would open the opportunities for the new types of business models for energy production and for non-for profit models (Maclurcan and Hinton, 2019). Such forms of the new types of provision would be in contrast to the existing practices of energy provision. For the current energy provision practices, especially in the Global South, nowadays it is common to be considered as for-profit business opportunities that can foster green growth not only in the Global South but also in the Global North (e.g. Bachram, 2004;

Newell and Bumpus, 2012). Considering this, social sustainability aspect of the 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, to comparing fossil fuels and renewables, fossil fuels are much more compatible with creating the winner-loser dynamics, because of the resource distribution specificities, dependency on the stock or resources, scarcity component associated with the resource itself (e.g. Olson and Lenzmann, 2016). Prosuming is hardly compatible with the fossil-fuel-based energy system. At the part of the household electricity generation for covering household needs, prosuming practice is possible with the use of the fossil-fuel-based technologies. However, in this case, there the dependency on the fossil fuel resource remains, and thus prosuming cannot be considered as self-sufficient as in the case of prosuming with the use of renewable energy sources. Overall, in a fossil-fuels-based energy system, an actor in the energy system has to accept either a role of energy producer or the one of energy consumer (McCauley, 2018).

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 building it. Based on the social science research findings, there is a causal relation between community trust and decentralized energy systems (e.g. Koirala *et al.*, 2018). More insights and deeper understanding of how energy system design is connected to the democratic processes in society can be found in the energy democracy literature (e.g. Burke and Stephens, 2017; Szulecki, 2018).

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 undermines community trust (Labanca, 2017: 44).

One more driving principle for designing technologies for socially sustainable energy system design is avoiding creation of technological inertia and technological lock-ins (Unruh, 2000; Unruh and Carrillo-Hermosilla, 2006). Winners versus losers principle can be applied not only to the energy system actors, but also to the technological solutions for energy provision. Socially sustainable energy system would aim for minimizing technological inertia in energy provision solutions. Large-scale, centralized technological systems have higher technological inertia than decentralized, small-scale energy systems (e.g. Negro, Alkemade and Hekkert, 2012). Level of technological inertia associated with the energy systems development in the different regions, would influence the patterns of energy system transformation. In the Global North, where there are already established energy systems with the high level of inertia, transformation to a more sustainable energy system would be associated with relatively longer time and higher cost. Stranded assets associated with the existing fossil-fuel-based energy systems is an example of the challenges associated with those cost (Caldecott, 2017). Along with the stranded assets, there are “vested interests” of the powerful energy system actors interested in keeping energy system status quo (Moe, 2015).

In terms of designing sustainable energy provision solutions for the Global South, where existing energy systems are not as developed and have 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).

Another aspect to consider in the context of a procedural justice is that centralized energy provision solutions are often connected to a centralized political decision-making. This makes energy system planning highly dependent on the political realities and political regime changes. This especially needs to be taken into account in the least developed countries, where political regimes can often be unstable (Best and Burke, 2017).

The last aspect that we would like to mentioned int his part and that is important to consider within a socially sustainable energy provision relates to a procedural justice and has to do with minimizing the time for setting up energy provision system. Prioritizing meeting basic human needs and human wellbeing drives the choice of faster ways of energy provision over the slower ones (table 1: 3.5). The limits for choosing the fastest solutions, however would be not compromising all other aspects of long-term sustainability including environmental, political and social components.

All the principles of socially sustainable energy provision discussed in this part can be summarized in the three main overarching principles that should guide the choice of solutions for socially sustainable energy system development:

- Energy provision solutions should prioritize basic needs of individuals and households above any other types of energy use.
- Energy provision solutions should be compatible with the idea of contributing to building low energy society rather than high energy society.
- Energy provision solutions should prevent creating power imbalances in the energy system at all levels.

These three principles, together with the universal goal of the energy sufficiency with the minimum and maximum levels of a desired amount of energy per capita, are the principle components of a socially sustainable energy system and thus of the universal energy sufficiency narrative. With this study we conclude that reaching the goal of energy sufficiency globally following the above-mentioned principles of energy provision can be qualified as reaching the energy sufficiency goal in a socially sustainable way.

4. Conclusion

Sustainable energy system goals, the way they are formulated in the SDG7, are primarily focused on meeting specific numerical targets, such as a share of renewable energy sources in the energy mix, percent of the energy efficiency increase, etc. Such set of targets and indicators does not give a holistic understanding of what sustainable energy system is. However, having this understanding is very important, because a fragmented view of a sustainable energy system can be misleading for designing the policies aiming to contribute to a long-term energy system sustainability. The ultimate energy system's purpose is providing energy services to satisfy basic human needs. This purpose is manifested in the energy sufficiency as a universal energy system goal. Explicitly setting the minimum and maximum limits for the energy sufficiency in the Global South and the Global North should be a departure point for designing socially sustainable energy system. Energy sufficiency seen this way could shape the principles of the energy systems planning and lead to the choice of those technological solutions that would prevent creating power imbalances in the energy system and would benefit households as the main beneficiaries of the energy system services. Energy justice pillars is a good theoretical foundation for defining a set of principles for the socially sustainable ways of energy provision. Universal energy sufficiency together with the energy-justice-based criteria for energy access provision form the narrative of a socially sustainable energy system. This narrative can act as a normative vision for a sustainable energy policy design. It can also act as the set of theoretical assumptions for the energy system modelling. Besides, this socially sustainable energy system narrative can contribute to the sufficient economy visions which usually contain rather blurred pictures of the compatible energy systems, especially at the global scale.

The energy system narrative presented in this paper, would contribute from the future research supplementing a social sustainability dimension with a biophysical and economic parts.

A Case of Electricity Sufficiency for Sub-Saharan Africa: Combining System Dynamics Modelling with the Socially Sustainable Energy System Narrative

Ganna Gladkykh[1,2], Brynhildur Davíðsdóttir[2], Arnaud Diemer[1]

[1] Department of Economics, University of Clermont Auvergne, 63000 Clermont Ferrand, France

[2] Department of Life and Environmental Sciences, University of Iceland, Reykjavik 101, Iceland, Sæmundargata 2, 101 Reykjavík, Iceland

Abstract

For the energy access provision projects that are being implemented and planned, it is important to ensure that their design does not contradict sustainability principles. In this study, we present an approach that can be used for sustainable energy system planning and assessment, with the focus on the social sustainability aspect of the energy system design. By combining a conceptual narrative of the socially sustainable energy system with energy system modelling, we bridge theoretical work on sustainable energy system development with energy system modelling approach. Providing a case for a household electricity provision in Sub-Saharan Africa, we discuss to what extent different combinations of centralized, decentralized, fossil-fuel-based and renewables-based electricity access provision are compatible with the socially sustainable energy system principles. The research design of this study can be interesting for energy system modellers as well as for the scholars working on the theoretical development of the sustainable energy systems principles.

1. Introduction

Energy access provision, including electricity access provision, is among the top sustainable development priorities in the world. This is explicitly addressed in SDG7 (UNDP, 2015). When it comes to the number of people lacking electricity access, the situation in the Global South is the most critical (Fig.1).

More than 1bln people living today without access to electricity (Fig.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” (International Energy Agency, 2017:21).

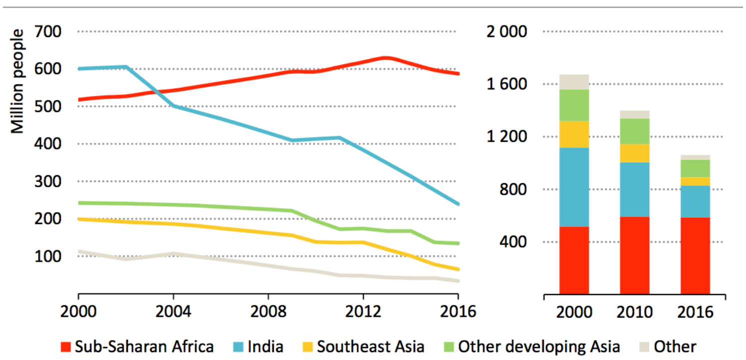


Fig. 1. *Population without access to electricity by region (International Energy Agency, 2017:41)*

The active measures on the international level to provide electricity access have been taken place for the last ten years (IEA, IRENA, UNSD, WB, 2019). However, the fact that energy access provision have been implemented does not mean that energy access provision solutions have been chosen in accordance with sustainability principles. In the Fig. 2., the data on the types of energy technologies used for providing electricity access in developing countries is presented. It is evident that most of electricity access provision since 2000 has been provided with the use of fossil fuels. This way of electricity provision is controversial from the environmental sustainability point of view (Bruckner et al., 2014). However, It can be argued, that negative environmental effects associated with the use of fossil fuels have been counter-balanced by the social benefits that this type of electricity provision can bring (e.g. Olson and Lenzmann, 2016).

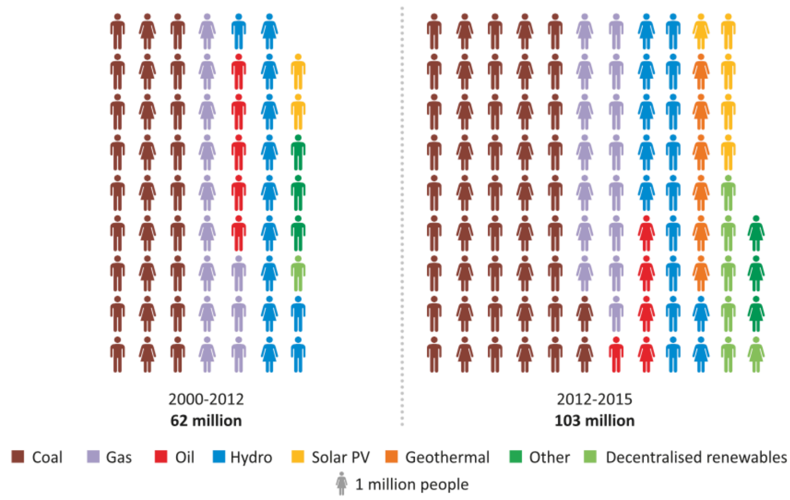


Fig. 2. *Annual number of people gaining electricity access by fuel type in developing countries (International Energy Agency, 2017:45)*

To say whether in the Global South the use of environmentally unsustainable solutions could be justified by receiving social benefits, there should be a normative framework providing criteria to classify different technological solutions as socially sustainable or unsustainable. During the last years, social scientists have been studying energy systems from a social justice perspective (Sovacool et al., 2015). As a part of a theoretical contribution to the domain of social sustainability principles of the energy system design, the authors of this paper previously developed a framework for understanding how socially sustainable energy system could be defined and what the principles of socially sustainable energy provision could be. Energy sufficiency as a universal energy system goal and energy justice principles as the guiding criteria for the sustainable energy system design are the socially sustainable energy system framework that we developed (Gladkykh et al., unpublished draft). In this study, we bring this theoretical framework further and test its applied value for analyzing and designing energy policies. In this paper, we combine the developed theoretical principles with the energy system modelling. By doing this, we aim to bridge the practice of energy system modelling which has been actively developing for the last several decades (Spittler et al., 2019) with the social science advancement in the sustainable energy research. The main methodological objective of this research is contributing to the methods of combining quantitative and qualitative narratives of the sustainable energy systems (Ansari and Holz, 2019).

Here, we present a model for electricity access provision in Sub-Saharan Africa un till 2040 and discuss how the modelling process and the modelling results are connected to the previous theoretical work on understanding what socially sustainable energy system means and how it can be achieved.

At a methodological level, this study is an experiment which aims at exploring how theoretical principles of socially sustainable energy system design can be connected to energy system modelling and provide an instrumental value for energy policy-making and, particularly, for designing the policies for energy access provision.

This paper consists of the 3 main parts. In the part two, we present the research design of this study, providing the details of how modelling is connected to the theoretical work at the different stages of modelling. In the part three, we give an overview of the model structure, including qualitative and quantitative modelling phases. In the part four, we present the results of the three different simulation scenarios discuss then in the context of socially sustainable energy policy design.

2. Research design

At the core of the research design in this study is connecting a theory of a socially sustainable energy system design with energy system modelling. This includes several main stages:

- building qualitative and quantitative model structure, based on the core theoretical principles;
- simulating several electricity access provision scenarios with the different level of compatibility with the socially sustainable energy provision principles;
- contrasting and analyzing different scenarios' simulation results, exploring the trade-offs associated with the different types of electricity access provision.

By combining the theoretical development with the modelling exercise, we explore what could be an example of the model that would grasp the key components of a socially sustainable energy access provision. In this study, we aim at showing an example of the research design that could be useful for the further research efforts related to understanding how theoretical development of the alternative energy system narratives can be translated into the models' structures. On the one hand, this approach can provide the insights of how theoretical work related to the sustainable energy systems can become more instrumental for energy policy analysis and design. On the other hand, this research design can help energy system modelling practice by giving an example of how theoretical assumptions can be incorporated into a model at different stages of the modelling process.

An important aspect of this modelling exercise that is worth emphasizing is that obtaining precise numerical modelling results is not a principal goal of the modelling. The numerical output of the model presented in this paper is not a focus of this research. The role of the numbers presented in the results and discussion section is primarily aimed to demonstrate the differences between the basic and the normative scenarios. Apart from discussing the actual simulation results, in this study, we see a great value in describing the modelling process, including setting the model's boundaries, conceptualization and structure-building phase, as well as scenario simulation. By describing the modelling stages in detail, we aim at proving a better understanding of how theoretical background and the modelling processes are connected.

2.1. Theory of socially sustainable energy system design

This study is based on socially sustainable energy system narrative which we developed in the previous study aiming to understand the goals and the principles of the socially sustainable energy system. The main components of the socially sustainable energy system as it is defined in the (Gladkykh et al., unpublished draft) are as follows:

(1) Energy system is instrumental. Its purpose is providing the conditions for satisfying basic human needs (e.g. Day et al., 2016; Rao and Baer, 2012).
(2) Energy sufficiency is a universal energy system goal for both the Global North and the Global South. Energy sufficiency is associated with the minimum and maximum limits of a desired amount of energy and implies that energy growth per capita in the long-run is undesirable.
(3) Households are the primary beneficiaries of the energy system services. Non-household energy consumption is secondary.
(4) Socially sustainable energy system design is based on the vision of reaching the low-energy society.

(5) Energy provision technologies need to correspond to the recognition, distributional, procedural energy justice pillars (Jenkins et al., 2016).

In this study, the components of a socially sustainable energy system developed conceptually are used as a conceptual foundation for the modelling exercise.

2.2. System Dynamics modelling

System dynamics (Forrester, 1994) is used in this study as an energy systems modelling approach that includes both qualitative and a quantitative stages of the modelling process. System dynamics is usually applied as a method for understanding how complex systems are organized and how they can be transformed. System dynamics approach is based on exploring underlying feedback mechanisms in their structures (Sterman, 2000; Pruyt, 2006) and identifying leverage points for policy interventions (Meadows, 1999).

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

(1) It has the tools suitable for both qualitative and quantitative analysis, which provides a good foundation for integrating theoretical concepts in the modelling exercise.
(2) It is based on the systems-thinking principles and approaches the systems through understanding their (a) structure-behavior archetypes (Senge, 1997), (b) though portraying the feedback mechanisms embedded in them, (c) through defining material and information delays. All of these components provide a departure point for exploring the underlying dynamics of the energy system.
(3) The quantitative part of the system dynamics modelling is relatively easy to use without advanced modelling skills, since does not require programming skills and the used software (Stella Architect) has a user-friendly intuitive interface.
(4) System dynamics is suitable for designing the models on a highly aggregated scales, where the main research focus is understanding general structural and behavior patterns (Lane, 2001).

There are two main tools used in the system dynamics modelling that are also used in this study: Causal Loop Diagrams (CLDs) (a qualitative tool) (Spector et al., 2001) and Stock-and-Flow Diagrams (SFDs) (a quantitative tool) (Sterman, 2000). There are several examples of CLDs present in this paper (i.e. fig. 3, 4, 5) and one example of SFD (fig. 6). There are simple rules of reading CLDs. 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 provides a description of the bi-causal relationships between variables. A positive link is the 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. Similarly, a negative link is the one in which the causing and affected variables change in the opposite directions. Reinforcing and balancing loops are two foundational structures in System Dynamics. Depending on the number of positive and negative polarities within the loops, they can be classified as reinforcing or balancing. Reinforcing loops compound change in one direction with even more change. Balancing loops resist further changes in given direction and bring things to a desired state. SFDs are used as the tool for a quantitative modelling. They consist of the special types of models' components called stocks and flows. The stocks is defined by the accumulation inflows and outflows connected to them.

2.3. Connection between the theoretical framework and the modelling at different stages

In this section, we discuss how the main theoretical components of a socially sustainable energy system can be translated into the modelling language. In the table (table 1), there is a summary of how different theoretical aspects of the socially sustainable energy system narrative (Gladkykh et al., unpublished draft) are addressed in the modelling exercise at different stages of the modelling process.

Table 1. Connection between the modelling process and the theoretical development

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 (Gladkykh et al., unpublished draft). For 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 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.	Electricity provision for urban and rural households in Sub-Saharan Africa 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 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 (see part 3.3. of this paper). 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 prioritised 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.

In a dynamics modelling practice, there is a paradox related to designing a system undergoing structural transformation process. Ideally, the same model structure should be capable of reproducing a historical behavior and a transformed future behavior. Therefore, for the model to demonstrate a transformed behavior in the future, all the model components that are expected to be present in the after a transition period, should be initially present in the model structure. In this exercise, we did not aim at reproducing a historical behavior of the electricity provision system in Sub-Saharan Africa. The objective was already at the stage of setting up the model's boundaries and designing the model's structure that would include the components and connections which would need to be present in the normative simulation scenarios of a socially sustainable energy access provision.

A model-building process is always based on finding the balance between model's usefulness and an effort invested. The purpose of this modelling effort was not designing the most detailed possible system of electricity access provision in Sub-Saharan Africa. The aim was to design the structure which would include the main parts of a socially sustainable energy system narrative that can be modelled and those components which, at the same time, are the most fundamental for representing an underlying socially sustainable energy system narrative.

3. Model description

The model presented here demonstrates electricity provision for rural and urban population in SSA from 2016 until 2040. In this section, only the most principle components of the model structure are discussed. The full list the model's equations and documentation is provided in the Annex 2.

3.1. Model goals

It was mentioned in the table 1 that goal-seeking structure is the core of the model and it is designed around the goal of reaching 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 (Ackoff, 1971; Senge, 1997)

In fig. 3, the major dynamics embedded into the model is discussed and illustrated with the CLDs. From the system dynamics perspective, the driving dynamic mechanism of this model is a balancing loop. The balancing mechanism compares sufficient amount of electricity 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 a desired sufficient level.

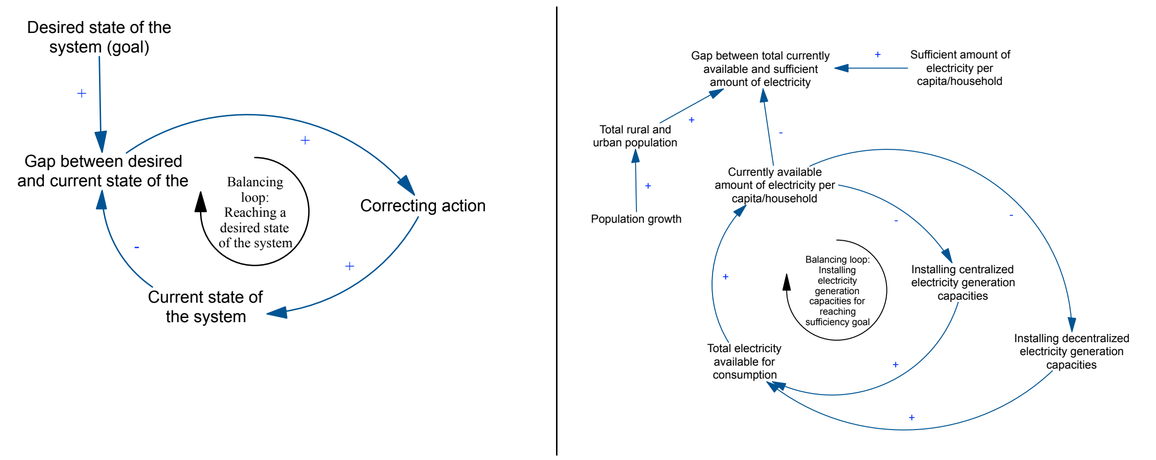


Fig. 3. *CLD of a goal-seeking behavior archetype in System Dynamics in its standard representation and in the way it is presented in the model*

In the SFD model structure, there are two different goals of sufficient amounts of electricity modelled – separately for the urban and for the rural households.

It is important to mention that even though the goal of the model, sufficient amount of electricity per capita in the model of electricity provision for the SSA region, does not change over time. However, total amount of electricity to be produced and to be consumed dynamically increases in the model due to population growth. Therefore, with the population growth effect included in the model, the goal of electricity sufficiency becomes a so-called moving target changing over time.

3.2. Model structure: demand and supply

In the fig. 4, there is a CLD presenting overall dynamics of the model. The number of rural and urban households provided with sufficient amount of electricity are the central stocks in the model. The parameters of a sufficient amount of energy to be provided for the rural and urban households are set at the level of 250 kWh per capita and 500 kWh per capita for the people living in rural and urban areas, correspondingly (International Energy Agency, 2016). This amount of electricity per capita is in line with the Tiers framework by the World Bank (Bhatia and Angelou, 2015) , specifically, with the Tier 2 which reflects the amount of electricity instrumental for satisfying basic human needs.

During the simulation, at each timestep the model compares actual amount of electricity provided to the households with their electricity demand. In case the actual amount provided is lower than a sufficient level, an additional electricity provision capacity is installed. There are both centralized and decentralized electricity generation capacities present in the model. Electricity grid and energy distribution systems are not included in the model structure for simplicity reasons. This limitation is reflected in the assumption that rural households can be supplied only by decentralized electricity provision technologies.

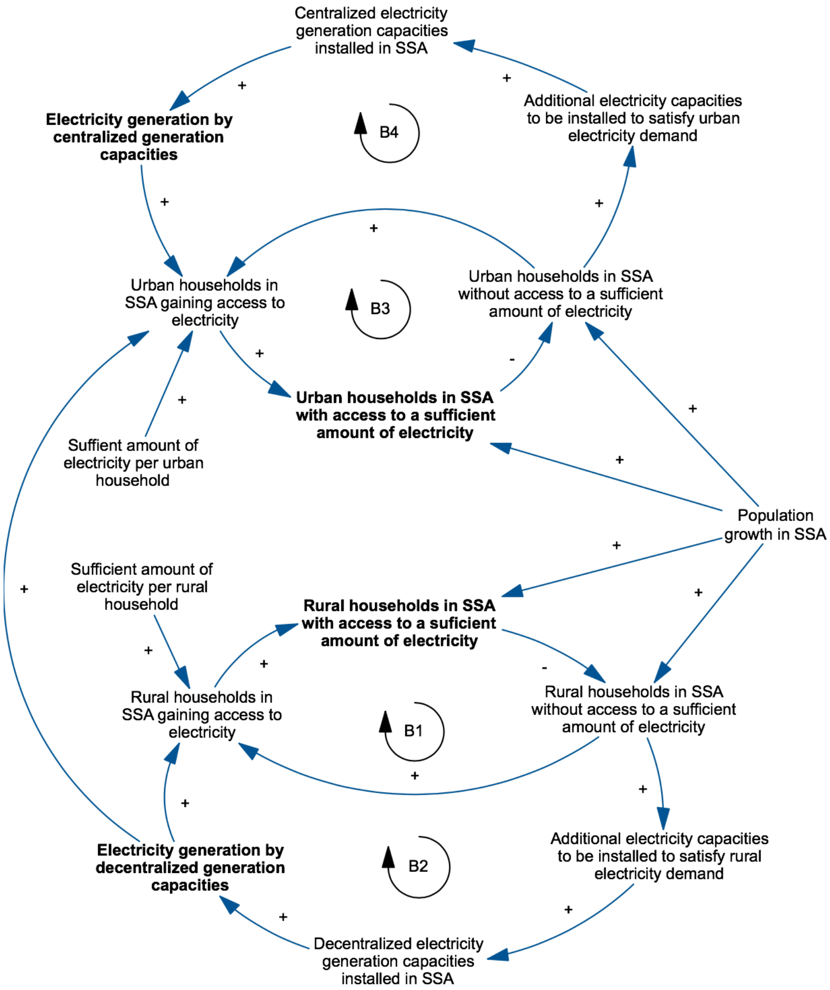


Fig. 4. Overview of the model structure in CLD

The driving dynamic mechanisms embedded in the model on the structural level includes only balancing loops (see the loops labelled B1, B2, B3, B4 in fig. 4). There are no feedback loops in the model which would drive a continuous increase of electricity consumption and electricity production. The only parameter in the model that drives electricity generation and electricity consumption increase is population growth. GDP growth is not is not included in the model structure.

Supply part of the electricity access provision for SSA is presented by centralized and decentralized electricity generation capacities. There are several different types of fossil-fuel-based and renewables-based energy technologies present in the model (table 2).

The mechanism of electricity cost generation is modelled in a simplistic way and includes only capacity installation costs for each energy technology. For every simulation year, the model chooses a certain mix of energy provision technologies. This selection is based on the cost-minimization principle. 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 2). After 2016, at every simulation time step, the cost are re-calculated based on the two main driving effects: a resource-scarcity effect and a learning effect which dynamically interact with each other (Annex 2). The dynamics interaction of the cost driving CLDs is portrayed in Fig. 5.

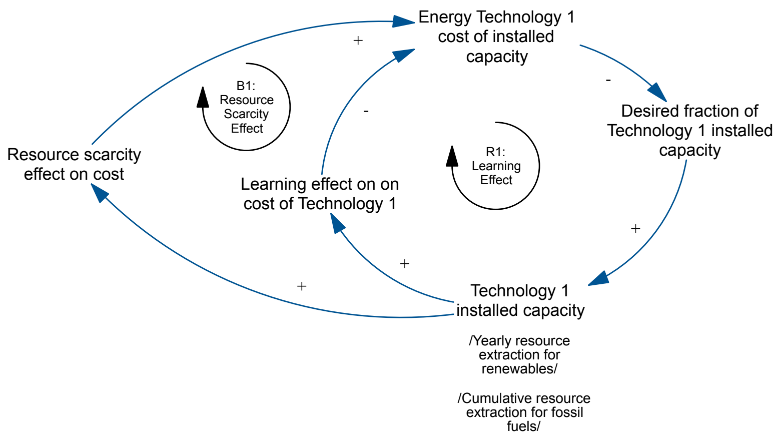


***Fig. 5.** CLD of the two energy cost driving effects incorporated in the model's equations*

In the SFD, every energy technology is modelled in a similar way. There are time delays in the model associated with different technologies' construction time and lifetime. The amount of electricity generated by different power capacities depends on the amount of generation capacities installed as well as on the capacity factors. Neither for the fossil fuels, nor for the renewables, there are no explicit limits of the energy resources modelled. However, the resource limits for each energy resource are embedded in the resource-cost curves (Annex 2). Learning ratio for every energy technology is constant over time, but the resulting learning effect in endogenous and changes with time depending on the total installed capacity. The system dynamics structure of the learning effect is based on Pruyt et al. (2011). In the fig. 6, there is a structure for a centralized PV electricity generation provided as an example of how different electricity generation technologies are presented in the model.

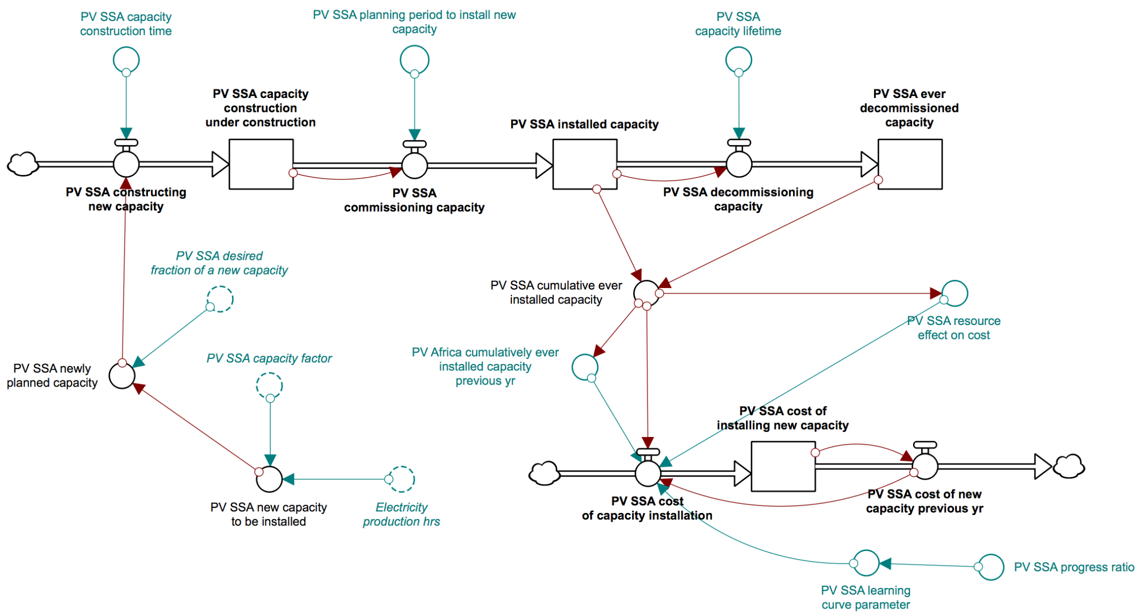


***Fig. 6.** Centralized Solar PV power generation structure: a fragment of the model*

The full list of all the electricity generation technologies modelled is presented in the table 2.

Table 2. List of the electricity generation technologies present in the model.

Centralized electricity generation	Decentralized electricity generation
Coal	Small hydro
Gas	Stand-alone PV
Oil	Mini-grid PV
Hydro	Mini-grid wind
Centralized PV	Stand-alone diesel
Centralized concentrating solar	Mini-grid diesel
Centralized wind	
Centralized geothermal	
Bioenergy-based	

3.3. Model scenarios: designing rules for alternative simulation runs

At the stage of the simulation stage, we compare three different scenarios of the system dynamics model: a basic one and the two normative scenarios.

In a *basic scenario*, a choice of a technological mix for electricity generation is driven by a cost-minimization principle. All the fossil-fuel-based and renewable energy technologies initially present in the model structure are present in this scenario.

The rationale behind having the *normative scenarios* is to design the rules for selecting electricity provision technologies based on the social sustainability principles. In these scenarios, some of the electricity generation technologies present in the basic scenario are excluded from the electricity generation mix, even if they allow for the cheapest and for the fastest electricity provision. Assumptions behind these scenarios are based on the conceptual principles of socially sustainable energy provision discussed earlier in this study (see 2.1.). The criteria behind socially sustainable principles of energy access provision are based on the three energy justice pillars (Jenkins et al., 2016). According to these pillars, some energy provision technologies are more compatible with a social sustainability concept than other technologies. The full list of the principles and their correspondence to the energy provision technologies is provided in the table 3.

Table 3: *Summarizing table for the principles of socially sustainable principles of energy provision and corresponding technologies for energy provision (REF unpublished paper) (source:* (Gladkykh et al., unpublished draft)*)*

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	+	+	-	-
	1.2. Technology allows for prosuming	-	+	-	-
	1.3. Technology can be associated with the intermittency of energy supply	+/-	+	-	+/-
	1.4. Technology can be accessible on the community level for direct provision for households	+	+	-	-
	1.5. Technology can be accessible in the remote rural areas with no access to centralized energy systems	+	+	-	-
2.Distribution justice pillar	2.1. Technology allows for minimizing dependencies between the Global North and the Global South	+/-	+/-	-	-
	2.2. Technology can contribute to community self-sufficiency and can create community co-benefits	+/-	+	-	-
	2.3. Technology depends on energy resource that is geographically widely available	-	+	-	+
3.Procedural justice pillar	3.1. Technology can be compatible with the alternative-to-growth business models	+	+	-	-
	3.2. Technology allows for maximizing use of locally available resources, technologies, expertise	-	+	-	-

	3.3. Technology is associated with a low risk of creating power imbalances in the energy system	-	+	-	-
	3.4. There is a low risk of stranded assets associated with the technology	+	+	-	+/-
	3.5. Technology allows for relatively fast installation of generating capacities	+	+	-	+/-

Technologies that have the biggest number of pluses next to the corresponding energy provision principles are those that are the most compatible with the principles of the socially sustainable energy access provision and, therefore, should be included in the normative scenarios. Technologies that are the least compatible with the socially sustainable energy provision principles are excluded from the normative scenarios. Based in these criteria, large-scale fossil-fuel-based technologies as well as the large scale renewables-based technologies, are excluded from the normative scenarios.

As for the decentralized technologies, renewables-based solutions are more compatible with the socially sustainable energy provision than fossil-fuel-based technologies. However, according to the Table 3, decentralized fossil-fuel-based technologies also compatible with a lot of socially sustainable energy provision principles.

Eventually, in this simulation exercise we compare a *basic scenario (later in the text – scenario 1)* with the two normative scenarios:

- *Decentralized renewables & Decentralized fossil fuels (later in the text – scenario 2)*
  In this scenario, decentralized renewables-based and fossil-fuel-based electricity generation technologies are included. Centralized renewables-based and centralized fossil-fuel-based technologies are excluded from this model run.
- *100% decentralized renewables (later in the text – scenario 3)*
  In this scenario, only decentralized renewables-based electricity generation is possible. All the fossil-fuel-based technologies and centralized renewables-based technologies are excluded from the potential technological mix.

For all three scenarios, the overall goal of providing urban and rural households with the sufficient amount of electricity remains the same.

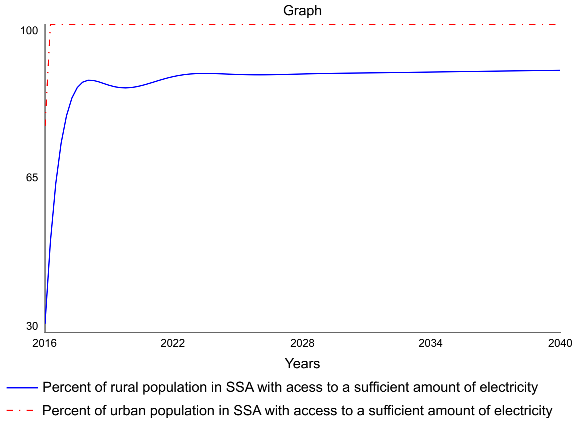
4. Results and discussion

In this section, the main results of the scenarios' simulations are presented and discussed. There are three main parameters that are included in the summary table with the model simulation output (table 4):

(i) *Percent of rural and urban population in the SSA provided with the sufficient amount of electricity;*
(ii) *Total investment cost in the electricity generation capacities;*
(iii) *Technological mixes for electricity generation.*

Table 4(1): *Basic Scenario: Model simulation output*

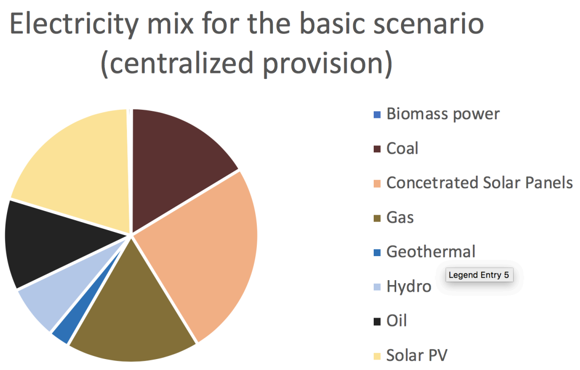
Scenario 1 (Basic): Model simulation output



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)

Total generation capacities investment cost until 2040:

421bln USD



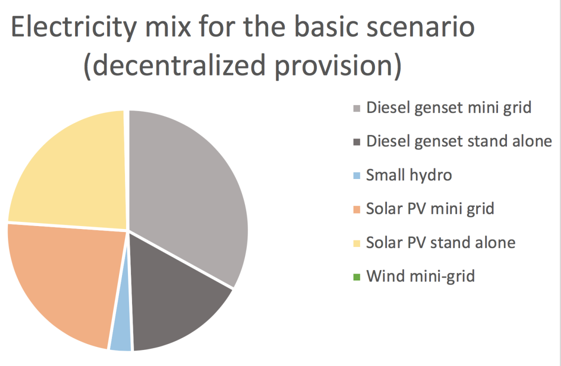
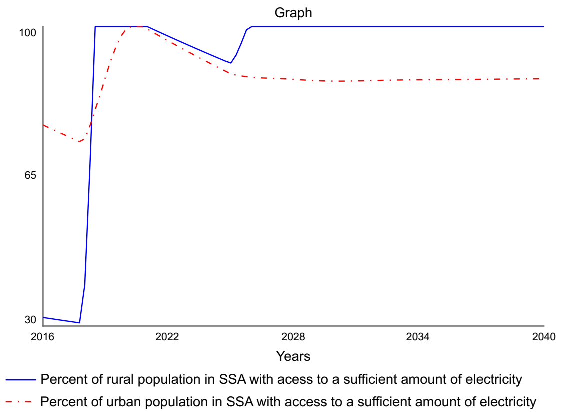
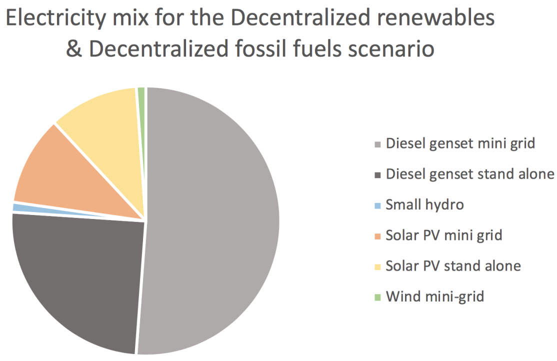


Table 4(2): *Normative Scenarios: Model simulation output*

Normative scenarios: Model simulation output

Scenario 2 (Decentralized renewables & Decentralized fossil fuels)

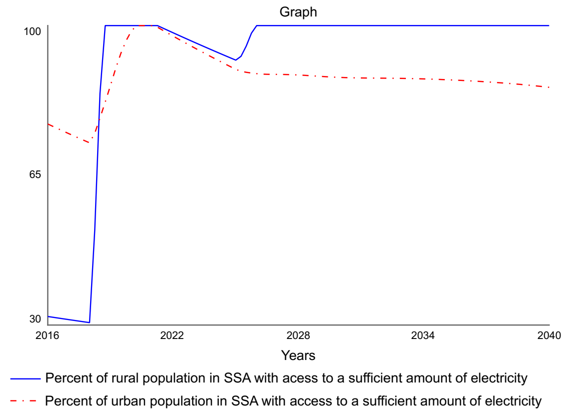
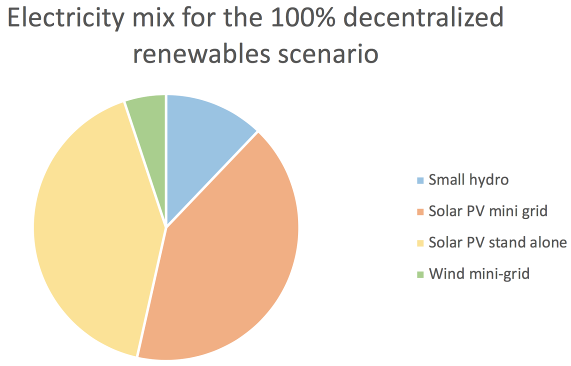




Percent of households provided with the sufficient amount of electricity in SSA by 2040: 100% of rural households (1,15bln people); 88% of urban households (878mln people).

Total generation capacities investment cost until 2040:

353bln USD

Scenario 3 (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)	**Total generation capacities investment cost until 2040:** 2,02trln USD

As it was 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 an absolute numerical output. Therefore, in the table 5, 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 mentioned above.

(i) Percent of rural and urban population in the SSA provided with the sufficient amount of electricity by from 2016 to 2040.

Among all three scenarios, scenario 1 allows for a highest percentage of electricity access for urban population in SSA by 2040. Scenario 2 and 3 show lower percentage of urban provision and higher percentage of the rural provision than scenario 1. However, none of the scenarios generates 100% sufficient electricity access for both rural and urban population. The reason for this is the population growth which effects the goals of sufficient electricity provision, making total electricity demand a moving target that changes every simulation timestep. In case 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.

Regarding the speed of the electricity access provision, it is evident (see table 5) that a maximum level of electricity provision is reached during the first several years of the simulation time in all three scenarios. The reason for this is a simplified model structure which assumes immediate information exchange between demand and supply; the absence of no technological, economic, social and political obstacles for increasing electricity generation capacities, constant availability of financial resources for investing in new generating capacities (IEA, IRENA, UNSD, WB, 2019). Even though the simulation results in this part are not very informative and insightful, they inspire a further discussion on the reasons that can prevent or foster rather fast electricity access provision in reality.

One more interesting aspect related to this part of the results' discussion is understanding how population growth is related to the overall electricity sufficiency vision which is at the core of this modelling exercise. Here, the question to answer 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 the population growth? We argue that the answer to this question is affirmative – yes, the model remains compatible with the energy sufficiency narrative. Regardless the presence of a population growth factor, a model can still be classified as the one of sufficiency provided the following conditions are fulfilled: (a) 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.

(ii) Total investment cost in the electricity generation capacities from 2016 until 2040

As it was mentioned previously, the cost structure of electricity generation in the model is very simplified (see 3.2. and Annex 2). Therefore, absolute values of cost are less informative than comparative ones. According to the simulation results, scenario 2 is associated with the lowest total cost of investment in electricity generation capacities. It is 16% less expensive than scenario 1. Scenario 3 is most expensive one. It is almost 4 times more expensive than the other scenarios. Interestingly, even in the scenario 1, where centralized fossil-fuel-based electricity generation is included, the shares of fossil fuels and renewables are almost equal in the final technological mix. This means that even based on solely cost-minimization principles of a technological selection, fossil-fuels-based technologies are not more competitive than renewables-based ones. This is an interesting finding in the context of the energy access provision projects that have been to a large extent fossil-fuels-powered, as it was mentioned in the Introduction (see fig. 2). This simulation result, in fact, questions how reasonable and desirable fossil-fueled-based electricity provision in the Global South not only from a social sustainability point of view but even from a pure cost-minimization perspective. This way, the scenario 1 inspires a discussion on whether current technological choices of energy access provision are really driven by the cost minimization principles of there are additional driving forces of a continuous investment in the fossil-fuel-based electricity provision (International Energy Agency, 2019).

(iii) Resulting electricity generation mixes

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 and do not show how electricity generation mixes have changed dynamically during the whole simulation time.

In the scenario 1, the shares of renewables and fossil fuels in 2040 are almost equal, in both centralized and decentralized electricity mixes. Interestingly, in the scenario 2, the share of the fossil-fuel-based technologies in a decentralized technological mix is 76% which is 27% higher than the share of fossil fuels in a decentralized electricity generation mix in the scenario 1. This result is caused by the fact that, in the scenario 2, diesel electricity generation gains a momentum at the beginning of the simulation and fills a large share of a gap in electricity supply. Rapid increase of the diesel-based generation capacities at the early stage leads to a cost decrease of diesel generation and eventually makes other renewable energy technologies uncompetitive until the end of the simulation time.

In the scenario 3, solar PV becomes a technological leader. In 2040, it provides 82% of the total electricity generation.

In general, interpretation of the modelling results related to the technological mixes is limited by the modelling assumptions related to the resource limits. Cost curves that drive the selection of different electricity provision technologies do not portray a real-world complexity of a resource-cost dynamics, especially in the long-run. Besides, explicit physical limits for the energy resources are present in the model only for the fossil fuels, in the form of the stocks of the corresponding resource reserves in the SSA region. For the renewable energy sources, no explicit resource limits are modelled. This is a limitation to be taken into account, especially in the scenarios with the large shared of solar PV in the electricity generation mixes, considering the fact that there are non-renewable resources required for producing PV panels (e.g. JRC, 2013; WWF, 2014).

Table 5. *Comparative summary of the three scenarios simulation results at 2040*

Scenario name	% of sufficient electricity provision among rural population	% of sufficient electricity provision among urban population	Cost of investment in generation capacities (compared to basic scenario)	Centralized electricity generation technologies mix	Decentralized electricity generation technologies mix
Scenario 1 (Basic)	90%	100%	n/a	**Fossil fuels (45%):** Gas(17%); Coal(16%); Oil (12%) **Renewables (55%):** CSP (25%); Solar PV (20%); Hydro (7%); Geothermal (3%).	**Fossil fuels (49%):** Diesel genset mini grid (33%); Diesel genset stand-alone (16%). **Renewables (51%):** Solar PV mini grid (24%) ; Solar PV stand-alone (24%); Small hydro (3%)
Scenario 2 (Decentralized renewables & Decentralized fossil fuels)	+10% (higher than basic scenario)	-12% (lower than basic scenario)	-16% (lower than basic scenario)	n/a	**Fossil fuels (76%):** Diesel genset mini grid (51%); Diesel genset stand-alone (25%). **Renewables (24%):** Solar PV mini grid (11%); Solar PV stand-alone (11%); Wind mini-grid (1%); Small hydro (1%)
Scenario 3 (100% decentralized renewables)	+10% (higher than basic scenario)	-14% (lower than basic scenario)	+380% (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%)

Running three different scenarios within this modelling exercise was initially aimed at testing the theoretical principles of socially sustainable ways of energy access provision (see table 3). What are the general findings related to this? Scenario 1 originally has not been intended to be compatible with the socially sustainable provision principles. Its main role is providing a baseline for discussing the normative scenarios simulation results. In contrast, scenarios 2 and 3 were initially designed to be compatible with the socially sustainable principles of energy access provision. Simulation results demonstrated that scenario 2, which resulted in 76% fossil-fuel-based decentralized electricity provision in 2040, is 4 times cheaper than 100%-renewables-based scenario 3. Judging by the number of socially sustainable provision criteria (see table 3) in these two scenarios, scenario 3 can be considered more socially sustainable than scenario 2. From the cost-benefit perspective, the benefit of four-times cheaper electricity access provision in the scenario 2 is counter-balanced by a higher social sustainability cost. Similarly, higher social sustainability benefit of the scenario 3 is counter-balanced by its four-times higher monetary cost for the electricity provision. Regarding the specific social sustainability criteria differences between scenarios 2 and 3, the criteria that are not met by the scenario 2 are related to the fossil fuel use and include a restricted access to electricity prosuming as well as potential dependencies on the fossil resources that are not locally available. The aggregation scale of this exercise does not allow to discuss the social cost and trade-offs in detail. However, the main intention of this discussion 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 cost and benefit can be weighted.

It is worth reminding that in this study a biophysical aspect of a sustainable energy access provision is not included. This study argues, however, that even with the exclusion of the biophysical parameters from the scenario comparison criteria, fossil-fuel-based provision, meets less of the social sustainability criteria. However, the discussion of cost and benefit of different energy provision scenarios can be brought further by comparing environmental cost associated with different energy provision technologies. The parameters that could be included in such analysis would particularly include environmental cost associated with building new energy generation capacities and decommissioning old capacities, environmental cost associated with different stages of energy production and energy consumption (Bruckner et al., 2014).

5. Conclusion

In this study, providing an example of the electricity access provision in Sub-Saharan Africa and trying to understand the principles of socially sustainable ways of energy access provision in the Global South, we conclude that socially sustainable energy access provision needs to prioritize reaching energy sufficiency goals for the households. Decentralized renewables-based energy access provision is the most compatible with the social justice principles of the energy system design. However, the most socially sustainable energy access provision options can be associated with relatively high cost of provision, which can be an especially sensitive issue in the developing countries' context, and when it comes to assessing the trade-offs between the different aspects of the energy system sustainability embedded in the design of the energy access provision.

Building on the principles of a socially sustainable energy system that we developed prior to this study, in this paper, we connected theoretical principles of sustainable energy systems with the energy system modelling approach. With this research design, we provided a methodological case which can be instrumental and can have an applied value for energy policy design and assessment as well as energy system research purposes. This study demonstrated how energy system modelling can be connected to the theoretical work. We see this study being primarily relevant on the methodological level. In our opinion, simulation results and a discussion related to understanding the principles of a socially sustainable energy access provision in the Global South has as much research value as the research design process itself. We believe that this study can be useful for the energy system modellers, in that part of the modelling process which relates to integrating specific theoretical assumptions in the energy models' structures. For the researchers working on the theory development for sustainable energy systems design, this study can also be relevant providing an example of how certain conceptual principles can be tested with the help of qualitative and quantitative modelling tools.

9. CONCLUSION

9.1. Synthesis of the thesis

In my PhD thesis, I explore 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 of this thesis: energy system modelling and sustainable energy system narratives. At the initial stage of the research, there are several research gaps identified that became a foundation of the further research design: (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, I designed the research strategy which aimed at addressing these gaps in order to answer the main research questions. As a result, there are 8 papers written, most of which are collaborative studies. Below, is the list of the main research results obtained during this PhD.

(i) The current energy paradigm has been formulated

The current energy paradigm has been formulated. 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, related to modelling the limits of renewables as well as to addressing social dynamics driving energy system development and climate policy-making.

(ii) Steady state of energy with the goal of energy sufficiency was defined

Steady state of energy concept has been designed inspired by Daly's the steady-state economy theory. 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 the energy system development in different world regions. Defining energy sufficiency as a universal energy system goal within the steady state of energy concept resulted from the 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 the 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 energy policies correspond to lower impact leverages. Overall, the work on the steady state of energy can be considered as a theoretical contribution to the sustainable and alternative-to-growth energy system narratives.

One more argument related to the energy sufficiency goal in this study is defining energy transition and energy access provision as the sub-goals of the universal energy sufficiency goal. Energy transition goal would be more applicable in the Global North where dominating energy policy objective is shifting from the use of fossil fuels to the renewables use. Energy provision, in its turn, would be the goal applicable in the Global South where there is a lack of available energy services. I argue that explicitly separating the goals of the energy access provision for those regions that suffer from a lack of energy services, from the goals of energy transition for the regions that already have enough energy services can be instrumental value for energy policy-making and give insights for designing more targeted energy policies to reach sustainable energy system state.

(iii) The principles of a sustainable energy provision were designed

To complete a sustainable energy system narrative, the goal of a universal energy sufficiency was connected to the principles of a sustainable energy provision with the focus on a social sustainability aspect of energy provision. Energy justice theory uses a theoretical foundation based on which the socially sustainable energy provision principles are formulated. As a result of conducted research, there are defined three main principles of socially sustainable energy provision: (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 full list of socially sustainable energy provision principles contains the overarching principles in a more detailed version, where energy justice principles are connected to the different types of the technological solutions for energy provision:

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

This table can be used as 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 potential social injustices that can be potentially associated with this process. 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. Designing the principles of a socially sustainable energy provision has strong ethical implications on the way sustainable energy policy is designed. It emphasizes that solving energy crisis is essential not only from a biophysical point of view but also from an ethical perspective.

Additional contribution of this study on a theoretical level is a connection of energy sufficiency as a universal energy system goal with the energy justice theory and three energy justice pillars. Particularly, this PhD provides the case of how energy justice theory can be operationalized for designing alternative-to-growth sustainable energy system narratives.

(iv) The system dynamics model integrating sustainable energy provision narrative was built

In this PhD thesis, connecting system dynamics modelling with the designed narrative of a sustainable energy provision is primarily a methodological contribution to the sustainable energy research field. On the example of providing access to a sufficient amount of electricity for rural and urban households in Sub-Saharan Africa, I demonstrate how the case of energy system modelling can be combined with the sustainable energy system narratives. This case aims to address methodological and disciplinary gaps in the energy system research and to contribute to a better sustainable energy policy design and assessment. The modelling process is linked to the developed theoretical energy system narrative at the several main stages of the modelling process, from a conceptualizing phase to a scenario simulation one. In the table 2, the connection between the modelling process and the theoretical narrative is provided in more detail.

Table 2. *Connection between the modelling process and the theoretical sustainable energy system narrative*

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 (Gladkykh et al., unpublished draft). For 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 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.	Electricity provision for urban and rural households in Sub-Saharan Africa 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 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 (see part 3.3. of this paper). 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 model simulation results demonstrated relative trade-offs between a default cost-minimization scenario of energy access provision, a 100% decentralized renewables scenario and a mix decentralized provision one. In this modelling exercise, the research design and relative comparison of different scenario outputs are more valuable than an absolute numerical output and can be insightful for designing interdisciplinary methodological cases in the future sustainable energy research. The results of this study can encourage critical thinking in relation to designing energy access provision policies in the Global South, showing that the technological solutions associated with the lowest economic cost can unsustainable from a social sustainability point of view and can potentially lead to creation of undesired energy system dynamics and energy system lock-ins in the less developed part of the world.

9.2. Limits of the research

(i) Limits related to the formulation of the current energy paradigm

There is a limited number of energy models that have been 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 bigger number of energy models belonging to each of the modelling approaches could add more strength to the validity of the provided arguments. The list of questions formulated within the current energy paradigm was designed based on the major research and political changes in relation to a sustainable development agenda that had an impact on the way the energy system was seen. However, this list cannot be absolutely unbiased and exhaustive. Therefore, the current energy paradigm would benefit from a critical revision of the presented list of the questions.

(ii) Steady state of energy with the goal of energy sufficiency defined as sustainable

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. The discussion on the concept of energy sufficiency and the theoretical background related to its concept would contribute from a deeper elaboration of the argument, e.g., in 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 my PhD thesis only briefly and thus needs to be explored further.

(iii) The system dynamics model integrating sustainable energy provision narrative was built

The boundaries of the model include only electricity provision and only in one of the Global South. Including, for example, access to clean and modern cooking fuels and more regions inside the model structure could have provided better insights into the technological dimension as well as into the dynamics between the regions in relation to the explored energy system narrative. From the system dynamics point of view, the model does not reproduce a historical behavior and, therefore, has a limited potential to be validated. The absolute numerical output of the model is not realistic due to the limitations of the model structure. Particularly, the cost structure of the installed 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. There are only three model scenarios simulated for the purposes of this research. There is a potential for exploring more combinations of the energy provisions technologies and include additional factors such as subsidies or taxes that would better correspond to the existing energy system and the cost structures behind different energy provision technologies.

9.3. Further research

Based on the results of this study, there are several main areas of the further research that can be interesting in the context of sustainable energy system development and that can benefit from the results of this PhD:

1) Further research on exploring interregional dynamics between the Global North and Global South, especially in the context of systems analysis, can 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 can be brought 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 the examples of sustainable economic narratives that could be explored in the connection to the 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. Regarding bioeconomy, there has been already a study conducted as a part of this thesis which explored bioeconomy visions in different parts of the world, and, among other main sectors in the economy, explored representations of the energy sectors in those visions. Considering a specific focus of bioresources and renewable resources use, it is a concept that have a lot to benefit from and to contribute to the sustainable energy system narratives.

10. REFERENCES

Introduction

Biros, C., Rossi, C., Sahakyan, I., 2018. Discourse on climate and energy justice: a comparative study of Do It Yourself and Bootstrapped corpora. http://journals.openedition.org/corpus.

Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fun-gtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs- Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom and New York, NY, USA.

Daly, H.E., 1974. The Economics of the Steady State. Am. Econ. Rev. https://doi.org/10.2307/1816010

Darby, S., Fawcett, T., 2018. Energy sufficiency – an introduction: A concept paper for ECEEE. https://doi.org/10.13140/RG.2.2.31198.08006

Evans, S., Hausfather, Z., 2018. How 'integrated assessment models' are used to study climate change [WWW Document]. Carbon Br. URL https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change (accessed 10.12.19).

Forrester, J.W., 1994. System dynamics, systems thinking, and soft OR. Syst. Dyn. Rev. 10, 245–256. https://doi.org/10.1002/sdr.4260100211

Gambhir, A., Butnar, I., Li, P.-H., Smith, P., Strachan, N., 2019. A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS. Energies 12, 1747. https://doi.org/10.3390/en12091747

Hitch, C.J., Institute of Management Sciences., Operations Research Society of America., 1977. Modeling energy-economy interactions : five approaches. Resources for the Future.

IEA, I.E.A., 2018. World Energy Outlook 2018, IEA Paris, World Energy Outlook. OECD. https://doi.org/10.1787/weo-2018-en

Intitute, S.E., 2018. SEI Initiative on Governing Bioeconomy Pathways | SEI [WWW Document]. SEI. URL https://www.sei.org/projects-and-tools/projects/sei-initiative-bioeconomy/ (accessed 7.19.19).

IPCC, 2014. Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jenkins, K., McCauley, D., Forman, A., 2017. Energy justice: A policy approach. Energy Policy 105, 631–634. https://doi.org/10.1016/j.enpol.2017.01.052

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016a. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/J.ERSS.2015.10.004

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016b. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/J.ERSS.2015.10.004

JRC, 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. JRC Scientific & Policy Report, European Commission. https://doi.org/10.2790/46338

Meadows, D., 1997. Places to intervene in a system. Whole Earth.

https://doi.org/10.1080/02604020600912897
Meadows, D.H., Wright, D., 2008. Thinking in systems : a primer.
Mingers, J., 2014. Systems thinking, critical realism and philosophy: A confluence of ideas, Systems Thinking, Critical Realism and Philosophy: A Confluence of Ideas.
https://doi.org/10.4324/9781315774503
Parrique, T., Barth, J., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., Spangenberg, J.H., 2019. De-coupling
Debunked.
Pruyt, E., Pruyt, E., 2006. What is System Dynamics? A Paradigmatic Inquiry.
Ramazan, S., Voyvoda, E., Lacey-Barnacle, M., Karababa, E., Topal, C., Islambay, D., 2017. Energy Justice: a Social Sciences and Humanities Cross-Cutting Theme Report. Cambridge.
Schlosberg, D., 2007. Defining Environmental Justice: Theories, Movements, and Nature, Defining Environmental Justice: Theories, Movements, and Nature. Oxford University Press.
https://doi.org/10.1093/acprof:oso/9780199286294.001.0001
Shue, H., 2014. Climate justice : vulnerability and protection. Oxford University Press, USA.
Sovacool, B.K., 2014. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. Energy Res. Soc. Sci. 1, 1–29.
https://doi.org/10.1016/j.erss.2014.02.003
Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World, Management. https://doi.org/10.1057/palgrave.jors.2601336
United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. Gen.
Assem. 70 Sess. 16301, 1–35. https://doi.org/10.1007/s13398-014-0173-7.2
WWF, 2014. Critical Materials for the transition to a Sustainable Energy Future. Gland, Switzer-land. Xu, X., Goswami, S., Gulledge, J., Wullschleger, S.D., Thornton, P.E., 2016. Interdisciplinary research in
climate and energy sciences. Wiley Interdiscip. Rev. Energy Environ. https://doi.org/10.1002/wene.180

Paper 1: Understanding the current energy Paradigm and Energy System Models for More Sustainable Energy System Development

1. Najam, A.; Cleveland, C.J. Energy and Sustainable Development at Global Environmental Summits: An Evolving Agenda. Environ. Dev. Sustain. 2003, 5, 117–138. doi:10.1023/A:1025388420042.
2. Helm, D. The assessment: The new energy paradigm. Oxford Rev. Econ. Policy 2005, 21, 1–18. doi:10.1093/oxrep/gri001.
3. Jefferson, M. Energy Policies for Sustainable Development. World Energy Assessment. In World Energy Assessment: Energy and the Challenge of Sustainability; UNDP: New York, NY, USA, 2000; pp. 415–447.
4. Ringkjøb, H.K.; Haugan, P.M.; Solbrekke, I.M. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew. Sustain. Energy Rev. 2018, 96, 440–459, doi:10.1016/j.rser.2018.08.002.
5. Lopion, P.; Markewitz, P.; Robinius, M.; Stolten, D. A review of current challenges and trends in energy systems modelling. Renew. Sustain. Energy Rev. 2018, 96, 156–166, doi:10.1016/j.rser.2018.07.045.
6. Bhattacharyya, S.C.; Timilsina, G.R. A review of energy system models. Int. J. Energy Sect. Manag. 2010, 4,

494–518, doi:10.1108/17506221011092742.
7. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modelling for twenty-first century energy
challenges. Renew. Sustain. Energy Rev. 2014, 33, 74–86, doi:10.1016/j.rser.2014.02.003.
8. IIASA. Global Energy Assessment (GEA); Cambridge University Press: Cambridge, UK, 2012;
doi:10.1017/CBO9780511793677.
9. Jaccard, M. Sustainable fossil fuels: The unusual suspect in the quest for clean and enduring energy. Sustain.
Foss Fuels Unusual Suspect Quest Clean Endur. Energy 2006, 35, 1–381, doi:10.1017/CBO9780511754104.
10. United Nations. Sustainable Development Goals. About Sustain Dev Goals 2018. https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed on 28 November
2018).
11. Fuso Nerini, F.; Tomei, J.; To, L.S.; Bisaga, I.; Parikh, P.; Black, M.; Borrion, A.; Spataru, C.; Castán Broto,
V.; Anandarajah, G.; et al. Mapping synergies and trade-offs between energy and the Sustainable
Development Goals. Nat. Energy 2018, 3, 10–15, doi:10.1038/s41560-017-0036-5.
12. United Nations. Sustainable Development Goals. Goal 7 Ensure Access to Affordable, Reliab Mod Energy
All 2018. Available online: https://www.un.org/sustainabledevelopment/energy/ (accessed on 27 August
2018).
13. Tvaronavičienė, M.; Prakapienė, D.; Garškaitė-Milvydienė, K.; Prakapas, R.; Nawrot, Ł. Energy Efficiency
in the Long-Run in the Selected European Countries. Econ. Sociol. 2018, 11, 245–254. doi:10.14254/2071- 789x.2018/11-1/16.
14. IEA (International Energy Agency). Energy and Air Pollution—World Energy Outlook 2016 Special Report; IEA: Paris, France, 2016.
15. WWF. Critical Materials for the Transition to a Sustainable Energy Future; WWF: Gland, Switzerland, 2014.
16. Rosenthal, J.; Quinn, A.; Grieshop, A.P.; Pillarisetti, A.; Glass, R.I. Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. Energy Sustain. Dev. 2018, 42, 152–159, doi:10.1016/j.esd.2017.11.003.
17. Kasperowicz, R. Economic growth and energy consumption in 12 European countries: a panel data approach. J. Int. Stud. 2015, 7, 112–122, doi:10.14254/2071-8330.2014/7-3/10.
18. Jabareen, Y. Building a Conceptual Framework: Philosophy, Definitions and Procedure. Int. J. Qual. Methods 2009, 8, 49–62.
19. Kuhn, T.S. The Structure of Scientific Revolutions; University of Chicago Press: Chicago, IL, USA, 1970.
20. UN. Report of the United Nations Conference on the Human Environment; United Nations: Stockholm, Sweden. 1972.
21. Ephraums, J.J.; Jenkins, G.J.J. Climate Change 1992; Press Syndicate by the University of Cambridge: New York, NY, USA, 1992.
22. United Nations. Department of Public Information. The Millennium Development Goals, List of Millennium Development Goals; United Nations: New York, NY, USA, 2000.

23. Breidenich, C.; Magraw, D.; Rowley, A.; Rubin, J.W. The Kyoto Protocol to the United Nations Framework Convention on Climate Change. Am. J. Int. Law 1998, 92, 315, doi:10.2307/2998044.
24. IAEG-SDGs. Final list of proposed Sustainable Development Goal indicators. Rep Inter-Agency Expert Gr Sustain Dev Goal Indic 2016: Annex IV; United Nations: New York, NY, USA, 2016; ISBN 978 92 4 150848 3.
25. Economic and Social Council. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (20 20 by 2020 Europe's Climate change opportunity); United Nations: New York, NY, USA, 2008.
26. UN. Adoption of the Paris Agreement. Conference of the Parties: Twenty-First Session; United Nations: New York, NY, USA, 2015, doi:FCCC/CP/2015/L.9.
27. UNCED. Proceedings of the UN Conference on Environment and Development Earth Summit'92, vol. Rio de Janeiro, Brazil, 3–14 June 1992; doi:10.1007/s11671-008-9208-3.
28. United Nations. Johannesburg Declaration on Sustainable Development; United Nations: Johannesburg, South Africa, 2002; pp. 24–27.
29. UN Commission on Sustainable Development. Report on the Ninth Session; United Nations: New York, NY, USA, 2001.
30. Commission for Social Development. The current global crises and their impact on social development; United Nations: New York, NY, USA, 2009.
31. Greene, L.A. United nations framework convention on climate change. Environ. Health Perspect. 2000, 108, doi:10.1289/ehp.108-a353.
32. Ebinger, J.; Vergara, W. Climate Impacts on Energy Systems; The World Bank: Washington D.C., WA, USA, 2011; doi:10.1596/978-0-8213-8697.
33. Schaeffer, R.; Szklo, A.S.; Pereira de Lucena, A.F.; Moreira Cesar Borba, B.S.; Pupo Nogueira, L.P.; Fleming, F.P.; Troccoli, A.; Harrison, M.; Sadeck Boulahya, M. Energy sector vulnerability to climate change: A review. Energy 2012, 38, 1–12, doi:10.1016/j.energy.2011.11.056.
34. Huang, B.N.; Hwang, M.J.; Yang, C.W. Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. Ecol. Econ. 2008, 67, 41–54, doi:10.1016/j.ecolecon.2007.11.006.
35. Stern Nicholas, H. The Economics of Climate change: The Stern Review; Cambridge University Press: Cambridge, UK, 2007.
36. Stavytskyy, A.; Kharlamova, G.; Giedraitis, V.; Šumskis, V. Estimating the interrelation between energy security and macroeconomic factors in European countries. J. Int. Stud. 2018, 11, 217–238, doi:10.14254/2071-8330.2018/11-3/18.
37. Makarenko, D.; Streimikiene, D. Quality of life and environmentally responsible behaviour in energy sector. J. Int. Stud. 2014, 8, 58–67, doi:10.14254/2071-8330.2014/7-3/17.
38. Nashawi, I.S.; Malallah, A.; Al-Bisharah, M. Forecasting World Crude Oil Production Using Multicyclic Hubbert Model. Energy Fuels 2010, 24, 1788–1800, doi:10.1021/ef901240p.
39. Keeble, B.R. The Brundtland report: Our common future. Med. War 1988, 4, 17–25, doi:10.1109/ICRA.2018.8462871.
40. Meier, A. What is the cost to you of conserved energy? Harv. Bus. Rev. 1983, 61, 36–37.
41. Meier, A.K.; Rosenfeld, A. Supply Curves of Conserved Energy. Energy 1982, 7, 347–358, doi:10.1016/0360- 5442(82)90094-9.
42. Nakicenovic, N.; Jefferson, M. Global Energy Perspectives to 2050 and Beyond. World Energy Council and IIASA: Laxenburg, Austria, 1995.
43. Wanger, T.C. The Lithium future-resources, recycling and the environment. Conserv. Lett. 2011, 4, 202–206, doi:10.1111/j.1755-263X.2011.00166.x.

44. Sovacool, B.K.; Heffron, R.J.; McCauley, D.; Goldthau, A. Energy decisions reframed as justice and ethical concerns. Nat. Energy 2016, 1, 16024, doi:10.1038/nenergy.2016.24.
45. Jenkins, K.; McCauley, D.; Forman, A. Energy justice: A policy approach. Energy Policy 2017, 105, 631–634, doi:10.1016/j.enpol.2017.01.052.
46. Biros, C.; Rossi, C.; Sahakyan, I. Discourse on climate and energy justice: a comparative study of Do It Yourself and Bootstrapped corpora. Corpus 2018, 18, 1–28.
47. Bataille, C.; Waisman, H.; Colombier, M.; Segafredo, L.; Williams, J. The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. Clim. Policy 2016, 16, S1–S6, doi:10.1080/14693062.2016.1179620.
48. IEA (International Energy Agency). Water Energy Nexus—Excerpt from the World Energy Outlook 2016; OECD/IEA publishing: Paris, France, 2016; p. 60, doi:10.1021/es903811p.
49. Steffen, W.; Sanderson, A.; Tyson, P.; Jäger, J.; Matson, P.; Moore III, B.; Oldfield, F.; Richardson, K.; Schellnhuber, H.J.; Turner, B.L.; et al. Global Change and the Earth System; Springer: Berlin/Heidelberg, Germany, 2005.
50. Modi, V.; McDade, S.; Lallement, D.; Saghir, J. Energy Services for the Millennium Development Goals. UNDP: New York, NY, USA, 2005.
51. Nakata, T.; Silva, D.; Rodionov, M. Application of energy system models for designing a low-carbon society. Prog. Energy Combust. Sci. 2011, 37, 462–502, doi:10.1016/j.pecs.2010.08.001.
52. UNDP. World Energy Assessment. Energy and the Challenge of Sustainability; UNDP: New York, NY, USA, 2000.
53. Vera, I.; Langlois, L. Energy indicators for sustainable development. Energy. 2007, 32, 875–882, doi:10.1016/j.energy.2006.08.006.
54. Meadows, D.H.; Meadows, D.L.; Randers, J.; Behrens, W.W. The Limits to Growth, 1st ed.; Universe Books: New York, NY, USA, 1972.
55. Simmons, J. Materials critical to the energy industry; BP: London, UK, 2011; pp. 6–7.
56. Jebaraj, S.; Iniyan, S. A review of energy models. Renew. Sustain. Energy Rev. 2006, 10, 281–311. doi:10.1016/j.rser.2004.09.004.
57. Nakata, T. Energy-economic models and the environment. Prog. Energy Combust. Sci. 2004, 30, 417–475. doi:10.1016/j.pecs.2004.03.001.
58. DeCarolis, J.F.; Hunter, K.; Sreepathi, S. The case for repeatable analysis with energy economy optimization models. Energy Econ. 2012, 34, 1845–1853. doi:10.1016/j.eneco.2012.07.004.
59. Després, J.; Hadjsaid, N.; Criqui, P.; Noirot, I. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 2015, 80, 486–495. doi:10.1016/j.energy.2014.12.005.
60. Hourcade, J.-C.; Jaccard, M.; Bataille, C.; Ghersi, F. Hybrid Modelling: New Answers to Old Challenges. Energy J. 2006, 27, 1–11, doi:10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-1.
61. Heap, C. Long Range Energy Alternative Planning System-user guide for version 2008. Available online: https://www.google.com.tw/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=2ahUKEwjproSC5erhAhWPOnAKHfVrBM8QFjABegQIBhAC&url=http%3A%2F%2Fwww.energycommunity.org%2Fdocuments%2FLEAP2011UserGuideEnglish.pdf&usg=AOvVaw3ufN5ypeLXKVIa--H4oSz_ (accessed on 25 March 2019).
62. Millennium Institute. Introduction and Purpose of Threshold 21; Millennium Institute: Washington, WA, USA, 2016.
63. Stehfest, E.; van Vuuren, D.; Bouwman, L.; Kram, T. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications; Netherlands Environmental Assessment Agency

(PBL): The Hauge, Netherlands, 2014. ISBN: 978-94-91506-71-0.
64. Walsh B, Rydzak F, Obersteiner M, Fritz S, McCallum I. The Felix Model. IIASA: Laxenburg, Austria. 2017.
65. Sterman J, Fiddaman T, Franck T, Jones A, McCauley S, Rice P, Sawin E, Siegel L. Climate interactive: the C-ROADS climate policy model. Syst Dyn Rev. 2012, 28, 295–305, doi:10.1002/sdr.1474.
66. Nordhaus WD. The “DICE” Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. Yale University: New Haven, US. 1992.
67. Klein, D.; Mouratiadou, I.; Pietzcker, R.; Piontek, F.; Roming, N. Description of the REMIND model; Potsdam Institute for Climate Impact Research: Potsdam, Germany, 2017.
68. Loulou, R.; Goldstein, G.; Noble, K. Documentation for the MARKAL Family of Models; 2004. Available online: http://www.etsap.org/tools.htm (accessed on 10 December 2018)
69. Loulou, R.; Remne, U.; Kanudia, A.; Lehtila, A.; Goldstein, G. Documentation for the TIMES Model: Part III; IEA Energy Technology Systems Analysis Programme (ETSAP). 2016. Available online: http://www.iea- etsap.org/web/Documentation.asp (accessed on 10 December 2018)
70. E3MLab. PRIMES Model, Version 6. Detailed Model Description; 2016. Available online: http://www.e3mlab.ntua.gr/e3mlab/PRIMES Manual/The PRIMES MODEL 2016-7.pdf (accessed on 10 May 2018)
71. Messner, S.; Strubegger, M. User’s Guide for MESSAGE III; IIASA: Laxenburg, Austria, 1995.
72. IEA. World Energy Model Documentation 2014; IEA: Paris, France. p. 54.
73. Capros, P.; van Regemorter, D.; Paroussos, L.; Karkatsoulis, P.; Fragkiadakis, C.; Tsani, S. GEM-E3 Model
Documentation. Publications Office of the European Union: Luxemborg, 2013. doi:10.2788/47872.
74. EIA. Assumptions to the Annual Energy Outlook 2017; EIA: Paris, France, 2017.
75. EIA. The National Energy Modelling System: An Overview 2009; EIA: Paris, France,. 2009.
76. Messner, S.; Schrattenholzer, L. MESSAGE-MACRO: Linking an energy supply model with a
macroeconomic module and solving it iteratively. Energy 2000, 25, 267–282. doi:10.1016/S0360-
5442(99)00063-8.
77. Rao, S.; Keppo, I.; Riahi, K. Importance of Technological Change and Spillovers in Long-Term Climate
Policy. Energy J. 2006, 27, 123–139. doi:10.2307/23297059.
78. Pachauri, S.; Nagai, P. The IIASA Energy Access Tool (Energy-ENACT); IIASA: Laxenburg, Austria, 2012.
79. Siegel L.S.; Homer, J.; Fiddaman, T.; Mccauley, S.; Franck, T.; Sawin, E. EN-ROADS Simulator Reference
Guide. Technical Report. Climate Interactive: Washington, WA, USA, 2018.
80. En-ROADS. Climate Interactive. Available online: https://www.climateinteractive.org/tools/en-roads/
(accessed on 19 April 2018).
81. Park, M.; Liu, X. Assessing Understanding of the Energy Concept in Different Science Disciplines. Sci. Educ.
2016, 100, 483–516. doi:10.1002/sce.21211.
82. Jefferson, M. Closing the gap between energy research and modelling, the social sciences and modern

realities. Energy Res. Soc. Sci. 2014, 4, 42–52, doi:10.1016/j.erss.2014.08.006.
83. E3Mlab. PRIMES Model—Version 6, 2016–2017; E3MLab: Athens, Greece,2016.
84. IEA. World Energy Outlook 2017; OECD Publishing: Paris, France, 2017; doi:10.1787/weo-2017-en.
85. Helgesen, P.I. Top-down and Bottom-up : Combining energy system models and macro-economic general
equilibrium models. Cent. Sustain. Energy Stud. Work Pap. 2013, 30.
86. Energy Information Administration. The National Energy Modelling System: An Overview 2009; Volume 0581;
Energy Information Administration: Washington, DC, USA, 2009.
87. EIA. Renewable Fuels Module of the National Energy Modelling System: Model Documentation 2016; EIA: Paris,
France, 2016.
88. Vrontisi, Z.; Abrell, J.; Neuwahl, F.; Saveyn, B.; Wagner, F. Economic impacts of EU clean air policies
assessed in a CGE framework. Environ. Sci. Policy 2016, 55, 54–64. doi:10.1016/j.envsci.2015.07.004.
89. Grubb, M. Policy modelling for climate change. The missing models. Energy Policy 1993, 21, 203–208,
doi:10.1016/0301-4215(93)90242-8.
90. Holz, F.; Ansari, D.; Egging, R.; Helgesen, P.I. Hybrid Modelling: Linking and Integrating Top-Down and
Bottom-Up Models; NTUA-EPU: Athens, Greece, 2016.
91. Giupponi, C.; Borsuk, M.E.; de Vries, B.J.M.; Hasselmann, K. Innovative approaches to integrated global
change modelling. Environ. Model. Softw. 2013, 44, 1–9, doi:10.1016/j.envsoft.2013.01.013.
92. Osborn, D.; Cutter, A.; Ullah, F. Universal Sustainable Development Goals: Understanding the
transformational challenge for developed countries. Univers. Sustain. Dev. Goals 2015, 1–24.
93. Bassi, A.M.; Shilling, J.D. Informing the US Energy Policy Debate with Threshold 21. Technol. Forecast. Soc.
Change 2010, 77, 396–410, doi:10.1016/j.techfore.2009.10.007.
94. Verburg, P.H.; Dearing, J.A.; Dyke, J.G.; van der Leeuw, S.; Seitzinger, S.; Steffen, W.; Syvitski, J. Methods
95. Thomson, A.M.; Calvin, K.V.; Smith, S.J.; Kyle, G.P.; Volke, A.; Patel, P.; Delgado-Arias, S.; Bond-Lamberty, B.; Wise, M.A.; Clarke, L.E.; et al. RCP4.5: A pathway for stabilization of radiative forcing by 2100. Clim. Change 2011, 109, 77–94, doi:10.1007/s10584-011-0151-4.
96. van Vuuren, D.P.; de Vries, B.; Beusen, A.; Heuberger, P.S.C. Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. Glob. Environ. Chang. 2008, 18, 635–654, doi:10.1016/j.gloenvcha.2008.06.001.
97. Masui, T.; Matsumoto, K.; Hijioka, Y.; Kinoshita, T.; Nozawa, T.; Ishiwatari, S.; Kato, E.; Shukla, P.R.; Yamagata, Y.; Kainuma, M. An emission pathway for stabilization at 6 Wm-2 radiative forcing. Clim. Change 2011, 109, 59–76, doi:10.1007/s10584-011-0150-5.
98. Monier, E.; Paltsev, S.; Sokolov, A.; Chen Y.H.H.; Gao, X.; Ejaz, Q.; Couzo, E.; Schlosser, A. C.; Dutkiewicz, S.; Fant, C.; et. al. Toward a consistent modelling framework to assess multi-sectoral climate impacts. Nat. Commun. 2018, 9, 1–8, doi:10.1038/s41467-018-02984-9.

99. Matsumoto, K.; Tachiiri, K.; Kawamiya, M. Evaluating multiple emission pathways for fixed cumulative carbon dioxide emissions from global-scale socioeconomic perspectives. Mitig. Adapt Strateg. Glob. Chang. 2018, 23, doi:10.1007/s11027-016-9726-8.
100. Matsumoto, K.; Tachiiri, K.; Kawamiya, M. Impact of climate model uncertainties on socioeconomics: A case study with a medium mitigation scenario. Comput. Oper. Res. 2016, 66, 374–383, doi:10.1016/j.cor.2015.01.011.
101. Dietrich, J.P.; Bodirsky, B.L.; Humpenöder, F.; Weindl, I.; Stevanović, M.; Karstens, K.; Kreidenweis, U.; Wang, X.; Mishra, A.; Klein, D.; et. al. MAgPIE 4 – a modular open-source framework for modeling global land systems. Geoscience 2019, 12, 1299–1317, doi:10.5194/gmd-12-1299-2019.
102. Kriegler,E.;Bauer,N.;Popp,A.;Humpenöder,F.;Leimbach,M.;Strefler,J.;Baumstark,L.;Bodirsky,B.L.; Hilaire, J.; Klein, D.; et. al. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Glob. Environ. Chang. 2017, 42, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.
103. Endo,A.;Tsurita,I.;Burnett,K.;OrencioPM.Areviewofthecurrentstateofresearchon-thewater,energy and food nexus. J. Hydrol. Reg. Stud. 2015, doi:10.1016/j.ejrh.2015.11.010.
104. Dai, J.; Wu, S.; Han, G.; Weinberg, J.; Xie, X.; Wu, X. Water-energy nexus: A review of methods and tools for macro-assessment. Appl. Energy 2018, 210, 393–408, doi:10.1016/j.apenergy.2017.08.243.
105. IPCC. Summary for Policymakers: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; Cambridge University Press: Cambridge, UK, 2011.
106. Ackerman,F.;Fisher,J.Isthereawater-energynexusinelectricitygeneration?Long-termscenariosforthe western United States. Energy Policy 2013, 59, 235–241, doi:10.1016/j.enpol.2013.03.027.
107. Liebert, W.; Englert, M. Risiken der Uranproduktion und der Urannutzung–Risiken für die Nutzung der Kernenergie; IEWT: Vienna, Austria, 2015; pp. 1–26.
108. Busch, J.; Steinberger, J.K.; Dawson, D.A.; Purnell, P.; Roelich, K. Managing critical materials with a technology-specific stocks and flows model. Environ. Sci. Technol. 2014, 48, 1298–1305, doi:10.1021/es404877u.
109. Dale, M.; Krumdieck, S.; Bodger, P. Global energy modelling—A biophysical approach (GEMBA) Part 2: Methodology. Ecol. Econ. 2012, 73, 158–167, doi:10.1016/j.ecolecon.2011.10.028.
110. Murphy, D.J.; Hall, C.A. Energy return on investment, peak oil and the end of economic growth. Ann. N. Y. Acad. Sci. 2011, 1219, 52–72, doi:10.1111/j.1749-6632.2010.05940.x.
111. Mandelli, S.; Barbieri, J.; Mereu, R.; Colombo, E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew. Sustain. Energy Rev. 2016, 58, 1621–1646, doi:10.1016/j.rser.2015.12.338.
112. Palit, D. Solar energy programs for rural electrification: Experiences and lessons from South Asia. Energy Sustain. Dev. 2013, 17, 270–279, doi:10.1016/j.esd.2013.01.002.
113. Riva,F.;Ahlborg,H.;Hartvigsson,E.;Pachauri,S.;Colombo,E.Electricityaccessan-druraldevelopment: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. Energy Sustain. Dev. 2018, 43, 203–223, doi:10.1016/j.esd.2018.02.003.
114. Collste, D. Policy coherence to achieve the SDGs : using integrated simulation models to assess effective policies. Sustain. Sci. 2017, doi:10.1007/s11625-017-0457-x.

Paper 2: Renewable Energy – Characteristics and representation in macroeconomic energy-climate models

CAPROS P., PAROUSSOS L., FRAGKOS P., TSANI S., BOITIER B., WAGNER F., BOLLEN J. (2014), «Description of models and scenarios used to assess European decarbonisation pathways », *Energy Strategy Reviews*, *2*(3), p. 220-230.

CAPROS P. (1996), PRIMES and GEM-E3 Contribution to Climate Change Policy Debate. *Athens, National Technical University of Athens*.

CAPROS P.D, GEORGAKOPOULOS T., FILIPPOUPOLLITIS A., KOTSOMITI S., ATSAVES G., PROOST S., SCHMIDT T.F.N (1997). The GEM-E3 model : Reference manual. *National University of Athens, Athens*.

COMMISSIE EUROPESE (2011), A Roadmap for moving to a competitive low carbon economy in 2050, *Europese Commissie, Brussel*.

DESERTEC Foundation – About, (2016). Retrieved October 14, from http://www.desertec.org/about-desertec

E3MLAB (2016), The Primes Energy Syste Model Description, http://www.e3mlab.ntua.gr/e3mlab/PRIMES%20Manual/The%20PRIMES%20MODEL%202016-7.pdf last accessed April 2017

EDENHOFER O., PICHS MADRUGA R., SOKONA Y. (2012), « Renewable Energy Sources and Climate Change Mitigation", *Special Report of the Intergovernmental Panel on Climate Change,* vol 6, p. 1 – 1088.

EUROPEAN PARLIAMENT (n.d.), How the European Union works - Activities of the institutions and bodies. https://doi.org/10.2775/20055

EUROPEAN COMMISSION (2016), *EU Reference Scenario 2016: Energy, transport and GHG emissions, trends for 2050,* Luxembourg, Publications Office of the European Union, 220 p. GARCIA-OLIVARES A., BALLABRERA-POY J., GARCIA-LADONA E., TURIEL A. (2011). "A global renewable mix with proven technologies and common materials", *Energy Policy*, 41, p. 561–574.

GERMAN ADVISORY COUNCIL ON GLOBAL CHANGE (2003), *World in Transition – Towards Sustainable Energy Systems*. Retrieved from http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2003/wbgu_j g2003_engl.pdf

IIASA (2012), *Global Energy Assessment Toward a Sustainable Future*, 1884. INTERNATIONAL ENERGY AGENCY (2014), *World Energy Outlook,* Paris.

MEADOWS D.H, MEADOWS D.L, RANDERS J., BEHRENS W.W (1972), The Limits to Growth, 1st Edition, New York, Universe Books.

MOBAREK, SAMEH I. (2016), *Morocco - MA-Noor Ouarzazate Concentrated Solar Power Project : P131256 - Implementation Status Results Report : Sequence 03* (No. ISR23914) (p. 1–0). The World Bank. Retrieved from http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP//

MOSS R.L, TZIMAS E., WILLIS P., ARENDORF J., THOMPSON P., CHAPMAN A., TERCERO-ESPINOZA L. (2013), «Critical metals in the path towards the decarbonisation of the EU energy sector», *Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. JRC Report EUR, 25994*.

ROADMAP ENERGY (2011), 2050. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels*, *15*, 12.

ROTMANS J., VAN ASSELT M. (1999), "Integrated Assessment Modelling " In *Climate Change: An Integrated Perspective, edited by Pim Martens, Jan Rotmans, Darco Jansen, and Koos Vrieze,* p. 239–75. *Dordrecht: Springer Netherlands.*

SCHAEFFER R. and Al. (2012) "Energy Sector Vulnerability to Climate Change : A Review*",* *Energy*, vol 38, n° 1, p. 1–12.

STEFFEN W., SANDERSON A., TYSON P., JAGER J., MATSON P., MOORE III B., VERA I., LANGOIS L. (2007), "Energy indicators for sustainable development"

WASSON R.J. (2005). *Global Change and the Earth System*. Berlin Heidelberg New York: Springer.

WWF (2014), *Critical materials for the transition to a 100 % sustainable energy future contents.*

Paper 3: Integrated Assessment Models (IAM): How to integrate Energy, Climate and Economics?

ALCAMO J. (1994), *IMAGE 2.0, Integrated Modelling of Global Climate Change*, Kluwer Academic Publishers.

ALCAMO J., SHAW R., HORDIJK L. (1990), *The RAINS Model of Acidification: Science and Strategies in Europe*, Dordrecht, Netherlands, Kluwer.

ALLEN T.F.H, TAINTER J.A, HOEKSTRA T.W (2003°, Supply Side Sustainability, Columbia University Press.

AMBROSI P., COURTOIS P. (2004), « Impacts du changement climatique et modélisation intégrée, la part de l'arbitraire », *Natures, Sciences et Sociétés,* vol 12, p. 375 – 386.

BALA G., DUFFY P.B, TAYLOR K.E (2008), « Impact of Geoengineering Schemes on the Global Hydrological Cycle", *Proceedings of the National Academy of Sciences of the United States of America*, vol 105, n°22, june, p. 7664 – 7669.

BARKER T., SERBAN-SCRIECIU S. (2010), "Modeling Low Climate with E3MG: Towards a New Economics Approach to Simulating Energy-Environment-Economy System Dynamics*", The Energy Journal*, vol 31, Special Issue, January, p. 137 – 164.

BLANCHARD E.V. (2011), « L'origine des modèles intégrés du changement climatique », *Recherches internationales*, n°89, janvier-mars, p. 181-211.

BAUER N. (2018), REMIND – MAgPIE Model, *CNRS Summer School on IAM*, Clermont-Ferrand, France, june, 59 p.

BAUER N., BAUMSTARK L., LEIMBACH M. (2012), The Remind-R Model : The role of renewables in the low carbon transformation – first best vs second best worlds, climate change, DOI : 10.1007/s10584-011-0129-2.

BAUER N., EDENHOFFER O., KYPREOS S. (2008), Linking Energy System and Macroeconomic Growth Models, *Journal of Computational Management Science* 5, 95-117.

BOUTRON C.F, CANDELONE J.P, HONG S. (1993), « Le plomb dans les neiges er les glaces du Groenland », *Pollution atmosphérique*, Juillet-Septembre, p. 128-131.

BRUCKNER T. and al. (2014), Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

DALMEDICO D.A. (2007), *Les modèles du futur. Changement climatique et scénarios économiques : enjeux scientifiques et politiques.* Recherche La Découverte.

DIEMER A., NDIAYE A., GLADKYKH G. (2017), « Le climat, du savoir scientifique aux modèles à intégration assignée », *Revue francophone du développement durable*, n°9, mars, p. 6 – 52.

DIEMER A., DIERICKX F., GLADKHYK G., MORALES M., PARRIQUE T., TORRES J. (2017), *European Union and Sustainable Development*, Editions Oeconomia.

DIEMER A. (2004), « Le développement durable et la dynamique des systèmes », *document de travail*, n°2004/05, HERMES, Université de Reims, 24 mai, 12 p.

D'ODORICA P., LAIO F., PORPORATO A., RIDOLFI L., RINALDO A., RODRIGUEZ-ITURBE I. (2010), Ecohydrology of terrestrial Ecosystems", *BioScience,* vol 60, n°11, December, p. 898 – 907.

DOWLATABADI H., MORGAN M.G (1993), « Integrated Assessment of Climate Change », *Science*, vol 259, (5103).

EUROPEAN COMMISSION (2016), *EU Reference Scenario 2016 – Energy, transport and GhG emissions, trends to 2050*, july 15th, Luxembourg Publications Office, 220 p.

GIDDENS M. (2018), MESSAGEix, Cutting Edge Research and Challenges, *CNRS Summer School*, Clermont-FErrand, France, June, 33 p.

GLADKYKH G., SPITTLER N., DIERICKX F. (2017), "Renewable Energy: Characteristics and Representation in Macroeconomic Energy-Climate Models sources for climate change models" in Diemer A. et al. (eds), *European Union and Sustainable Development*, Editions Oeconomia.

HA-DONG M., MATARASSO P. (2006), « Comment intégrer l'économie, l'énergie et le climat ? », *Pour la Science*, dossier 52, p. 92 – 97.

HOURCADE J.C, LE TREUT H. (2002), *Modélisation intégrée, évaluation des risques climatiques et des politiques de précaution,* CIRED, LMD, SMASH, Rapport de Synthèse, Juillet, 29 p.

KELLY D.L, KOLSTAD C.D (1999), « Integrated Assessment Models For Climate Change Control » in Folmer H. and Tietenberg T. (eds), *International Yearbook of Environmental and Resource Economics 1999/2000: A Survey of Current Issues*, Cheltenham, UK, Edward Elgar.

KIEKEN H. (2003), « Genèse et limites des modèles d'évaluation intégrée », *Annales des Ponts et Chaussées*, n°107-108, p. 84 – 91.

KNORR W ;, SCHNITZLER K.G (2006), "Enhanced albedo feedback in North Africa from possible combined vegetation and soil formation processes", *Climate Dynamics*, 26, p. 55 – 63.

IIASA MESSAGE 2017. International Institute of Applied Systems Analysis. http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html (accessed October 15, 2018).

LEIMBACH M., BAUMSTARK L., EDENHOFER O. (2010), Mitigation costs in a globalized world : climate policy analysis with Remind-R, *Environmental Modeling and Assessment*, vol 15, p. 155 – 173.

LEIMBACH M., BAUER N., BAUMSTARK L., LUKEN M., EDENHOFER O. (2010), Technological Change and International Trade, Insights from Remind, Special Issue of the Energy Journal, vol 31, p. 109 – 136.

LUDERER G., LEIMBACH M., BAUER N., KRIEGLER E. (2011), *Description of the REMIND R Model*, http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1

MANNE A.S, MENDELSOHN R., ROCHELS R.G (1993), "MERGE: A Model for Evaluating Regional and Global Effects of GhG Reduction Policies", *Energy Policy*, vol 23, p. 17 – 34.

MANNE A.S, ROCHELS R.G (1990), "CO2 Emission Limits, An Economic Cost Analysis for the USA", *Energy Journal*, vol 12, p. 87 – 107.

MATARASSO P. (2007), « La construction historique des paradigmes de modélisation intégrés : William Nordhaus, Alan Manne et l'apport de la Cowles Commission » in Dalmedico A.D (ed), *Les modèles du futur. Changement climatique et scénarios économiques : enjeux scientifiques et politiques.* Recherche La Découverte.

MATARASSO P. (2003), « Evaluation intégrée et modélisation du changement climatique », *Annales des Ponts et Chaussées*, p. 71 – 79.

MEADOWS D.H, RANDERS J., MEADOWS D. (2004), *Limits to Growth, The 30-year Update*, Chelsea Green Publishing.

MEADOWS D.H, MEADOWS D.L, RANDERS J. (1992), *Beyond the Limits*, Earthscan Publications Limited.

MEADOWS D.H, MEADOWS D.L, RANDERS J., BEHRENS III W.W (1972), *The Limits to growth*, Universe Books Publishers.

MESSNER S., STRUBEGGER M. (1995), User ' s Guide for MESSAGE III. Laxenburg, Austria.

MESSNER S., SCHRATTENHOLZER L.. MESSAGE-MACRO: Linking an energy supply.

NORDHAUS W. (2016), "Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies*", Cowles Foundation*, Discussion Paper, n°257, 44p.

NORDHAUS W., BOYER J. (1999), "Roll the DICE Again: Economic Models of Global Warming", Chapter 1, Yale University, October 25, 10 p.

NORDHAUS W. (1998), *Economics and Policy Issues in Climate Change*, Resources for the Future, New York.

NORDHAUS W. (1992), "An Optimal Transition Path for Controlling Greenhouse Gases", *Science*, vol 258, November, p. 1315 – 1319.

NORDHAUS W. (1991), "To Slow or not to slow: The Economics of the Greenhouse Effect", *Economic Journal,* vol 101, p. 920 – 937.

NORDHAUS W. (1977), “Economic Gorwth and Climate: The Carbon Dioxide Problem”, *The American Economic Review*, vol 67, n°1, p. 341 – 346.

NORDHAUS W. (1974), « Resources as a Constraint on Growth”, *American Economic Review,* vol 64, n°2, May, p. 22 – 26.

NORDHAUS W. (1973), « The allocation of energy resources », *Cowles Foundation Papers*, n° 401.

NORDHAUS W. (1973), “World Dynamics, Measurement Without Data”, The *Economic Journal*, vol 83, n° 332, p. 1156 – 1183.

NORDHAUS W., TOBIN J. (1972), “IS Growth Obsolete?”, in Nordhaus W., Tobin J. (eds), *Economic Research, Retrospect and Prospect*, vol 5, *Economic Growth*, NBER, p. 1 – 80.

PARSON E.A, FISHER-VANDEN K. (1997), “Integrated Assessment Models of Global Climate Change”, *Annual Review of Energy and Environment*, vol 22, p. 589 – 628.

PRUYT E. (2013), *Small Dynamics Models for Big Issues*, Delft Library, The Netherlands.

RASKIN P., MONKS F., RIBEIRO T., VAN VUUREN D., ZUREK D. (2005), Global scenarios in historical perspective. In: Carpenter, S.R., et al. (Eds.), *Ecosystems and Human Well-Being: Scenarios: Findings of the Scenarios* Working Group. Island Press, Washington, DC, pp. 35–44.

RIAHI K., ROEHRL R.A (2000), Greenhouse gas emissions in a dynamics-as-usual scenario of economic and energy development. Technol Forecast Soc Change, 63, 175–205. doi:10.1016/S0040-1625(99)00111-0.

ROTHMAN D.S, AGARD J., ALCAMO J. (2007), *The Future Today*, in United Nations Environment Programme, in Global Environment Outlook 4. UNEP, Nairobi, pp. 397–454.

SCHNEIDER S., LANE J. (2005), “Integrated Assessment Modeling of Global Climate Change: Much Has Been Learned – Still a Long and Bumpy Road Ahead”, *The Integrated Assessment Journal*, vol 5, n°1, p. 41 – 75.

CHWANITZ V.J (2013), “Evaluating Integrated Assessment Models of Global Climate Change”, *Environmental Modeling and Software*, vol 50, p. 120 – 131.

SHERWOOD S., BONY S., BOUCHER O., BRETHERTON C., FORSTER P., GREGORY J.M, STEVENS B. (2015), “Adjustments in the forcing – feedback framework for understanding climate change”, *Bulletin of the American Meteorological Society*, vol 96, n°2, February, p. 217 – 228.

STEHFEST E., VAN VUUREN D., BOUWMAN L., KRAM T. (2014). *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. Netherlands Environmental Assessment Agency (PBL). (http://www.pbl.nl/sites/default/files/cms/PBL-2014-Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_30-735.pdf

SOKOLOV A.P and ali. (2005), *The MIT Integrated Global System Model 5IGSM), Version 2, Model Description and Baseline Evaluation*, Science Global Policy Change, Report n°124, July, 46 p.

TOL R.S.J, FANKHAUSER S. (1998), “On the Representation of Impact in Integrated Assessment Models of Climate Change”, *Environmental Modeling and Assessment*, vol 3, p. 63 – 74.

VAN VUUREN D., KRAM T., STEHFEST, E. (2015). IMAGE STRATEGY DOCUMENT 2015-2020.

VAN VUUREN D.P, KOK M.T.J, GIROD B., LUCAS P.L, DE VRIES B. (2012), Scenarios in global environmental assessments : key characteristics and lessons for future use, *Global Environ. Change,* 22 (4), 884–895.

VIEILLE-BLANCHARD E. (2007), “Croissance ou stabilité ? L’entreprise du Club de Rome et le débat autour des modèles », in Dalmedico D.A. (ed), *Les modèles du futur. Changement climatique et scénarios économiques : enjeux scientifiques et politiques.* Recherche La Découverte.

WALSH K. (1994), « On the Influence of the Andes on the General Circulation of the Southern Hemisphere », *Journal of Climate*, vol 7, n°6, p. 1019 – 1025.

Paper 4: Grounding social foundations for Integrated Assessment Models of climate change

1. D. Loorbach, J. Rotmans *Future* **42,** 237-246 (2010).
2. W. D., Nordhaus, *Resource and Energy Economics* **15**, 27–50 (1993).
3. J. Alcamo, *IMAGE 2.0 Integrated Modelling of Global Climate Change*, Kluwer Academic Publishers, Dordrecht / Boston / London (1994)
4. R. S. Pindyck, *Journal of Environmental Economics and Management* **94**, 140-160 (2019).
5. R. Mearns, A. Norton, *Social Dimensions of Climate Change : Equity and Vulnerability in a Warming World*. New Frontiers of Social Policy. World Bank (2010).
6. Ackerman, F., DeCanio, S.J., Howarth, R.B. et al. Climatic Change (2009) 95: 297.
7. K. T. Stevenson, M. N. Peterson, S. J. Carrier, R. L. Strnad, E. Seekamp, *Nature Climate Change* **9**(6), 458-462 (2019).
8. J. D. Farmer *et al.*, *Science* **364**(6436) (2019).
9. L. Hirth, F. Ueckerdt, F. *Energy Policy* **62**, 934-947 (2013).
10. S. Fankhauser, R. S. J. Tol, D. W. Pearce, *Environmental and Resource Economics* **10**(3), 249-266 (1997).
11. H. Chockler, J. Y. Halpern, *Journal of Artificial Intelligence Research* **22**, 93-115 (2004).
12. K. C. Meng, A. Rode, *Nature Climate Change* **9**(6), 472-476, (2019).
13. R. Zafarani, M. A Abbasi, H. Liu, *Social media mining: an introduction.* Cambridge University Press (2014).
14. 14 F. Moulaert, D. MacCallum, A. Mehmood, A. Hamdouch, *The International Hanbook of Social Innovations*, Edward Elgar, UK. (2013).
15. 15 G. Dubois, *et al.*, *Energy Research & Social Science* **52**, 144-158 (2019).

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

Banks, F.E., 2000. Energy Economics: a Modern Introduction. Springer US, Boston, MA. http://dx.doi.org/10.1007/978-0-85729-268-1.

Boulding, K.E., 1966. The economics of the coming spaceship earth. A survey of ecolo- gical economics / edited by Rajaram Krishnan, Jonathan M. Harris, and Neva R. Goodwin, pp. 1–8.

Buchert, M., Schüler, D., Bleher, D., 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential, Available at: 〈http://www.unep.fr/shared/publications/pdf/DTIx1202xPA-Critical〉 Metals and their Recycling Potential.pdf (Accessed 31 October 2016).

Campbell, C.J., Laherrère, J.H., 1998. The end of cheap oil. Sci. Am. 278 (3), 60–65.

CIFOR, 2003. Integrated Natural Resource Management: Linking productivity, the environment and development., p.309 p. Available at: https://books.google.com.ua/ books?hl=uk&lr=&id=3T8NIgax6zQC&oi=fnd&pg=PA247&dq=accumulation +of+waste+absorption+natural+system&ots=_SOqkvhaBc&sig= V5KVYkpgag6gfeVwMDDJ908jS5w&redir_esc=y#v=onepage&q=waste&f=false (Accessed 8 August 2017).

Cleveland, C.J., et al., 1984. Energy and the U.S. economy : a biophysical perspective. Science.

Daly, H.N., 1974. The economics of the steady state. Am. Econ. Rev. 64 (2), 15–21. (Available at:). 〈http://econpapers.repec.org/article/aeaaecrev/v_3a64_3ay_ 3a1974_3ai_3a2_3ap_3a15-21.htm〉 (Accessed 8 August 2017).

Daly, H.E., 2011. The Economics of the Steady State 64(2).

Davidsson, S., et al., 2014. Growth curves and sustained commissioning modelling of renewable energy: investigating resource constraints for wind energy. Energy Policy 73, 767–776. http://dx.doi.org/10.1016/j.enpol.2014.05.003.

Dewulf, J., et al., 2016. Criticality on the international scene: quo vadis? Resour. Policy 50, 169–176. (Available at). http://linkinghub.elsevier.com/retrieve/pii/S0301420716301556 (Accessed 30 July 2017).

Dincer, I., 2002. The role of exergy in energy policy making. Energy Policy 30 (2), 137–149. Energy Roadmap 2050, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 15, 12.

Eurostat, 2015. eurostat - statistics explained. Energy from renewable sources. Available at: http://ec.europa.eu/eurostat/statisticsexplained/index.php/Energy_from_renewable_sources (Accessed 12 September 2017).

Forman, A., 2017. Energy justice at the end of the wire: Enacting community energy and equity in Wales. Energy Policy 107, 649–657. http://linkinghub.elsevier.com/retrieve/pii/S0301421517302902 (Accessed 16 September 2017). García-Olivares, A., et al., 2012. A global renewable mix with proven technologies and common materials. Energy Policy 41, 561–574.

García-Olivares, A., Ballabrera-Poy, J., 2015. Energy and mineral peaks, and a future steady state economy. Technol. Forecast. Social. Change 90 (PB), 587–598. http://dx.doi.org/10.1016/j.techfore.2014.02.013.

German Advisory Council on Global Change, 2003. World in Transition – Towards Sustainable Energy Systems,.

Goldemberg, J., Teixeira Coelho, S.,, 2004. Renewable energy—traditional biomass vs. modern biomass. Energy Policy 32 (6), 711–714. http://linkinghub.elsevier.com/retrieve/pii/S0301421502003403.

Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy Policy 64, 141–152. 〈https://ac.els-cdn.com/ S0301421513003856/1-s2.0-S0301421513003856-main.pdf?_tid=8346b5b4-6149-49af-9394-45eccebe8e5c&acdnat=1524242557_ d9a6be73a40f56d611e6487017822b4a〉 (Accessed 20 April 2018).

Höhne, N., den Elzen, M., Weiss, M., 2006. Common but differentiated convergence (CDC): a new conceptual approach to long-term climate policy. Clim. Policy 6 (2), 181–199.

Husar, J., Best, D., 2013. Energy Invest. Technol. Transf. Across Emerg. Econ. 〈https:// www.iea.org/publications/freepublications/publication/PCS_ChinaBrazil_FINAL_ WEB.pdf〉 (Accessed 13 November 2017).

IEA, 2004. World Energy Outlook 2004. OECD Publishing, Paris. http://dx.doi.org/10. 1787/weo-2004-en.

IIASA, 2012. In: Johansson, T.B. (Ed.), Global Energy Assessment (GEA), eds. Cambridge University Press, Cambridge. 〈http://ebooks.cambridge.org/ref/id/CBO9780511793677〉.
IRENA, 2015. Synergies Between Renewable Energy and Energy Efficiency, A Working Paper Based on Remap 2030. International Renewable Energy Agency (IRENA), 1(1), pp.1–52. Available at: 〈http://www.irena.org/DocumentDownloads/Publications/
IRENA_C2E2_Synergies_RE_EE_paper_2015.pdf〉. (Accessed 31 August 2017). Jackson, T., 2016. Prosperity Without Growth: Foundations for the Economy of Tomorrow. Taylor & Francis. Jefferson, M., 2014. Closing the gap between energy research and modelling, the social sciences, and modern realities. Energy Res. Social. Sci. 4 (C), 42–52. http://dx.doi.org/10.1016/j.erss.2014.08.006.
Jenkins, K., et al., 2016. Energy justice: a conceptual review. Energy Res. Social. Sci. 11, 174–182. 〈http://linkinghub.elsevier.com/retrieve/pii/S2214629615300669 (Accessed 16 September 2017).
JRC, 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. JRC Scientific & Policy Report, European Commission.
Kallis, G., 2011. In defence of degrowth. Ecol. Econ. 70 (5), 873–880. http://linkinghub.elsevier.com/retrieve/pii/S0921800910005021 (Accessed 30 May 2014).
Kerschner, C., 2010. Economic de-growth vs. steady-state economy. J. Clean. Prod. 18 (6), 544–551. 〈http://linkinghub.elsevier.com/retrieve/pii/S0959652609003473 (Accessed 29 June 2014).
Kesicki, F., Anandarajah, G., 2011. The role of energy-service demand reduction in global climate change mitigation: Combining energy modelling and decomposition analysis. Energy Policy 39 (11), 7224–7233. http://dx.doi.org/10.1016/j.enpol.2011.08.043.
Mazur, A., Rosa, E., 1974. Energy and life-style. Science 186 (4164), 607–610.
McDonald, A., Schrattenholzer, L., 2001. Learning rates for energy technologies. Energy Policy 29 (4), 255–261. http://linkinghub.elsevier.com/retrieve/pii/S0301421500001221 (Accessed 8 August 2017).
Meadows, D., 1997. Places to intervene in a system. Whole Earth, Winter(August) 78–84. https://www.bfi.org/sites/default/files/attachments/pages/PlacesInterveneSystem-Meadows.pdf (Accessed 8 August 2017).
Meadows, D.H., et al., 1972. The Limits to Growth, 1st ed. Universe Books, New York.
Mercure, J.-F., Salas, P., 2012. An assessment of global energy resource economic potentials. Energy 46 (1), 322–336. http://dx.doi.org/10.1016/j.energy.2012.08.018.
Meyer, A., 2000. Contraction & Convergence: the Global Solution to Climate Change. Green Books.
Moriarty, P., Honnery, D., 2016. Can renewable energy power the future? Energy Policy 93, 3–7. http://dx.doi.org/10.1016/j.enpol.2016.02.051.
Munro, P., van der Horst, G., Healy, S., 2017. Energy justice for all? Rethinking sustainable development Goal 7 through struggles over traditional energy practices in Sierra Leone. Energy Policy 105, 635–641. 〈http://ac.els-cdn.com/ S0301421517300472/1-s2.0-S0301421517300472-main.pdf?_tid=20f4af84-9aec-11e7-a6c4-00000aab0f01&acdnat=1505572643_ 053d359df4d2317b45d84dbd9cbf7562〉 (Accessed 16 September 2017).
Murphy, D.J., Hall, C.A.S., 2011. Energy return on investment, peak oil, and the end of economic growth. Ann. N. Y. Acad. Sci. 1219 (1), 52–72. http://dx.doi.org/10.1111/ j.1749-6632.2010.05940.x. (Accessed 20 April 2018).
Najam, A., Cleveland, C.J., 2003. Energy and sustainable development at global environmental summits: an evolving agenda. Environ. Dev. Sustain. 5 (1/2), 117–138. http://dx.doi.org/10.1023/A:1025388420042. (Accessed 8 August 2017).

Nashawi, I.S., Malallah, A., Al-Bisharah, M., 2010. Forecasting world crude oil production using multicyclic Hubbert model. Energy Fuels 24 (3), 1788–1800. http://dx.doi.org/ 10.1021/ef901240p.
Nations, U., 2007. Our Common Future, Chapter 7: Energy: Choices for Environment and Development, Available at: 〈http://www.un-documents.net/ocf-07.htm〉 (Accessed 31 August 2017).
O'Neill, D.W., 2012. Measuring progress in the degrowth transition to a steady state economy. Ecol. Econ. 84, 221–231. http://dx.doi.org/10.1016/j.ecolecon.2011.05. 020.
OECD/NEA & IAEA, 2014. Uranium 2014: Resources Production and Demand. Pachauri, R.K., et al., 2014. Climate Change 2014 Synthesis Report The Core Writing Team Core Writing Team Technical Support Unit for the Synthesis Report, IPCC. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf (Accessed 8 August 2017).
Pasternak, A.D., 2000. Global Energy Futures and Human Development: a Framework for Analysis. US Department of Energy, Oak Ridge.
Quéré, C.Le., et al., 2009. Trends in the sources and sinks of carbon dioxide. Nature Geoscience, Published online: 17 November 2009; | doi:10.1038/ngeo689, 2(12), p. 831. Available at: 〈http://www.nature.com/ngeo/journal/v2/n12/full/ngeo689. html〉 (Accessed 8 August 2017).
Rockström, J., et al., 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. 14 (2).
Rosa, E.A., 1997. Cross-national trends in fossil fuel consumption, societal well-being and carbon releases. Environ. Signif. Consum.: Res. Dir. 100–109.
Schaffernicht, M., 2010. Causal loop diagrams between structure and behaviour: a critical analysis of the relationship between polarity, behaviour and events. Syst. Res. Behav. Sci. 27 (6), 653–666. http://www.springerlink.com/index/10.1007/s11213-010- 9182-4%255Cnhttp://linkinghub.elsevier.com/retrieve/pii/ S1475158504000025%255Cnhttp://informahealthcare.com/doi/abs/10.1080/ 13561820802168125%255Cnhttp://www.springerlink.com/index/10.1007/ s11213-009-9140-1%255.
Schneider, F., Kallis, G., Martinez-Alier, J., 2010. Crisis or opportunity? Economic de- growth for social equity and ecological sustainability. Introduction to this special issue. J. Clean. Prod. 18 (6), 511–518. http://dx.doi.org/10.1016/j.jclepro.2010.01. 014.
Seppelt, R., et al., 2014. Synchronized peak-rate years of global resources use. Ecol. Soc. 19 (4).
Simmons, J., 2011. Materials critical to the energy industry., pp. 6–7. Available at: http://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/ESC_ Materials_handbook_BP_Apr2014.pdf (Accessed 30 July 2017).
Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thorne, J.P., Duffer, H., Senior, A., 2013. Critical Commodities for a High-tech World: Australia's Potential to Supply Global Demand. Geoscience Australia, Canberra.
Sorrell, S., Dimitropoulos, J., 2008. The rebound effect: Microeconomic definitions, limitations and extensions. Ecological Econ. 65 (3), 636–649. 〈http://www. sciencedirect.com/science/article/pii/S0921800907004405〉 (Accessed 10 November 2017).
Sovacool, B.K., et al., 2017. New frontiers and conceptual frameworks for energy justice. Energy Policy 105, 677–691. 〈http://linkinghub.elsevier.com/retrieve/pii/ S0301421517301441〉 (Accessed 16 September 2017).
Sovacool, B.K., Dworkin, M.H., 2014. Global energy justice: Problems, principles, and practices, Available at: 〈http://www.scopus.com/inward/record.url?Eid=2-s2.0-

84952879088&partnerID=40&md5=917fea6b4e118e162584e6e9773d9f89〉 (Accessed 8 August 2017).
Speirs, J., McGlade, C., Slade, R., 2015. Uncertainty in the availability of natural re- sources: fossil fuels, critical metals and biomass. Energy Policy 87, 654–664. 〈http://linkinghub.elsevier.com/retrieve/pii/S0301421515001044〉 (Accessed 8 August 2017).
Steffen, W., et al., 2005. Global Change and the Earth System. Springer, Berlin Heidelberg New York.
Steffen, W., et al., 2015. Article: planetary boundaries: guiding human development on a changing planet (pp.235–235).. J. Educ. Sustain. Dev. 9 (2). http://dx.doi.org/10.1177/0973408215600602a.
Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005. Ecol. Econ. 70 (2), 425–433. http://dx.doi.org/10.1016/j.ecolecon.2010.09.014.
Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World, Available at: 〈http://www.lavoisier.fr/notice/frJWOAR6SA23WLOO.html.
Tao, C.S., Jiang, J., Tao, M., 2011. Natural resource limitations to terawatt-scale solar cells. Sol. Energy Mater. Sol. Cells 95 (12), 3176–3180. http://dx.doi.org/10.1016/j.solmat.2011.06.013.
UNFCCC, 2010. The Contribution of the Clean Development Mechanism under the Kyoto Protocol to Technology Transfer 49. pp. 19–22.
United Nations General Assembly, 2015. Transforming our world: The 2030 agenda for sustainable development, Available at: 〈https://sustainabledevelopment.un.org/content/documents/21252030〉 Agenda for Sustainable Development web.pdf (Accessed 8 December 2017).
van der Zwaan, B., Gerlagh, R., 2006. Climate sensitivity uncertainty and the necessity to transform global energy supply. Energy 31 (14), 2235–2251.
Vera, I., Langlois, L., 2007. Energy indicators for sustainable development. Energy 32, 875–882. 〈http://linkinghub.elsevier.com/retrieve/pii/S0360544206002337.
Verbruggen, A., et al., 2010. Renewable energy costs, potentials, barriers: Conceptual issues. Energy Policy 38 (2), 850–861. http://www.sciencedirect.com/science/article/pii/S0301421509007836 (Accessed 8 December 2017).
Victor, P.A., 2012. Growth, degrowth and climate change: a scenario analysis. Ecol. Econ. 84, 206–212. http://dx.doi.org/10.1016/j.ecolecon.2011.04.013.
de Vries, B.J.M., van Vuuren, D.P., Hoogwijk, M.M., 2007. Renewable energy sources: their global potential for the first-half of the 21st century at a global level: an integrated approach. Energy Policy 35 (4), 2590–2610.
Walker, G., 2012. Environmental Justice: Concepts, Evidence and Politics. Routledge. World Energy Council, 2016. World Energy Perspectives. Energy Efficiency: A Straight Path Towards Energy Sustainability,. 〈https://www.worldenergy.org/wp-content/uploads/2016/10/EnergyEfficiencyAStraightPathFullReport.pdf.
WWF, 2014. Critical Materials for the transition to a Sustainable Energy Future, Gland, Switzerland.

Paper 6: Designing a Socially Sustainable Energy System Narrative Based on the Energy Justice Principles

Alexander, S., 2015. Sufficiency economy.
Alexander, S., Gleeson, B., 2019. Degrowth in the Suburbs, Degrowth in the Suburbs. Springer Singapore, Singapore. https://doi.org/10.1007/978-981-13-2131-3
Alfani, G.P., Tadei, F., 2017. Income Inequality in Colonial Africa: Building Social Tables for Pre-

Independence Central African Republic, Ivory Coast, and Senegal.
Arroyo Abad, L., Astorga Junquera, P., 2017. Latin American earnings inequality in the long run. Cliometrica 11, 349–374. https://doi.org/10.1007/s11698-016-0150-9
Best, R., Burke, P.J., 2017. The Importance of Government Effectiveness for Transitions toward Greater Electrification in Developing Countries. Energies 10, 1247. https://doi.org/10.3390/en10091247
Burke, M.J., Stephens, J.C., 2017. Energy democracy: Goals and policy instruments for sociotechnical transitions. Energy Res. Soc. Sci. 33, 35–48. https://doi.org/10.1016/J.ERSS.2017.09.024
Caldecott, B., 2017. Introduction to special issue: stranded assets and the environment. J. Sustain. Financ. Invest. 7, 1–13. https://doi.org/10.1080/20430795.2016.1266748
Dados, N., Connell, R., 2012. The Global South. Contexts 11, 12–13. https://doi.org/10.1177/1536504212436479
Darby, S., Fawcett, T., 2018. Energy sufficiency – an introduction: A concept paper for ECEEE. https://doi.org/10.13140/RG.2.2.31198.08006
Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255–264. https://doi.org/10.1016/J.ENPOL.2016.03.019
De Deker, K., 2018. How Much Energy Do We Need? Low Tech Mag.
EC–European Commission, 2016. Clean energy for all Europeans.
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
Hiteva, R., Sovacool, B., 2017. Harnessing social innovation for energy justice: A business model perspective. Energy Policy 107, 631–639. https://doi.org/10.1016/J.ENPOL.2017.03.056
Hornborg, A., 2012. Global Ecology and Unequal Exchange. Routledge. https://doi.org/10.4324/9780203806890
IEA, I.E.A., 2018. World Energy Outlook 2018, IEA Paris, World Energy Outlook. OECD. https://doi.org/10.1787/weo-2018-en
Ingleby, M., Randalls, S., 2019. Just Enough: An Introduction: The History, Culture and Politics of Sufficiency, in: Just Enough. Palgrave Macmillan UK, London, pp. 3–12. https://doi.org/10.1057/978-1-137-56210-4_1
International Energy Agency, I., 2017. WEO-2017 Special Report: Energy Access Outlook.
IPCC, 2014. Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016a. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/j.erss.2015.10.004
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016b. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/J.ERSS.2015.10.004
Jones, B.R., Sovacool, B.K., Sidortsov, R. V., 2015a. Making the ethical and philosophical case for “energy justice.” Environ. Ethics 37, 145–168. https://doi.org/10.5840/enviroethics201537215
Jones, B.R., Sovacool, B.K., Sidortsov, R. V., 2015b. Making the Ethical and Philosophical Case for “Energy Justice.” Environ. Ethics 37, 145–168. https://doi.org/10.5840/enviroethics201537215
JRC, 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. JRC Scientific & Policy Report, European Commission. https://doi.org/10.2790/46338
Kerschner, C., Wächter, P., Nierling, L., Ehlers, M.H., 2018. Degrowth and Technology: Towards feasible, viable, appropriate and convivial imaginaries. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.07.147

Koirala, B.P., Araghi, Y., Kroesen, M., Ghorbani, A., Hakvoort, R.A., Herder, P.M., 2018. Trust, awareness, and independence: Insights from a socio-psychological factor analysis of citizen knowledge and participation in community energy systems. Energy Res. Soc. Sci. 38, 33–40. https://doi.org/10.1016/J.ERSS.2018.01.009
Labanca, N. (Ed.), 2017. Complex Systems and Social Practices in Energy Transitions, Green Energy and Technology. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-33753-1
Maclurcan, D., Hinton, J., 2019. The Emerging Not-for-Profit World Economy.
McCauley, D., 2018. Energy Justice. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-62494-5
Mccauley, D., Heffron, R.J., Jenkins, S.K., n.d. Advancing energy justice : the triumvirate of tenets and systems thinking.
McDonald, D.A. (David A., 2009. Electric capitalism : recolonising Africa on the power grid. Earthscan.
McGee, J.A., Greiner, P.T., 2019. Renewable energy injustice: The socio-environmental implications of renewable energy consumption. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2019.05.024
Meadows, D., Sustainability Institute, 1999. Leverage Points: Places to Intervene in a System. World 1–12. https://doi.org/10.1080/02604020600912897
Moe, E., 2015. Renewable energy transformation or fossil fuel backlash : vested interests in political economy. Palgrave Macmillan.
Moezzi, M., Janda, K.B., Rotmann, S., 2017. Using stories, narratives, and storytelling in energy and climate change research. Energy Res. Soc. Sci. 31, 1–10. https://doi.org/10.1016/j.erss.2017.06.034
Monyei, C.G., Jenkins, K., Serestina, V., Adewumi, A.O., 2018. Examining energy sufficiency and energy mobility in the global south through the energy justice framework. Energy Policy 119, 68–76. https://doi.org/10.1016/J.ENPOL.2018.04.026
Moriarty, P., Honnery, D., 2016. Can renewable energy power the future? https://doi.org/10.1016/j.enpol.2016.02.051
Negro, S.O., Alkemade, F., Hekkert, M.P., 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renew. Sustain. Energy Rev. 16, 3836–3846. https://doi.org/10.1016/J.RSER.2012.03.043
Newell, P., Bumpus, A., 2012. The Global Political Ecology of the Clean Development Mechanism. Glob. Environ. Polit. 12, 49–67. https://doi.org/10.1162/GLEP_a_00139
Olson, C., Lenzmann, F., 2016. The social and economic consequences of the fossil fuel supply chain. MRS Energy Sustain. 3, E6. https://doi.org/10.1557/mre.2016.7
Parrique, T., Barth, J., Kerschner, C., Kraus-Polk, A., Kuokkanen, A., Spangenberg, J.H., 2019. Decoupling Debunked.
Rao, N.D., Baer, P., 2012. “Decent Living” emissions: A conceptual framework. Sustainability 4, 656–681. https://doi.org/10.3390/su4040656
Sovacool, B.K., Axsen, J., Sorrell, S., 2018. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2018.07.007
Sovacool, B.K., Burke, M., Baker, L., Kotikalapudi, C.K., Wlokas, H., 2017. New frontiers and conceptual frameworks for energy justice. Energy Policy 105, 677–691. https://doi.org/10.1016/j.enpol.2017.03.005
Sovacool, B.K., Ryan, S.E., Stern, P.C., Janda, K., Rochlin, G., Spreng, D., Pasqualetti, M.J., Wilhite, H., Lutzenhiser, L., 2015. Integrating social science in energy research. Energy Res. Soc. Sci. 6, 95–99. https://doi.org/10.1016/J.ERSS.2014.12.005
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. https://doi.org/10.3390/en12081584
Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. Ecol. Econ. 70, 425–433. https://doi.org/10.1016/J.ECOLECON.2010.09.014
Szulecki, K., 2018. Conceptualizing energy democracy. Env. Polit. 27, 21–41. https://doi.org/10.1080/09644016.2017.1387294
Thomas, S., Brischke, L.-A., Thema, J., Kopatz, M., 2015. Energy sufficiency policy : an evolution of energy efficiency policy or radically new approaches?
Todd, I., De Groot, J., Mose, T., McCauley, D., Heffron, R.J., 2019. Response to “Monyei, Jenkins, Serestina and Adewumi examining energy sufficiency and energy mobility in the global south through the energy justice framework.” Energy Policy 132, 44–46. https://doi.org/10.1016/J.ENPOL.2019.05.012
UNDP, 2015. Goal 7: Affordable and clean energy [WWW Document]. 2030 Agenda Sustain. Dev. URL http://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy.html (accessed 8.17.18).
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7
Unruh, G.C., Carrillo-Hermosilla, J., 2006. Globalizing carbon lock-in. Energy Policy 34, 1185–1197. https://doi.org/10.1016/J.ENPOL.2004.10.013
WWF, 2014. Critical Materials for the transition to a Sustainable Energy Future. Gland, Switzerland.
Xu, X., Goswami, S., Gulledge, J., Wullschleger, S.D., Thornton, P.E., 2016. Interdisciplinary research in climate and energy sciences. Wiley Interdiscip. Rev. Energy Environ. https://doi.org/10.1002/wene.180

Paper 7: A Case of Electricity Sufficiency for Sub-Saharan Africa: Combining System Dynamics Modelling with the Socially Sustainable Energy System Narrative

Ackoff, R.L., 1971. Towards a System of Systems Concepts. Manage. Sci. 17, 661–671. https://doi.org/10.1287/mnsc.17.11.661
Agency, I.E., 2016. World Energy Outlook.
Ansari, D., Holz, F., 2019. Anticipating global energy, climate and policy in 2055: Constructing qualitative and quantitative narratives. Energy Res. Soc. Sci. 58, 101250. https://doi.org/10.1016/J.ERSS.2019.101250
Bhatia, M., Angelou, N., 2015. Beyond Connections: Energy Access Redefined, The World Banlk.
Bruckner, T., Bashmakov, I.A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H.B., Riahi, K., Strachan, N., Wiser, R., Zhang, X., 2014. Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom and New York, NY, USA.
Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255–264. https://doi.org/10.1016/J.ENPOL.2016.03.019
Forrester, J.W., 1994. System dynamics, systems thinking, and soft OR. Syst. Dyn. Rev. 10, 245–256. https://doi.org/10.1002/sdr.4260100211
IEA, IRENA, UNSD, WB, W., 2019. Tracking SDG 7: The Energy Progress Report 2019. Washington DC.
International Energy Agency, 2019. World Energy Investment 2019.

International Energy Agency, 2017. WEO-2017 Special Report: Energy Access Outlook.
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: A conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/J.ERSS.2015.10.004
JRC, 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. JRC Scientific & Policy Report, European Commission. https://doi.org/10.2790/46338
Labanca, N. (Ed.), 2017. Complex Systems and Social Practices in Energy Transitions, Green Energy and Technology. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-33753-1
Lane, D.C., 2001. Rerum cognoscere causas: Part I ? How do the ideas of system dynamics relate to traditional social theories and the voluntarism/determinism debate? Syst. Dyn. Rev. 17, 97–118. https://doi.org/10.1002/sdr.209
Meadows, D., Sustainability Institute, 1999. Leverage Points: Places to Intervene in a System. World 1–12. https://doi.org/10.1080/02604020600912897
Olson, C., Lenzmann, F., 2016. The social and economic consequences of the fossil fuel supply chain. MRS Energy Sustain. 3, E6. https://doi.org/10.1557/mre.2016.7
Pruyt, E., Kwakkel, J., Yücel, G., Hamarat, C., 2011. Energy transitions towards sustainability: A staged exploration of complexity and deep uncertainty. The 29th International Conference of the System Dynamics SocietyThe 29th International Conference of the System Dynamics Society.
Pruyt, E., Pruyt, E., 2006. What is System Dynamics? A Paradigmatic Inquiry.
Rao, N.D., Baer, P., 2012. "Decent Living" emissions: A conceptual framework. Sustainability 4, 656–681. https://doi.org/10.3390/su4040656
Senge, P.M., 1997. The fifth discipline. Meas. Bus. Excell. https://doi.org/10.1108/eb025496
Sovacool, B.K., Ryan, S.E., Stern, P.C., Janda, K., Rochlin, G., Spreng, D., Pasqualetti, M.J., Wilhite, H., Lutzenhiser, L., 2015. Integrating social science in energy research. Energy Res. Soc. Sci. 6, 95–99. https://doi.org/10.1016/J.ERSS.2014.12.005
Spector, J.M., Christensen, D.L., Sioutine, A. V, McCormack, D., 2001. Models and simulations for learning in complex domains: using causal loop diagrams for assessment and evaluation. Comput. Human Behav. 17, 517–545. https://doi.org/10.1016/S0747-5632(01)00025-5
Spittler, Gladkykh, Diemer, Davidsdottir, 2019. Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development. Energies 12, 1584. https://doi.org/10.3390/en12081584
Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World, Management. https://doi.org/10.1057/palgrave.jors.2601336
UNDP, 2015. Goal 7: Affordable and clean energy [WWW Document]. 2030 Agenda Sustain. Dev. URL http://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy.html (accessed 8.17.18).
WWF, 2014. Critical Materials for the transition to a Sustainable Energy Future. Gland, Switzerland.

Paper 8: Policy Dialogue on Bioeconomy for Sustainable Development

Bugge, M.M., Hansen, T., Klitkou, A., 2016. What is the bioeconomy? A review of the literature. Sustain. 8, 691. https://doi.org/10.3390/su8070691
Haarich, S., Kirchmayr-Novak, S., Fontenl, A., Toptsidou, M., & Hans, S. (2014). Bioeconomy development in EU regions. Mapping of EU Member States' regions' Research and Innovation plans & Strategies for Smart Specialisation (RIS3) on Bioeconomy for, 2020. Available at: https://ec.europa.eu/research/bioeconomy/pdf/publications/bioeconomy_development_in_eu_regions.pdf

H.Hoff, F.X.Johnson, B.Allen, L. Biber-Freudenberger, J.J. Förster (2018): Sustainable bio-resource pathways towards a fossil-free world: the European bioeconomy in a global development context, Policy Paper produced for the IEEP Think2030 conference, Brussels, October 2018. Available at: https://ieep.eu/uploads/articles/attachments/8b23e752-50e6-4c7c-a7e3-71a8bfa0a806/Think%202030%20Bioeconomy.pdf?v=63710015964

Förare, J. Swedish Research and Innovation Strategy for a Bio-based Economy, 2012. Available at: https://www.formas.se/download/18.462d60ec167c69393b91e60f/1549956092919/Strategy_Biobased_Ekonomy_hela.pdf

OECD, 2009. The bioeconomy to 2030: designing a policy agenda, Organisation for Economic Co-operation and Development. OECD. https://doi.org/10.1787/9789264056886-en

Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World, Management. https://doi.org/10.1057/palgrave.jors.2601336

SEI Stockholm Environment Institute

Annex 1. Paper 8 (draft): Policy Dialogue on Bioeconomy for Sustainable Development

Ganna Gladkykh[2], Francis X. Johnson[1]

[1] Stockholm Environment Institute

[2] Department of Economics, University of Clermont Auvergne

1. Introduction

This paper is based on the results of a workshop conducted in Bangkok, Thailand as a part of the project called the ‘Policy Dialogue on Bioeconomy for Sustainable Development’. The project explores the policies contributing to a more inclusive and sustainable bioeconomy. The overall goal of the project is to get better understanding of how bioeconomy is envisioned in different countries and regions of the world and what are the possible ways of achieving its goals.

2. Methodology part

2.1. Methodology of conducting participatory dialogues

The Policy Dialogues on Bioeconomy are designed in a participatory manner. There was a pre-selected group of participants with diverse backgrounds who have an expertise in the domains/sectors relevant to the bioeconomy development in Thailand and the SEA region. All participants were divided into three groups. The criteria of assigning the participants into the different groups were based on the similarity of their topical backgrounds. Thus, in the Group 1, the majority of the group participants had an expertise in agriculture. In the Group 2, there were participants specializing on the social, developmental aspects and big picture policy planning. Group 3 had a strong biotechnological expertise. In this way, even though none of the groups was homogenous background-wise and diverse opinions and expertise were present in each of them, it was expected that topical division would be present in the resulting bioeconomy visions produced by different groups.

The working process itself implied that the participants meet together for the 3,5 hrs workshop where they, with the help of facilitators, collectively construct the pathways for reaching the 2050 bioeconomy vision in SEA region in a backward manner. This means that policy actions to take and the objectives to reach were designed by moving from the future to the present time, going step by step from year 2050 to 2019. The main expectation related to the use of this methodology is that the participants, by moving from the future to today, would be more open to the ambitious and more imaginative ideas of the bioeconomy future could be like, instead of being constraint by the already established state of things.

Workshop participants were expected to build a step-by-step action plan achieving the desired bioeconomy vision, starting from the point in time in the future and moving backwards to the present day. The working process evolved around the main driving question which was: *How do we shift to a sustainable bioeconomy in SEA by 2050?*

Additionally to the main driving question, all the participans were guided by the supporting sub-questions to help designing more elaborated bioeconomy visions and action plans. Those questions were as follows:

(1) How is value created and realised in the bioeconomy? (2) Who are the key stakeholders and decision-makers? (3) What are the key feasible pathways for bioeconomy development? (4) Which instruments, regulations and policies are needed at different levels, and how are governance processes linked across the levels?

The workshop process itself included several divergent and convergent stages of knowledge generation and sharing between the group participants.

2.2. Methodology of analyzing the results of participatory dialogues

For processing of the workshop results, systems thinking approach and causal loop diagrams (CLDs) were used as conceptual system thinking tool (Sterman, 2000). The bioeconomy pathways that were designed during the workshop were in the form of sequential actions to be taken from 2019 until 2050. In contrast, a causal map portrays the same actions in their interconnectedness. An added value that causal analysis was supposed to bring is to reveal an underlying dynamics between the actions and thus giving interesting policy insights for designing bioeconomy implementation pans in Thailand and SEA.

For building the causal map, all the actions designed by the participants of each group during the bioeconomy pathways building brought in the same picture (one causal map per each group). All the connections mapped are based on the participants' discussions during the workshop. CLD is one of the main qualitative tools used in system dynamics modelling (Sterman, 2000). CLDs include the variables/parameters and the connections between them which are portrayed in the map in the form of the arrows. These connections can be either positive (a change of the variable A leads to a change of the variable B in the same direction) or negative (a change of the variable A leads to a change of the variable B in the opposite direction). CLDs, in general, can be used as both communication and analytical tool. As a communication tool, they are usually used as an aid for creating a comprehensive and user-friendly picture of the problem/system. As an analytical tool, they are used for better understanding of the underlying dynamics and feedbacks created between a system's components. For constructing the CLDs, the results of the participatory workshop and the actions designed by the participants were transformed into the CLDs' parameters in line with the system dynamics methodological requirements.

As a result of the causal analysis, it was expected to have not only a better understanding of not only the interconnections between the key actions to be taken in order to reach sustainable bioeconomy, but also in order to define the missing components in the designed bioeconomy visions. Additionally, causal mapping was intended to bring more clarity regarding the thematic clusters embedded into those visions and into the connections between them.

3. Bioeconomy visions: theoretical background

There are many already existing formalized bioeconomy visions each of which differ in specific goals to achieve as well as in policy nuances for achieving them. The descriptions of such bioeconomy visions can be found in the research literature as well as in policy documents (OECD, 2009; Forare, 2012; Haarich et al., 2014). There are, however, three most common bioeconomy visions that are currently often cited as the reference ones and stem from the categorization developed by (Bugge et al., 2016). In his paper, Bugge distinguishes between the three main bioeconomy visions:

(1) *A biotechnology vision* oriented at biotechnological development and a biotechnology commercialization.
(2) *A bioresource vision* centered around new ways of using and creating value from the biological raw materials across different economic sectors.
(3) *A bioecology vision* prioritizing environmental sustainability and importance of ecological processes within economic and technological development.

For the purposes of this report, there are in total seven bioeconomy visions taken from the available literature. Three of those given above (Bugge et al., 2016) and another four originate from the SEI report (Hoff et al., 2018). These seven visions are brought together in order to have more clarity on what is included in each of them, to compare them with each other and then to use them as the reference visions for analyzing the results from the policy dialogues workshops that were going to happen in 5 different countries.

The full list of the bioeconomy visions analyzed in this report is as follows:

(1) Biotechnology vision
(2) Biotechnology and innovation vision
(3) International cooperation and development vision
(4) Bioresource vision
(5) Bioresources (substitution) vision
(6) Agricultural innovation and rural development vision
(7) Bio-ecology vision

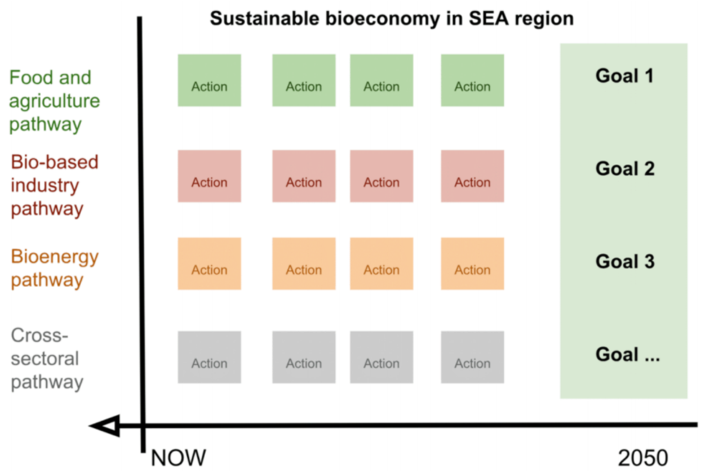
The comparative of these bioeconomy visions can be found further in the text, in the section <…>

4. Results and discussion

4.1. Bioeconomy sectors

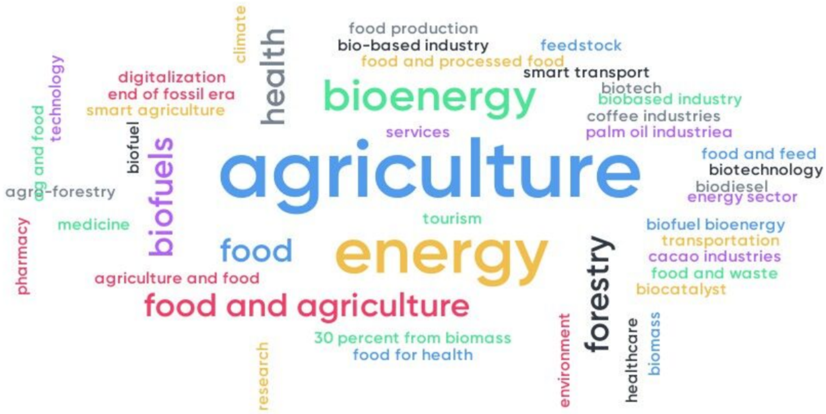
There is no universal understanding of the sectoral division of the bioeconomy. Commonly, agriculture and forestry are included in a bioeconomy as the key sector and as the primary suppliers of biomass. However, the bioeconomy sectoral division is always very contextual. For Thailand, there were several bioeconomy sectors and associated with them pathways that were identified before the workshop and given to the participants as the starting point. Those sectoral pathways were: (1) Food and agriculture pathway; (2) Bio-based industry pathway; (3) Bioenergy pathway; (4) Cross-sectoral pathway.

The template of the sectoral vision that the participants were given:



At the initial stage of the workshop, it was important to understand what were the participants' ideas of a sectorial division of bioeconomy in SEA region. By using Mentimeter (https://www.menti.com/), all the participants named the three most important, in their opinion, sectors of bioeconomy in SEI. The question was formulated as: *What would be the main sectors driving bioeconomy development in the SEA region in 2050?* The results of the Mentimeter exercise can be seen in the cloud below (fig. 1). It is evident that agriculture and energy sectors were most frequently mentioned by the participants. One of the additional objectives of the Mentimeter exercise was comparing its results with the bioeconomy sectors that were suggested to the participants as a starting point was for building the sustainable bioeconomy pathways until 2050.

Overall, the resulting were similar and there were no unexpected outcomes that came up in the bioeconomy sectors' cloud.



4.2. Bioeconomy pathways design

There were 3 groups of the workshop participants, who designed the sustainable bioeconomy pathways for ASEAN until 2050, as was mentioned in the previous section. The groups were composed according to the background of the participants. The majority of the participants in the Group 1 had a background in agriculture. Group 2 included the participants who have experience in working with the social aspects of the bioeconomy development. Most of the participants in Group 3 had an expertise in biotechnologies. By dividing the participants in this way, it was expected to have a diversity of the bioeconomy pathways at the end of the workshop. As it will be seen from the following discussion, the resulting sustainable bioeconomy pathways designed by the different groups indeed revealed that those sectors where the participants had more expertise were elaborated in more detail. At the same time, there were a lot of similarities between the key components bioeconomy pathways among the three groups, especially in the cross-sectoral part.

The resulting pictures of the sustainable bioeconomy pathways in ASEAN by 2050 looks as follows:

Group 1

List of the actions in the timeline:

2030

- Securing funding
- Goal setting and stakeholder identification
- Building platforms for stakeholders
- Raising awareness/capacity building
- Establishing Sub-national implementation plan
- Increasing crop production
- Ensuring efficient use of land and water
- Improving waste management

2050

- Transition to fossil-free energy

- Making certifications/standards affordable
- Taking regional rather than just national approach

2050 Goals

- Food Security
- Fossil-free energy
- Poverty reduction
- GHG reduction

Group 2

List of the actions in the timeline:

2020

- International initiation of a bioeconomy transition (similar to the SDGs)

2030

- A more interactive platform
- Science and research needs to continue and improve
- Decentralised electricity energy systems by 2030-2040 in SEA
- Transport and Logistics coming later (after energy transitions
- Identify the key champions of change and progress in the region
- Connecting farmers to consumers

2050

- Zero net waste from consumption and production

Group 3

List of the actions in the timeline:

Developing vision

- Development of sustained political will at country and regional level
- Development of inclusive policy environment for individua and SME and MAI (Market for Alternative Investment)

Communication

- Effective communication of vision
- Communication platform
- Build knowledge and awareness. Provide education.
- Recognition by public

Implementation

- Regulatory standard approach
- Economic growth based on society and environment
- Synergy bioeconomy to existing policy (R&D policy Framework, new s-curve)
- Policy dialogue (ASEAN/inter-regions)
- Drafting country policy according to local niche
- Cooperation with the same goals in policy level

Infrastructure

- Find partners from developed countries
- Encourage to do Public-Private Partnership (S-M-L enterprises + start-ups)
- R&D exchange
- Tech transfer to farmers for capability building and income distribution
- Agricultural technology and innovation Institute
- Pilot projects

Business Investment

- Sustainable production and higher productivity

- Public-Private Partnership mechanism
- Become competitive
- Entrepreneur support scheme
- Market mechanism
- Supply chain planned together
- Shared raw material/technology
- Accelerate bio-based product market
- Add value to agricultural feedstock and increase productivity

R&D

- Research consortium

Consumer behaviour

- Consumers' perspective
- Sustainable diets (food loss and waste)

As part of the pathways development process, each group identified and voted for the most important actions/factors of the sustainable bioeconomy pathways design. The results of this voting is the selection of the key variables is given in the following section where they are compared with the key variables derived from the causal mapping.

4.3. Causal analysis of the pathways

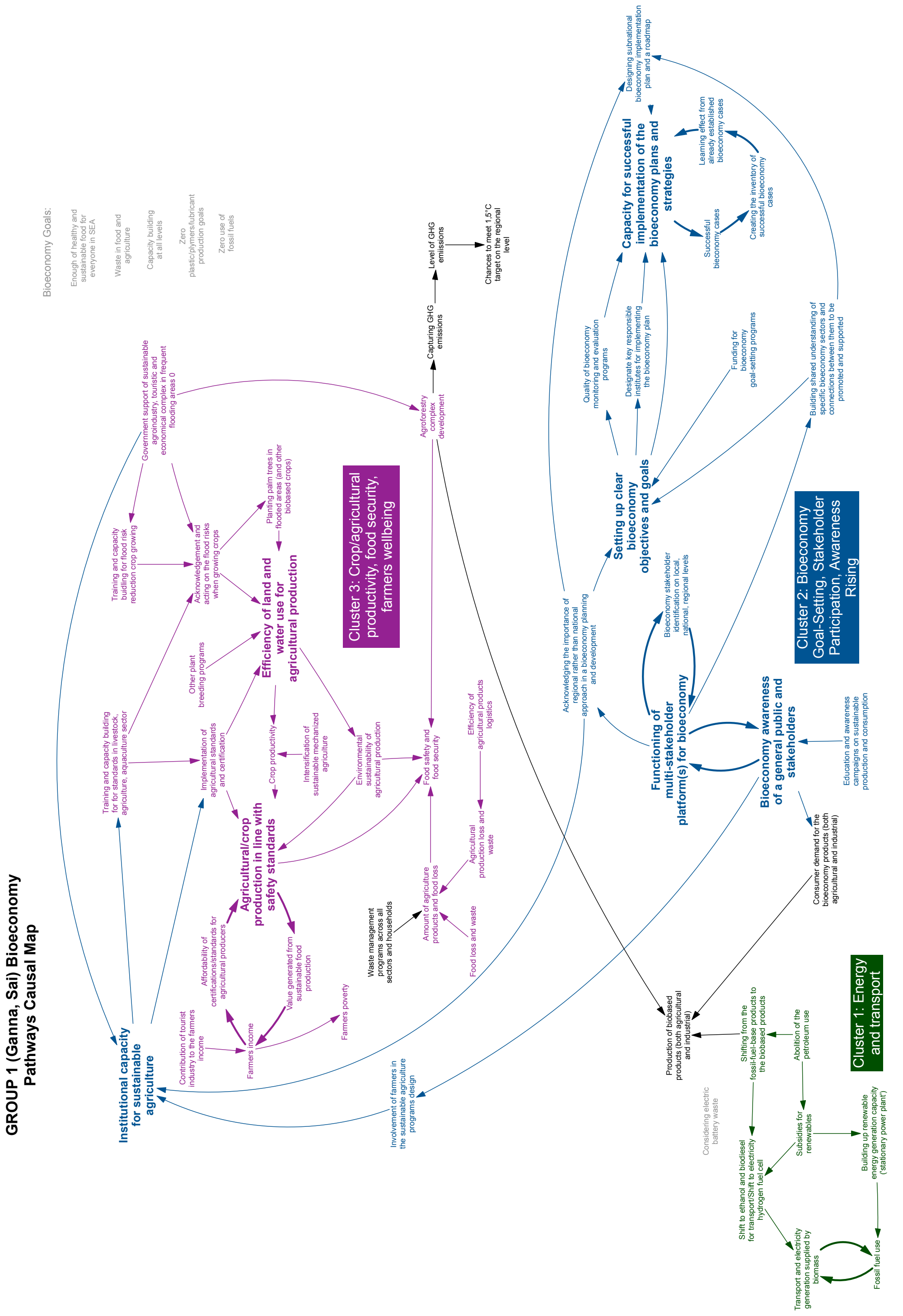
In this part, the causal maps based on the work of each of the three groups are presented and discussed. It is important to note that these causal maps should not be seen as exhaustive pictures of the developed bioeconomy visions. Instead, they are supposed to play the role of a supporting visual, communication and analytical tool to be used for identification of the missing or controversial actions and for building the connections between them. These CLDs would then help fostering further discussion between the workshop participants or any other interested actors.

How to read CLDs?

All the parameters in color are those that were brought by the participants as parts of the designed action plans. The variables in black are the ones added during the causal analysis and were not part of the action plan, but were brought by the participants during the discussion part. The connections between the variables that do not have any signs are the positive ones (the variables change in the same direction). The connections between the variable that change in the different directions are indicated with the minus sign.

4.3.1. Group 1

Below there is full causal map with the results of the work of Group 1. The most important fragments of this CLD as well as thematic clusters and the key variables are discussed below in more detail.



During the causal analysis, several groups of the thematic groups of factors (hereafter called clusters) were revealed. Color indication helps visually separate one cluster from another. As it was already mentioned above, clustering of the actions was one of the process during the pathway building process.

In the table below, there is a comparison between the clusters and key actions related to each of them that were revealed during the initial pathways building stage and during the causal mapping.

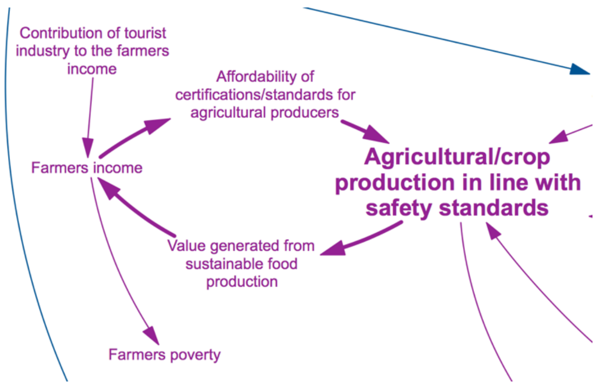
Overall, the clusters in the CLD correspond to the clusters defined by the participants during the pathways building. As for the key variables/actions, by causally connecting the actions designed by the participants, in the CLD, several key actions extra to those that were originally identified by the participants, were added.

Clusters and key variables/actions from the causal map	*Clusters and key variables/actions from originally developed pathways*
1: Energy and transport	**1: Energy**
2: Bioeconomy goal-setting, stakeholder participation and awareness raising 1. Functioning of multi-stakeholder platform(s) for bioeconomy. 2. Bioeconomy awareness of a general public and stakeholders. 3. Setting up clear bioeconomy objectives and goals. 4. Capacity for successful implementation of the bioeconomy plans and strategies.	**2: Cross-sectoral pathways, stakeholder cooperation, goal-setting** 1. Securing funding 2. Goal-setting and stakeholder identification on local, national, regional levels 3. Awareness raising
3: Crop/agricultural productivity, food security and farmers wellbeing 1. Agricultural/crop production in line with the safety standards. 2. Efficiency of land and water use for agricultural production.	**3: Agriculture**

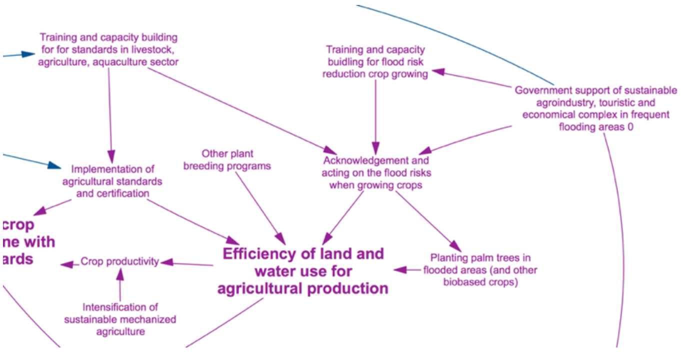
Causal analysis of the sustainable bioeconomy pathways designed by Group 1 revealed some dynamics and driving mechanisms that can help achieving sustainable bioeconomy state.

Below, there are zoom-ins of the key feedback loops related to the specific bioeconomy clusters that were revealed in the causal map.

Group 1: Zooming-in Crop/agricultural productivity, food security and farmers wellbeing cluster



According to the causal interpretation of the Group 1 bioeconomy vision, an increase of agricultural/crop production in line with the safety standards is one of the main factors which indicates achieving bioeconomy goals. An increase of agricultural and crop production leads to a higher value generation from this production, as well as to the increase of farmers income and corresponding affordability of certification and standards for agricultural producers which then leads to the increase of agricultural production. In a long run, these dynamics lead to a sustained increase of farmers income and reduction of farmers poverty, as well as to a continuous increase of a sustainable and safe agriculture and crop production. Accordingly, the actions to take for reaching the objectives of sustainable bioeconomy by 2050 can be thought through by asking the question of how to activate this feedback loop.



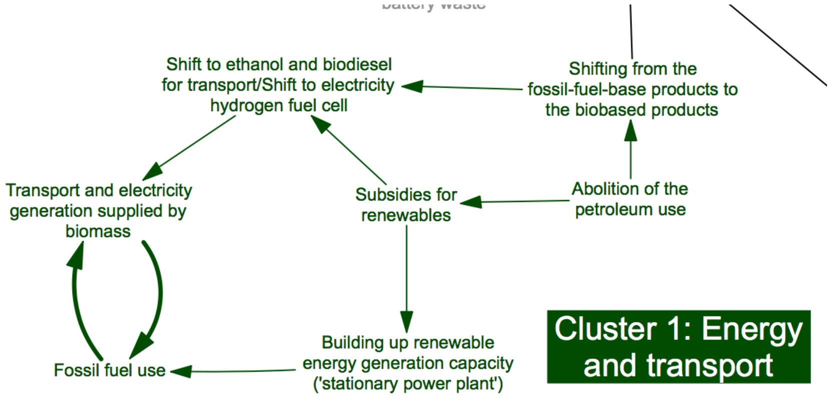
Some of the required policies and corresponding actions to take have been discussed by the participants during the workshop, but there are many more aspects to be discussed. For example, specifically for this cluster the follow-up questions can be as follows:

1. What is the mechanism of a tourist industry contribution to farmers income? What are the mechanisms and the corresponding actions for ensuring a fair income distribution created in the agriculture and crop production and for making sure that the farmers are the main beneficiaries of the created value?
2. Howe to make certifications and standards for agricultural producers more affordable for farmers?
3. What drives the intensification of sustainable mechanized agriculture?
4. What are the expected benefits and preferable mechanisms of farmers involvement in the agroforestry?
5. In what way can the farmers be involved in sustainable agriculture programs design within the general bioeconomy initiatives?
6. What type of technologies can be classified as knowledge-based bioeconomy when it comes to agricultural activities? E.g. can agricultural mechanization and the use of traditional knowledge on choosing right crops to plant be equally qualified as such?

During the discussion on the development of the agricultural part of a bioeconomy, a strong emphasis on environmental sustainability has been made. Efficiency of land and water use during agricultural production is revealed on the CLD as the key parameter for a sustainable agriculture. Acknowledging and acting on the flood risks while growing crops as well as implementation of agricultural standards and certification were discussed as some of the factors that can increase efficiency of land and water use. There is a room for having a more elaborated discussion in this part. For example, the following questions can be thought through:

1. What are the instruments of the government support in this area?
2. What are the possible bottom-up actions to foster environmental sustainability of agricultural practices?
3. What are the factors hindering efficiency of land and water use for agricultural production? How can they be addressed?

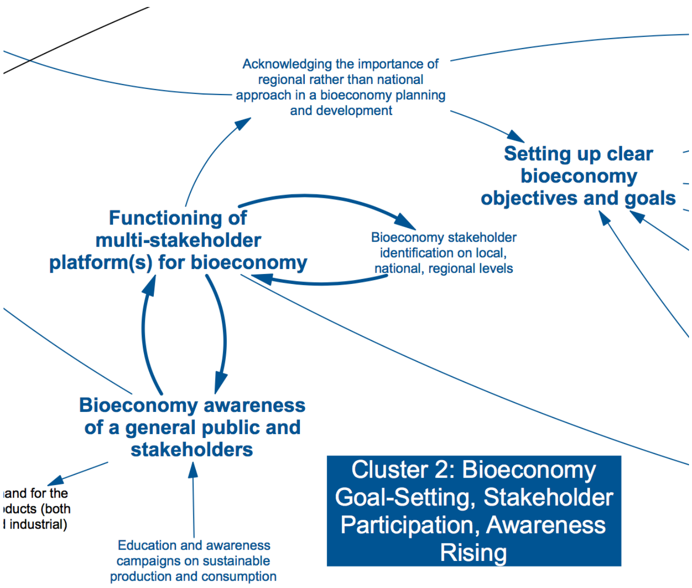
Group 2: Zooming-in Energy and transport cluster



A shift to renewable energy and transport was discussed as one of the most important parts of transitioning towards a sustainable bioeconomy. Subsidies for renewables and top-down measures for the abolishing of the fossil fuel use were discussed as the measures to support transition towards renewable energy and transport. However, specific details on what is the expected dynamics of the transition to the renewables are to be discussed. In this part, the questions to help can be as follows:

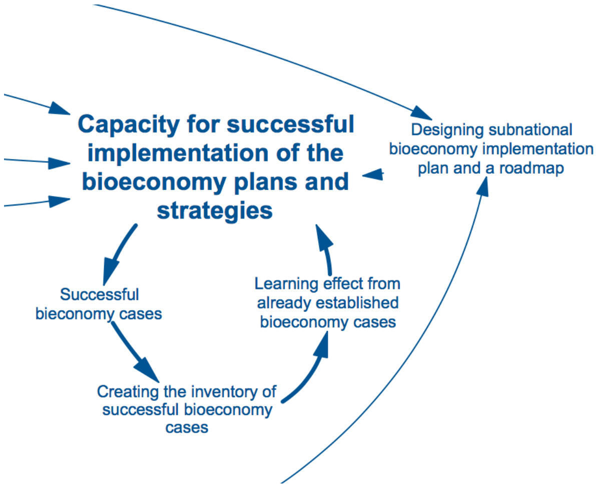
1. What is a desired mechanism for introducing subsidies for renewables? How will that influence the existing cost and price structure in the energy system?
2. What is the current situation with subsidizing energy system? Are there any subsidies on the national level available for fossil fuels? If yes, what are the mechanisms of dealing with them?
3. What is the a desired investment structure for supporting renewable energy and transport projects? What local/national/regional actors are the main providers and the main beneficiaries of this investment?
4.

Group 3: Zooming-in Bioeconomy goal-setting, stakeholder participation and awareness rising cluster



There are two main feedback mechanisms in this part that were revealed in the CLD. Functioning of multi-stakeholder platforms for bioeconomy is driven by the rise of bioeconomy awareness of general public and stakeholders. At the same time, those platforms lead to even more bioeconomy awareness among different actors. Setting-up clear bioeconomy goals, which is of the key factors in this cluster, is directly caused by effectively functioning multi-stakeholder bioeconomy platforms. In this part, a more detailed discussion on what are the instruments for bioeconomy awareness rising among the different groups of stakeholders, and what are the principles of the platforms functioning, may be helpful.

Another revealed underlying feedback mechanism for activating the capacity for successful implementation of the bioeconomy plans and



strategies is connected to the learning effect from the already realized successful bioeconomy cases on the local, national, regional scales. The more successful bioeconomy cases are realized and the better they are communicated, the higher chances for realizing other successful bioeconomy cases. In this part, there can be a more elaborated discussion on what is exactly meant by creating the inventory of successful cases, how such an inventory can be institutionalized, and who are the key actors that should be responsible for it.

Additional questions that can help designing more elaborated and detailed sustainable bioeconomy pathways based on the discussion of the Group 1 may evolve around the following questions:

1. What is a conceptual difference between food safety and food security? How relevant is the distinction between the two concepts for the bioeconomy development?
2. What are the general principles of the agroforestry organization in Thailand? How is it supposed to change existing agricultural practices and activities? How is agroforestry connected to food security and food safety? How is it related to the farmers wellbeing?

Summary of the sustainable bioeconomy narrative of the Group 1

Key words: <…>

Agriculture and energy are the most substantial parts of the bioeconomy. Zero use of fossil fuels and 100% access to a healthy and sustainable food are the main goals of the bioeconomy development in ASEAN are the key objectives of a sustainable bioeconomy development. Crop production, which accounts for the sustainable and efficient use of land and water, and minimum possible waste creation is a fundamental part of the agricultural part of a bioeconomy. Combination of mechanization and traditional crop-breeding practices that take into account regional climate and weather specificities are the key knowledge-based components of the agricultural part of a sustainable bioeconomy development in the region. Farmers are the key beneficiaries of the value created in the agricultural sector. Farmers income increase and connected to it farmers poverty reduction are the main indicators for accessing success of a bioeconomy.

Bioeconomy development is based on the interdisciplinary and intersectoral approach. In this way, systemic synergies created in a bioeconomy across different sectors. Transformation of the energy and transport sectors should be based on the mix of biofuels, renewable electricity sources and hydrogen. Shift to these sources is especially important for reaching the GHG emissions and 2 degrees targets. Strong participatory component with the stakeholder involvement on the local, national, regional levels, combined with the top-down decision-making is the core mechanism that drives a clear goal-setting in a bioeconomy as well as ensures implementing all the defined goals.

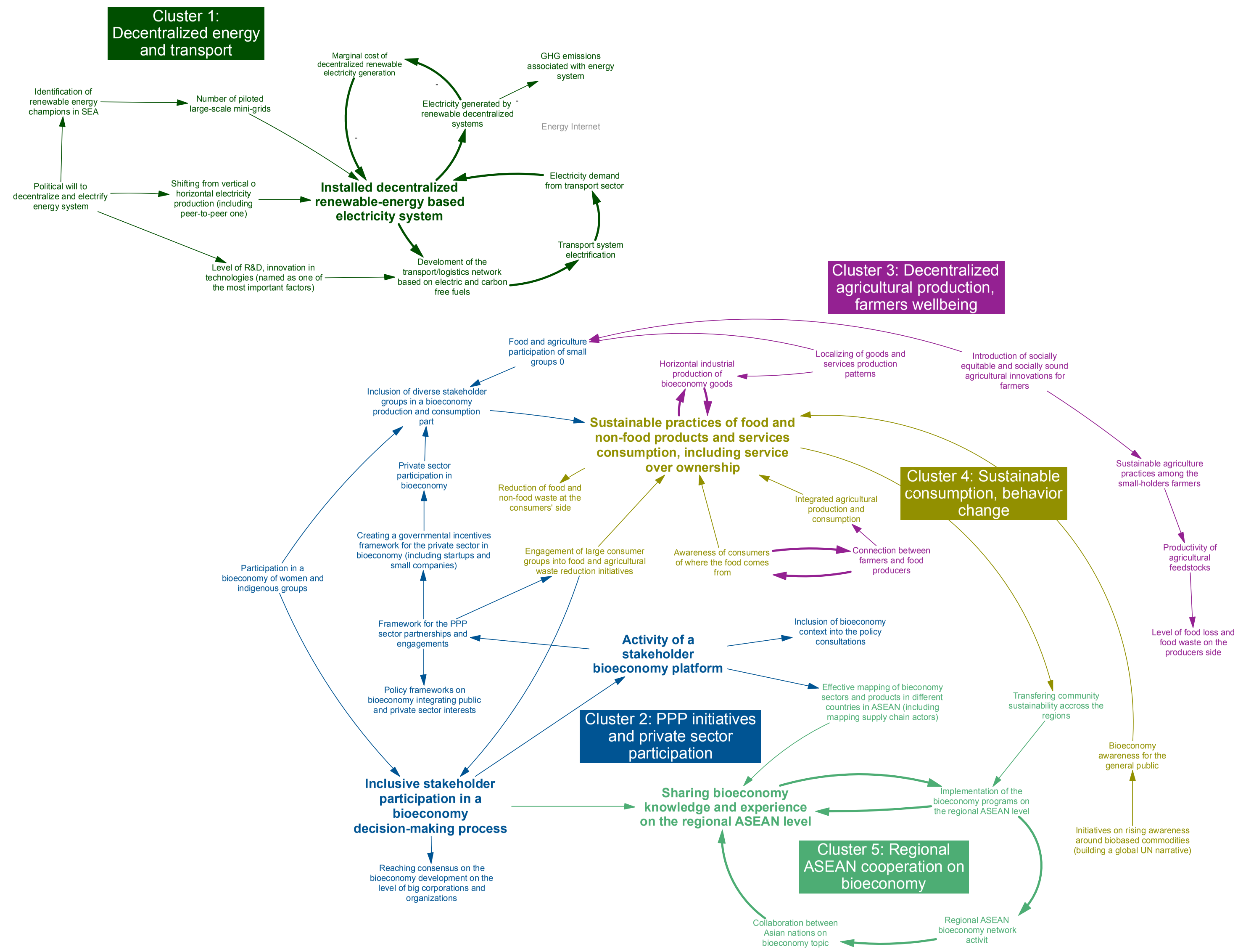
4.3.2. Group 2

For the Group 2, causal mapping revealed several clusters and corresponding key variables/actions that were not identified by the participants during the pathways building process. This is an interesting output of causal mapping that can bring insights for the further development of the bioeconomy action plan by the participants.

Similar to the previous sub-section, where the results of the Group 1 were discussed, in this part, there are several zooming-ins of the key dynamics and feedbacks that were revealed during the causal analysis of the actions designed by Group 2 with the sustainable bioeconomy pathways.

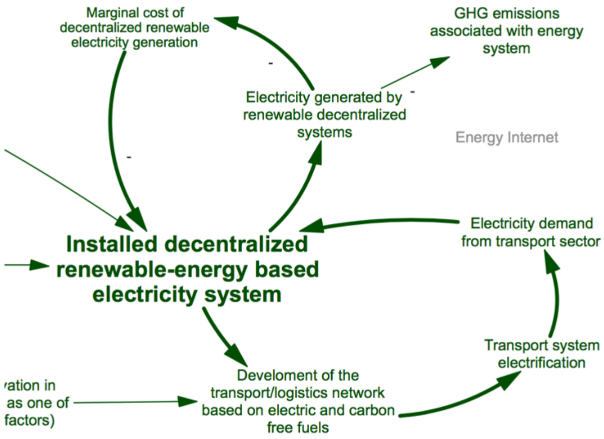
Clusters and key variables/actions from a causal map	Clusters and key variables/actions from originally developed pathways
1: Decentralized energy and transport 1. Installed decentralized renewable-energy-based electricity system.	**1: Energy** 1. Decentralized renewable energy systems
2: PPP initiatives and private sector participation 1. Activity of a stakeholder bioeconomy platform. 2. Inclusive stakeholder participation in a bioeconomy decision-making process.	**2: Cross-sectoral pathways** 1. Establishing a platform for discussion and participation. 2. Mapping of particular sectors/products/innovations
3: Decentralized agricultural production, farmers wellbeing	**3: Agriculture and food industries**
4: Sustainable consumption, behavior change 1. Sustainable practices of food and non-food products and services consumption, including service over ownership.	
5: Regional ASEAN cooperation on bioeconomy 1. Sharing bioeconomy knowledge and experience on the regional ASEAN level	

GROUP 2 (May, Anne) Bioeconomy Pathways Causal Map



SEI Stockholm Environment Institute

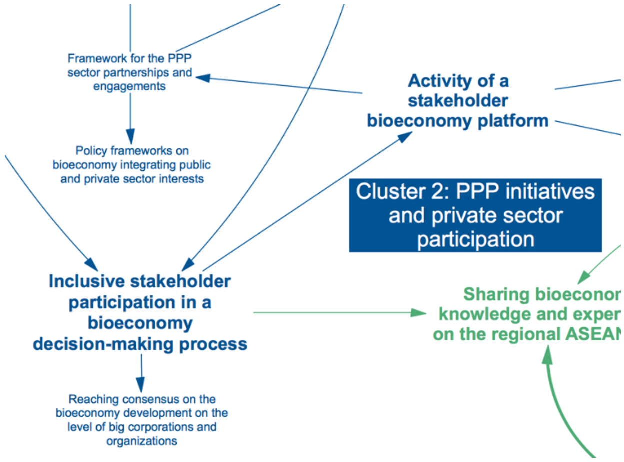
Group 2: Zooming-in Decentralized energy and transport cluster



According to the Group 2 participants, transformation of the existing energy system in Thailand should be based in installing a decentralized and renewables-based energy system, which is one of the crucial components of the functioning sustainable bioeconomy. It is expected that an increase of the renewable electricity production and the economy of scale effect will lead to the price drop for the renewable energy generation and, consequently, even more installation of renewable energy capacities and renewable energy generation. At the same time, there a desired increase of the electric transport use and expanding of the electric transport infrastructure. This would mean less use of the fossil-fuels but simultaneously create extra demand for the renewable electricity. There is definitely a room for an expanded discussion on the energy system sector within the sustainable bioeconomy visions and the potential questions that be a guidance for having such discussion are as follows:

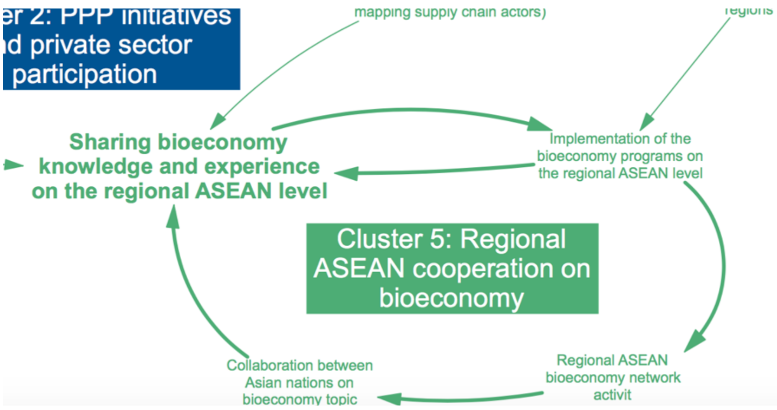
1. What could be an investment structure behind the decentralized renewable energy projects?
2. How can the cost of renewable energy generation change with the increase of the installed renewable energy capacity in a short and in a long run?
3. What is an expected renewable energy mix for Thailand? Are there any expected resource conflicts with the other sector of the economy? E.g. with the agriculture?
4. What is the expected balance between the renewable energy electricity and renewable fuels in the sustainable bioeconomy in Thailand by 2050?
5. What are the factors that can influence political will for building decentralized renewable energy system in Thailand?
6. How does the vision of a decentralized renewable energy system with the sustainable bioeconomy match with already existing energy policy plans both on the national (Thailand) and regional (ASEAN) level, some of which explicitly include the increase of investment in fossil fuel capacity installation?

Group 2: Zooming-in PPP initiative and private sector participation cluster



Similarly to the clusters of the required bioeconomy actions related to the Group 1, Group 2 emphasized the importance of a stakeholder involvement into the bioeconomy planning and decision-making process, highlighting the need for creation of inclusive bioeconomy stakeholder platforms. PPP instrument is seen by this group as one of the most effective instruments for establishing collaboration between private and public sectors for implementing bioeconomy plans. Some of the questions that can be discussed further in this part are related to better understanding of the mechanisms behind the stakeholder platform creation and behind the decision-making process associated with those platforms.

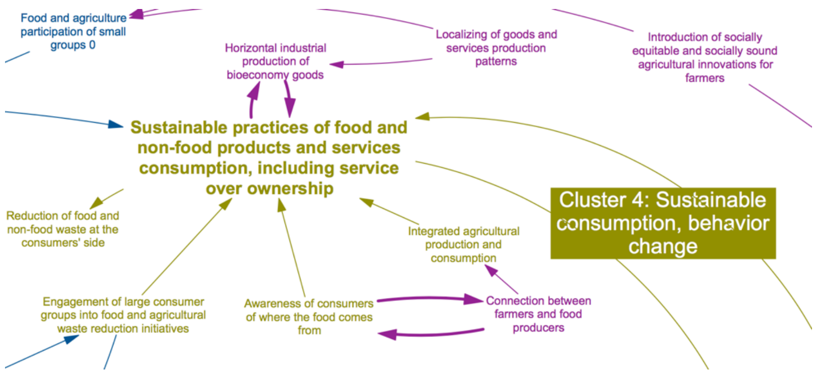
Group 2: Zooming-in Regional ASEAN cooperation on bioeconomy cluster



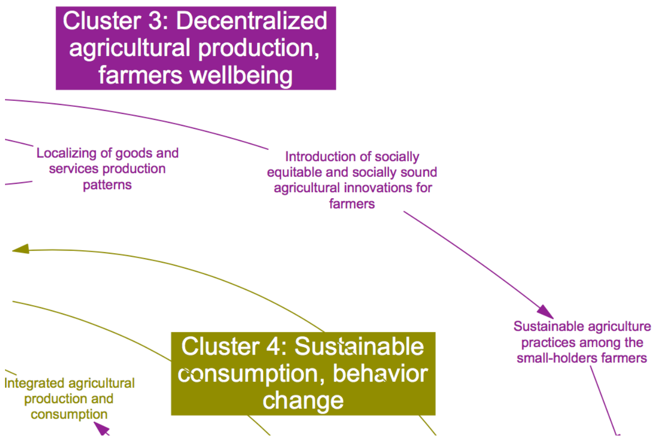
ASEAN cooperation on bioeconomy development has been revealed as a thematic bioeconomy cluster during the causal analysis, even though. However, originally, during the bioeconomy pathways development, it was not distinguished by the group members as a separate cluster. Sharing bioeconomy knowledge and experience on the regional ASEAN level is a key factor/action to put forward for reaching bioeconomy regional cooperation goals. Supported by the encouraged collaboration and networking between different ASEAN countries on implementing bioeconomy programs, knowledge and experience sharing is supposed to create a reinforcing dynamics for advancing regional collaboration on bioeconomy topic. In this part, a detailed action plan on bioeconomy development could benefit from discussing the following:

1. What are the key actors that are going to be involved in establishing a regional ASEAN bioeconomy cooperation?
2. What is the role and the possible formats of the top-down and the bottom-up initiatives in establishing and supporting such a cooperation?
3. What are the potential challenges and obstacles for achieving shared bioeconomy visions between different countries in ASEAN? How can those be overcome?
4. What is the existing political and economic power dynamics between different ASEAN nations that can influence the type of bioeconomy cooperation on the regional level?

Group 2: Zooming-in Sustainable consumption and Agricultural production clusters



Connection between supply and demand parts of the bioeconomy production, especially when it comes to the agricultural bioproduction is another key driver of a bioeconomy development regonized by the Group 2 participants. There is a number of factors impacting sustainable practices of food and non-food products and services consumption, including awareness rising initiatives, engagement of consumers in the waste reduction initiatives and in the formats of the integrated agricultural production and consumption. The mechanisms of activating these factors as well as adding additional factors that may impact sustainable practices of food and non-food consumption are to be further discussed in the context of developing a more elaborated bioeconomy action plan.



Decentralization of agricultural production and connection it to the farmers wellbeing was discussed as an important priority but not many details were brought there. Particularly, achieving social sustainability for farmers was agreed to be one of the main objectives for bioeconomy to be considered fully sustainable. With this regard, it would be logical to discuss further:

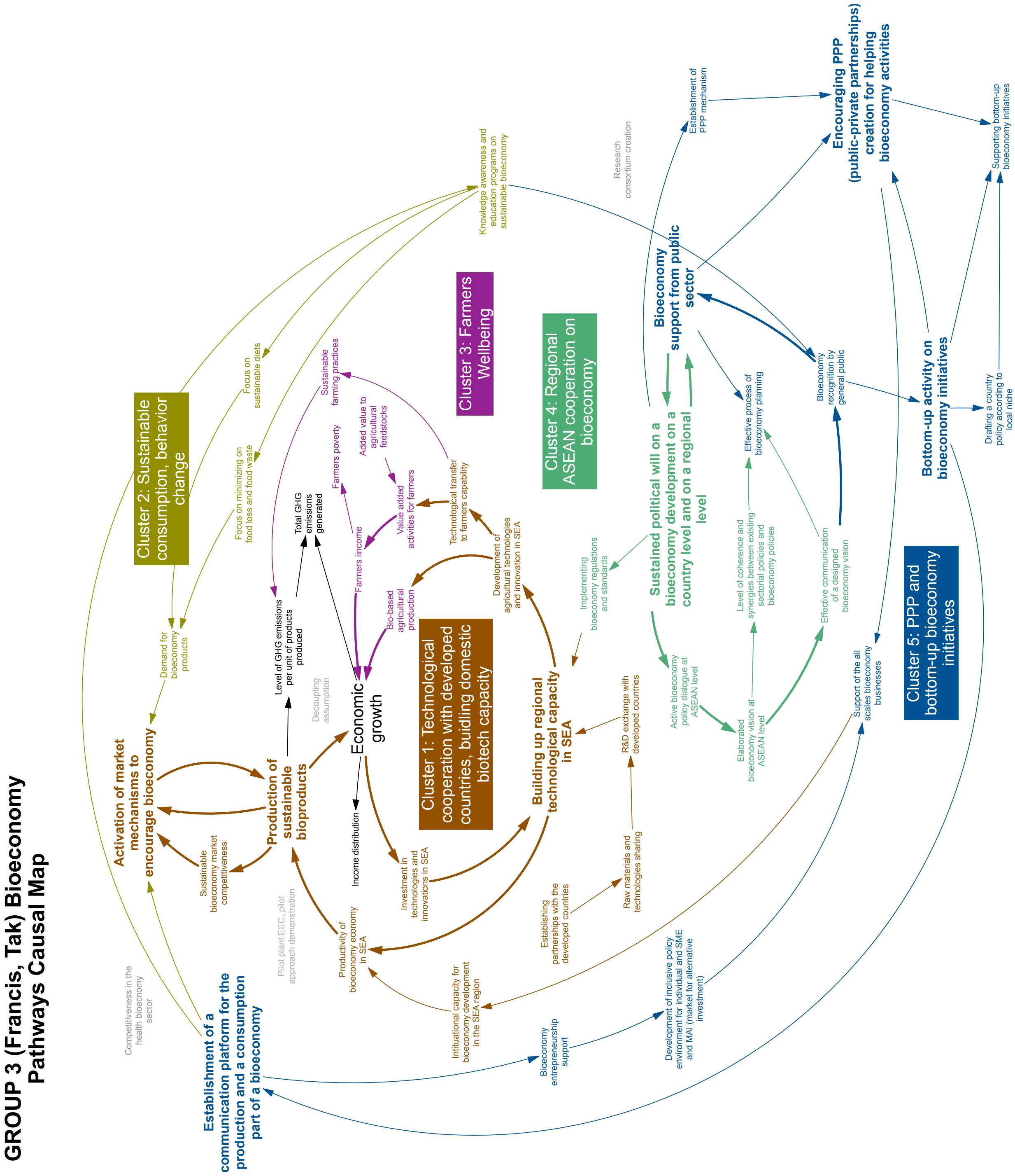
1. What are the components of such social sustainability for farmers, and what are the possible strategies for achieving it?
2. What exactly is meant by 'socially equitable and socially sound' agricultural innovations for farmers and what are the ways to bring them to the main beneficiaries?

Summary of the sustainable bioeconomy narrative of the Group 2

Key words: *small-scale, decentralized, cooperative, renewable*

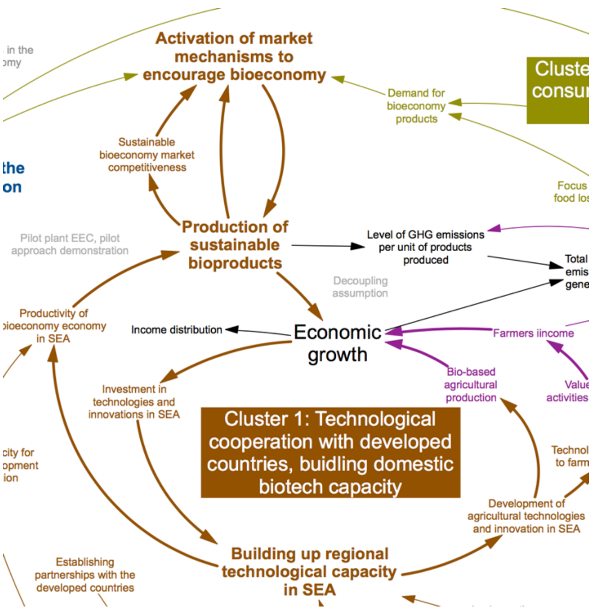
Decentralization of energy and agricultural production is a fundamental component of the bioeconomy development in Thailand and in the ASEAN region. Shifting from the vertical and large-scale production systems to the small-scale and horizontal ones, will ensure not reaching both environmental and social sustainability goals. Social and technical innovations should be designed specifically for contributing to the farmers wellbeing. Strong participatory decision-making core is crucial for bioeconomy goal-setting and implementation processes. PPP initiatives allowing for meeting the interests of private and public sectors for designing bioeconomy programs is one of the main instruments for bioeconomy visions to be realized. Maximum diversity of stakeholder participation, including women and indigenous groups is important and need to be institutionalized by creating a participatory bioeconomy platform. Regional ASEAN context and effective coordination of the bioeconomy strategies in different Asian nations is another essential component of bioeconomy visions to be successfully realized. Shift towards more sustainable consumer behavior supported by the awareness raising campaigns is also necessary for the bioeconomy being fully functioning.

4.3.3. Group 3



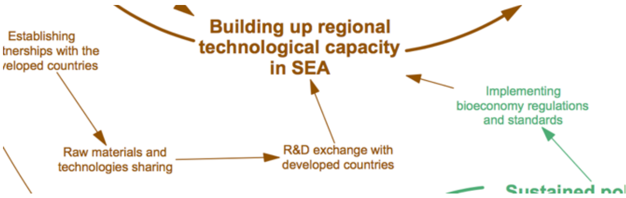
In the Group 3, the number of originally identified clusters was 7 which is even more that the number of clusters that were revealed in the CLD. Content-wise, most of the clusters that were identified by the group members match with those that can be distinguished in the CLD. Regarding the key variables/actions, most of them are located in the technological cooperation cluster and the PPP and bottom-up bioeconomy initiatives one.

Clusters and key variables/actions from a causal map	Clusters and key variables/actions from originally developed pathways
1: Technological cooperation with developed countries, building domestic biotech capacity 1. Building up regional technological capacity in SEA. 2. Production of sustainable bioproducts. 3. Activation of market mechanisms to encourage bioeconomy.	**1: Technology transfer** **R&D and multidisciplinary approach, Market approach**
2: Sustainable consumption, behavior change	**2: Behavior, Communication**
3: Farmers wellbeing	
4: Regional ASEAN cooperation on bioeconomy 1. Sustained political will on a bioeconomy development on a country level and on a regional level	**3: Policy and regulation**
5: PPP and bottom-up bioeconomy initiatives 1. Bioeconomy support from public sector. 2. Bottom-up activity related to bioeconomy initiatives. 3. Encouraging PPP creation for helping bioeconomy activities. 4. Establishing a communication platform for production and consumption parts of bioeconomy.	**4: Policy and regulation**

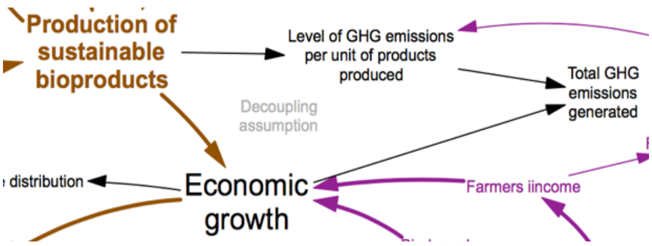


Group 3: Zooming-in technological cooperation with developed countries, building domestic biotech capacity

Technological development and building-up domestic R&D capacity is the main driving dynamics of bioeconomy as well as economic growth. Overall, economic growth is seen an the main engine of bioeconomy to be functioning in a long run. Economic growth leads to a higher investment in biobased technologies and innovations in SEA, building domestic technological capacity, which then leads to an increased production of biobased products – both agricultural and industrial. The most efficient way of making bioeconomy in Thailand and ASEAN work is through activating market mechanisms and encouraging competition between different producers of biobased products which in a long run can lead to a higher productivity of bioeconomy overall and to a further increase of biobased production. With this regard, the top-down measures for supporting bioeconomy should be primarily directed to support entrepreneurial activity.



Technological cooperation and knowledge exchange are crucial components of bioeconomy development, especially with some of the developed countries, where established and functioning bioeconomy capacity already exists.

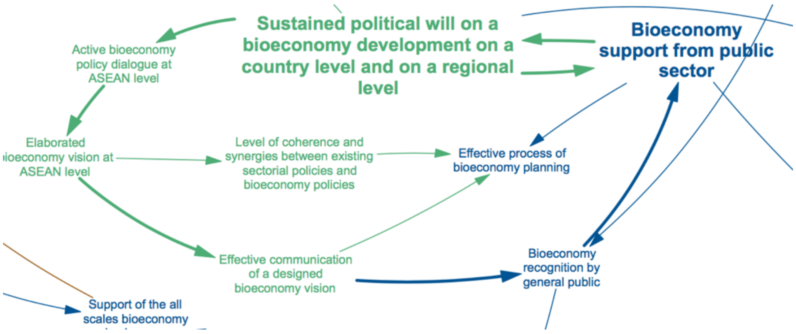


Environmental sustainability component is addressed in this technological bioeconomy cluster in the form of the GHG emissions. It is expected that biobased innovations will simultaneously foster economic growth and lead to a decrease of GHG emissions generated per the unit of produced products. Potential controversy with the environmental sustainability component, however, relates to a better understanding of what can happen to the total GHG emissions in a long run provided there is a constant economic growth.

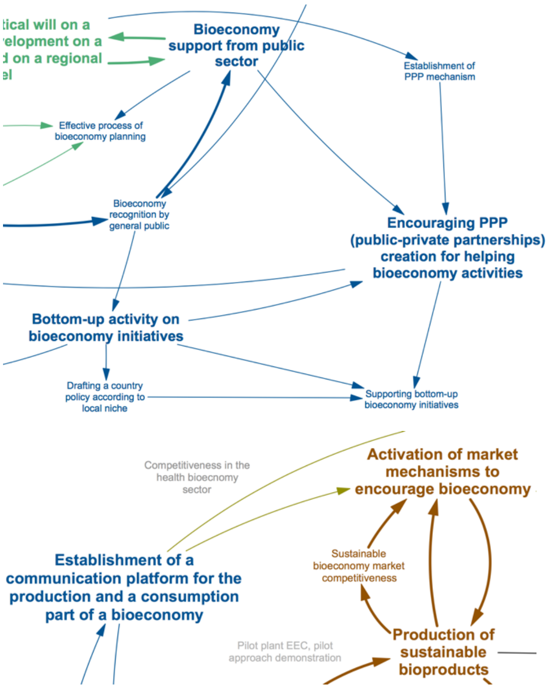
To elaborate this part of the Group 3 bioeconomy vision further and to get a more detailed understanding of how to act on fostering technological capacity for bioeconomy development, the following questions can be addressed:

1. How feasible is the assumption simultaneous economic growth and the GHG emissions reduction on the national and regional levels? Does an expected emissions reduction in this part correspond to a relative or absolute decoupling of economic activities from environmental impact?
2. How feasible are the emissions decoupling assumptions of having simultaneous economic growth and GHG emissions reduction on the national and on the regional level?
3. What could be the mechanisms of technological transfer and intellectual property management in the context of biotechnological exchange with developed countries?
4. What are the exact mechanisms of technological cooperation between ASEAN?
5. What are the specific developed counties to cooperate with while building up domestic bioeconomy capacity in Thailand and ASEAN?
6. What actors are supposed to be the main beneficiaries of the technological development in Thailand and the ASEAN region overall? What actors in Thailand and ASEAN can potentially be disadvantaged by a biotechnological advancement?
7. How does technological cooperation with developed countries need to be organized to prevent creating potential power dynamics and technological dependencies between the more and the less developed countries/regions?

Group 3: Zooming-in Regional ASEAN cooperation on bioeconomy and bottom-up bioeconomy initiatives



It was mentioned in the previous sections that market mechanisms are seen as the main driving engine for the national and regional bioeconomy development. At the same time, when it comes to the cluster of regional ASEAN cooperation for bioeconomy development, a sustained political for bioeconomy support is the key factor that defines success of bioeconomic activities planning and implementation. Political will activates participatory bioeconomy policy dialogues, which then can help developing coherent bioeconomy vision and enhance further effective communication on elaborating this vision. Consequently, the better elaborated bioeconomy vision is and the better it is communicated, the higher is bioeconomy recognition by general public and its further support by public sector manifested through further increase of a political will to work on bioeconomy development.



Bottom-up activities on bioeconomy initiatives and specifically encouragement of PPP creation are the key factors in the cluster related to the participatory activities for bioeconomy development. Talking about specific instruments of the public support of bioeconomy, PPP is named as one of the most effective ones. However, more specific details of how exactly this instrument and other bottom-up activities are supposed to function were not discussed.

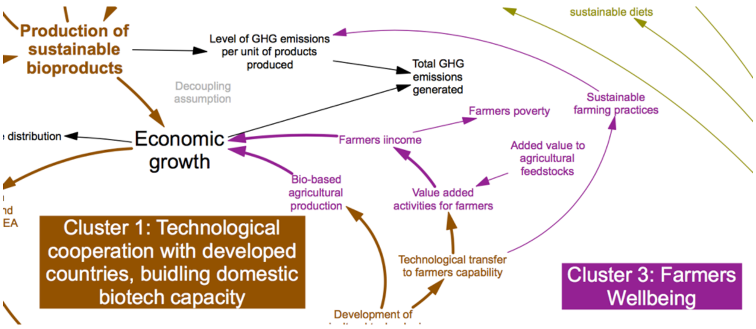
Establishment of a communication platform for production and consumption part of bioeconomy is another instrument that was named as a crucial component of a bottom-up bioeconomy activities. Similarly to PPP, there can be a more elaborated discussion on how this platform is supposed to function, what are the main actors involved in it, and what are the ways of their communication with each other.

Questions that can guide further development of a sustainable bioeconomy action plan in this part are as follows:

1. What is the role of a communication platform for bioeconomy production and consumption for activating bioeconomy market mechanisms?
2. Who is responsible for establishing and operating the bioeconomy communication platform?
3. What is the mechanism behind establishing PPPs? What are the expected benefits from PPP activity?
4. What are the other types of bottom-up activities that were no mentioned during the workshop that can help bioeconomy development in Thailand and ASEAN? What type of governance regime is needed for making realization of those activities possible? What are the potential obstacles?

Group 3: Zooming-in Farmers wellbeing cluster

Improvement of farmers wellbeing is one more cluster that is distinguished within a sustainable bioeconomy action plan of this group. The underlying dynamics of the farmers income increase and corresponding poverty decrease is driven by a technological development that leads to an increase of the value-added activities for farmers and favors sustainable farming practices. Overall, this cluster, as it is seen by the group 3 participants, is a part of an extended feedback loop of general market activities driven by technological development and innovations and fueling continuous economic growth and GHG emissions reduction. Accordingly, there is a lot of room for the further discussion here that can help getting more insights and contribute to a more elaborated action plan ensuring improvement of farmers wellbeing. Potential questions to be asked in this part are as follows:



1. How is technological development supposed to impact farmers production capability?
2. What are the specific agricultural technologies that were implied in the context of sustainable farming practices?
3. How to design a system (both on the national and regional level) where technological progress and building-up biotechnological capacities does not create a 'success to successful' dynamics by excluding small farmers and traditional agriculture practices from the bioeconomy value creation and by benefiting already established leaders of the technologically advanced agriculture?

Summary of the sustainable bioeconomy narrative of the Group 3

Key words: *Economic growth, R&D, innovation, power of market*

Technological development is the most essential component for the bioeconomy development in Thailand. Currently, there is not enough technological capacity available in the country and a massive boost of investment in R&D is required. For this, both cooperation between the ASEAN counties and cooperation between Thailand and developed countries of the Global North is needed. Top-down support for bioeconomy initiatives and sustained political will are important for fostering bioeconomy development. However, market should be the main driving force for activating and scaling up sustainable bioproducts production and consumption, with the competition between the bioeconomy actors and biotechnologies being the key market instrument. Cooperation between different bioeconomy actors, between bioproducts producers and consumers and overall support for the bottom-up bioeconomy initiatives is crucial. Creation of bioeconomy communication platforms and PPP initiatives are examples of the instruments for ensuring full-fledged communication and participation between different bioeconomy actors. Farmers wellbeing and small scale agricultural activities are important but are not necessarily the core of the bioeconomy future. When a major effort is directed towards a technological development, then farmers can also benefit from it. Overall, the goal of the bioeconomy is economic growth which, however, is supposed to be environmentally sustainable and leading, particularly, to a decrease of GHG emissions.

4.4. Analysis of the designed bioeconomy visions

In the table below, the seven reference bioeconomy visions are listed (see section 3 for a more detailed explanation of these visions). Each of them is analyzed and compared with the other visions based on the several structural components that can also be interpreted as bioeconomy objectives to be reached. The list of these components is far from exhaustive and can be altered/extended/shortened for the further analysis. All the components currently present in the table are taken on the literature sources from which the reference bioeconomy visions were derived (Bugge et al., 2016; Hoff et al., 2018) and are separated into 3 different categories:

(1) Environmental sustainability and resource efficiency priorities (colored in the table in green)

(2) Technological, cooperation priorities (colored in the table in orange)

(3) Social/economic priorities (colored in the table in blue)

The visions provided in the table are not mutually exclusive and many of them contain similar structural components. The main purpose of this table is to bring in the same picture the most popular bioeconomy visions in order to compare them with each other and to provide the reference framework for the bioeconomy visions elicited from the bioeconomy policy dialogues. Eventually, this comparison framework is supposed to help conceptually relate regional bioeconomy visions to the already existing bioeconomy literature. This is expected to bring not only a theoretical value but also a policy-relevant one. By better acknowledging what are the focuses and the gaps in the national/regional bioeconomy visions, better policies and action plans for reaching bioeconomy goals can be designed.

Apart from the bioeconomy visions from the literature, there are the visions elicited from the workshop results present in the table. The way bioeconomy visions from the literature are summarized in the table allows to see to what extent each of them is closer to an environmental sustainability and non-exhaustive resource use, focused on technological development and market cooperation, or oriented at meeting social goals.

There are several main ways the bioeconomy visions table is aimed to be used:

- It can be used as a visual and analytical tool for comparing different bioeconomy visions.
- It can help understanding of how the bioeconomy visions generated during the policy dialogues relate to the existing bioeconomy literature.
- It can be used as a support tool for initiating further discussion on those aspects of the visions that did not receive enough attention during the workshops.

	Environmental sustainability and resource efficiency priorities							Technological, cooperation priorities						Social/economic priorities							
	Focus on overall environmental sustainability	Focus on biodiversity and conservation	Climate change aspect, emissions reduction goals	Focus on limiting fossil materials use	Focus on addressing environmental risks	Land productivity increase focus	Material waste reduction and recycling focus	Focus on bio-based products	Focus on global value chains	International biotech, knowledge transfer cooperation	Focus on consumer part of bioeconomy	Focus on investment in and commercialization of research and innovation	Focus on shifting to renewable energy and transport	Focus on ethical issues related to biotech	Economic growth	Focus on sustainable agriculture practices	Focus on bringing technologies to the rural areas	Focus on food security	Focus on rural Development	Job creation	Focus on addressing poverty/inequality
1. Bio-technology vision																					
2. A biotechnology and innovations vision																					
3. An international cooperation and development vision																					
4. Bio-resource vision																					
5. A bioresources (substitution) vision																					
6. An agricultural innovation and rural development vision																					
7. Bio-ecology vision																					
8. Group 1 sustainable bioeconomy vision			Group 1	Group 1	Group 1	Group 1	Group 1				Group 1		Group 1			Group 1	Group 1	Group 1	Group 1		Group 1
9. Group 2 sustainable bioeconomy vision			Group 2	Group 2		Group 2	Group 2				Group 2	Group 2	Group 2			Group 2	Group 2		Group 2		Group 2
10. Group 3 sustainable bioeconomy vision			Group 3					Group 3	Group 3	Group 3	Group 3	Group 3			Group 3	Group 3	Group 3			Group 3	Group 3

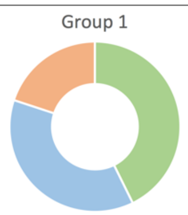
As it can be seen from the table above, there are a lot of gaps (blank squares) in the bioeconomy visions comparison table. Those gaps do not necessarily mean that corresponding components are not present in the related bioeconomy visions. What it actually means is that those components are not explicitly discussed in the literature, and thus making any decision on including or excluding them from particular bioeconomy visions would be arbitrary. Therefore, this table should be seen as a flexible analytical and conceptual tool, where the blank squares can be filled and/or comparison criteria of the visions can be changed, with the generation of a new knowledge in the bioeconomy domain.

The three bottom rows of the table present the resulting bioeconomy visions from the policy dialogues workshop in Thailand. These visions differ from each other, and each of them focus on different components of the bioeconomy.

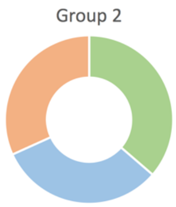
Below, there are comparison diagrams of the three resulting bioeconomy visions developed by each group. On these diagrams, it is indicated which categories of the bioeconomy priorities are given a higher priority.

Color legend:

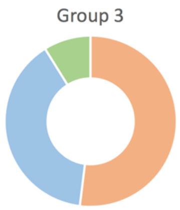
- Environmental Sustainability and Resource Efficiency priorities
- Technological and Cooperation priorities
- Social/Economic priorities



Bioeconomy vision of *Group 1* prioritizes environmental sustainability and social and wellbeing objectives over technological development and international cooperation. In the environmental sustainability category, the emphasis was made on acknowledging regional climate and weather specificities (e.g. flood risks). Social components of the bioeconomy vision are mentioned in this group primarily in the context of increasing farmers wellbeing and reducing farmers poverty.



Group 2 has the most balanced bioeconomy vision among the three bioeconomy visions, with almost equal presence of all three bioeconomy categories. Both in Group 2 and Group 3 technological priorities are given considerable weight. However, in Group 2 technological development is explicitly mentioned in the context of decentralization goals and prioritizing the needs of local communities.



Group 3 bioeconomy vision is primarily technologically oriented and has a very limited presence of environmental sustainability components. In contrast to Group 2, technological progress in the view of Group 3 drives economic growth and fosters international technological cooperation. Together with the technological priorities, a wide range of the social/economic components is present in the vision of Group 3. Those are mostly related to an increase of wellbeing in rural areas and are being primary driven by technological progress.

Talking about the relation between the bioeconomy visions designed by the groups and the reference bioeconomy visions, there is no hundred percent match between any of them. However, it is evident that the visions of Group 1 and Group 2 are closer to the bio-ecology visions, and Group 3 to the biotechnology visions. The closest match between the visions of the groups and the reference visions is between the vision of Group 1 and the Agricultural innovation and rural development vision. Interestingly, in all the bioeconomy visions produced by the workshop participants in Thailand, there is a strong emphasis on the social components, especially in relation to rural development and sustainable food production practices. Group 3 bioeconomy vision is especially interesting one in this context, because it includes both strong technological part and a strong social part, which is not very common, since most of biotechnological visions available in the literature exclude social components almost completely. The presence of a strong social component in the bioeconomy visions in Thailand, especially considering that they are related to the rural development and farmers wellbeing, can be explained by the specificities of the local context and a generally high importance of rural activities for the economy of Thailand.

Annex 2. Data related to the Paper 7: A Case of Electricity Sufficiency for Sub-Saharan Africa: Combining System Dynamics Modelling with the Socially Sustainable Energy System Narrative

(i) Initial cost of capacity installation:

Name of technology	Cost (USD/GW)	References
Bioenergy	1250*10^6	IRENA (2018), Renewable power generation cost in 2017. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf
Coal	3873*10^6	McKinsey (2015), Brighter Africa. Available at: https://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/EPNG/PDFs/Brighter_Africa-The_growth_potential_of_the_sub-Saharan_electricity_sector.ashx%203873%20USD/KW
Concentrated solar power	7500*10^6	IRENA (2010), African power sector
Diesel genset stand alone	938*10^6	Worldbank (2017), Global tracking framework report. Available at: https://www.worldbank.org/en/topic/energy/publication/global-tracking-framework-2017
Diesel genset mini-grid	721*10^6	Worldbank (2017), Global tracking framework report
Gas	1546*10^6	McKinsey (2015), Brighter Africa
Geothermal	4000*10^6	IRENA (2018), Renewable power generation cost in 2017
Centralized hydro	2800*10^6	IRENA (2018), Renewable power generation cost in 2017
Mini hydro	5000*10^6	Worldbank (2017), Global tracking framework report
Oil	1546*10^6	
Solar PV centralized	2500*10^6	IRENA (2018), Renewable power generation cost in 2017
Solar PV mini grid	4300*10^6	Worldbank (2017), Global tracking framework report
Decentralized Hydro	5000*10^6	Worldbank (2017), Global tracking framework report
Wind centralized	2000*10^6	IRENA (2018), Renewable power generation cost in 2017
Wind decentralized	2500*10^6	Worldbank (2017), Global tracking framework report

(ii) Lifetime of electricity generation technologies:

Name of technology	Technology lifetime in years	References
Diesel genset mini grid	15	
Diesel genset stand alone	10	
Gas	30	
Geothermal	30	

Hydro	30	Worldbank (2017), Global tracking framework report
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	IRENA (2018), Renewable power generation cost in 2017
Coal	0,73	EIA (2015), Electric generator capacity factors vary widely across the world. Available at: https://www.eia.gov/todayinenergy/detail.php?id=22832
Concentrated solar	0,3	EIA (2015), Electric generator capacity factors vary widely across the world
Gas	0,44	EIA (2015), Electric generator capacity factors vary widely across the world
Diesel genset mini grid	0,44	EIA (2015), Electric generator capacity factors vary widely across the world
Geothermal	0,8	IRENA (2018), Renewable power generation cost in 2017
Hydro	0,49	EIA (2015), Electric generator capacity factors vary widely across the world
Oil	0,54	EIA (2015), Electric generator capacity factors vary widely across the world
Solar PV centralized	0,2	IRENA (2018), Renewable power generation cost in 2017
Solar PV mini grid	0,2	IRENA (2018), Renewable power generation cost in 2017
Solar PV stand alone	0,2	IRENA (2018), Renewable power generation cost in 2017
Wind power	0,28	EIA (2015), Electric generator capacity factors vary widely across the world

(iv) Population data:

Urban population without access to electricity in Sub Saharan Africa in 2016	122 mln people	IEA (2017), Energy Access Outlook. Available at: https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf
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 2050	https://population.un.org/wpp/
Sufficient amount of electricity in rural Sub Saharan Africa	250 KWh/people/year (based on Multi-tier framework)	Energy Sector Management Assistance Program (2015), Beyond Connections: Energy Access Redefined. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y
Sufficient amount of electricity in urban Sub Saharan Africa	500 KWh/people/year (based on Multi-tier framework)	Energy Sector Management Assistance Program (2015), Beyond Connections: Energy Access Redefined

(v) Cost of technologies:

- Technological cost-resource curves are based on the xls approximation of the GCAM model learning curves. GCAM documentation available at: https://jgcri.github.io/gcam-doc/toc.html

- *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.*

Technologies generation progress ratio:

Bioenergy power progress ratio	0,93	Rubin, E. S., Azevedo, I. M., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, *86*, 198-218.
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	