Sustainable Energy System Planning: Renewable Resource Dynamics

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Abstract

A holistic understanding of the underlying dynamics of sustainable energy system development and its effects on socio-economic and environmental aspects, in different national contexts, is necessary for improved decision making with regards to sustainable energy system planning. In this thesis, systems thinking approach (i.e. causal loop diagrams) is first applied to explore the general dynamics of sustainable energy system development, including the feedbacks and leverages that promote or prevent sustainable energy system development. Second, the emerging energy paradigm (i.e. sustainable energy) and questions related to the challenges arising from it are defined. An extensive model review, which assesses to what extent existing energy system models can provide answers or address the questions arising from the current energy paradigm is presented. This helps identify strengths and weaknesses of energy system models. One of the identified gaps in current energy system models is the simplified representation of the physical realities of renewable resources. This is particularly the case for geothermal resources. Therefore, the third step involves the development of a system dynamics model that captures the behaviour of geothermal resources when they are utilised for electricity production. This geothermal resource dynamics model can capture the effects of geothermal resource dynamics on capacity expansion, resource availability, production levels as well as development and unit production costs at a national systems level. Based on the findings that estimated costs significantly increase when geothermal resource dynamics are considered, while resource availability is also affected, the developed geothermal resource dynamics model assesses the effects of geothermal resource dynamics in Iceland and Kenya. For Kenya, an electricity system model that includes the dynamics of geothermal and hydropower is built. This model explores the effects of renewable resource dynamics (i.e. geothermal and hydropower) on electricity system planning, which is seen as a central element of sustainable energy system development in Kenya. For Iceland, the geothermal resource dynamics model was connected to the Icelandic energy and transport system model (UniSyD_IS). This enables investigating the importance of geothermal resource dynamics in the country's transition to a low-carbon sustainable transport and energy system. Results show that despite the distinct contexts of the two countries (i.e. Global North and Global South), they face similar challenges arising from the character of renewable resource dynamics. In both cases, high electricity demand growth leads to unsustainable use of geothermal resources. This results in decreasing resource availability, thereby increasing the cost of geothermal electricity (development and unit production cost). The implications on sustainable (energy) system development for each country are distinct. This research shows that comprehending the implications of geothermal resource dynamics on sustainable energy system development in countries that already exploit or plan to exploit geothermal resources on a large scale is important. Additionally, this research draws attention to the need for understanding the context-specific dynamics of sustainable energy system development in more depth for achieving sustainable energy system development in different countries.

Útdráttur

Heildrænn skilningur á þróun sjálfbærra orkukerfa og áhrif þeirra á umhverfi og samfélög er nauðsynlegur fyrir bætta ákvarðanatöku við skipulagningu slíkra kerfa. Í þessarri ritgerð er kerfishugsun beitt til að greina samspil mismunandi þátta og orsakatengingar í þróun sjálfbærra orkukerfa, m.a. gagnkvæm áhrif og möguleg inngrip sem ýta undir eða koma í veg fyrir sjálfbæra þróun orkukerfa. Í kjölfarið er ný hugmyndafræði um sjálfbær orkukerfi og tengdar spurningar rýnd og skilgreind. Þessi rýni felur í sér ítarlega skoðun á núverandi líkönum fyrir orkukerfi og mat á því hversu vel þau ná utan um þessa nýju hugmyndafræði. Þar með eru helstu styrkleikar og veikleikar núverandi líkana fyrir orkukerfi greindir. Einn veikleiki núverandi líkana er mikil einföldun á eðli endurnýjanlegra orkuauðlinda, þá sérstaklega fyrir jarðvarma. Því er kvikt kerfislíkan þróað sem tekur tillit til eðlis jarðvarma þegar hann er nýttur til rafmagnsframleiðslu. Þetta jarðvarmalíkan nær utan um eðli jarðvarmauðlinda á einfaldaðan hátt og þar með sýnir hugsanlega framleiðslugetu, áhrif nýtingar á auðlindina, og kostnað vegna rafmagnsframleiðslu á landsvísu. Niðurstöður þessa líkans sýna að kostnaður eykst verulega þegar hvikult eðli jarðvarmaauðlinda er tekið til greina. Einnig má greina áhrif á framleiðslugetu þessara auðlinda. Tvö viðlíka líkön eru þróuð frekar til að endurspegla aðstæður á Íslandi, annars vegar, og Kenía, hins vegar. Líkanið af íslensku jarðvarmaauðlindinni er tengt við UniSyD_IS sem er líkan af orku- og samgöngukerfi Íslands. Þar með er hægt að meta áhrif eðli jarðvarmaauðlindarinnar á orkuskipti til lág kolefna og sjálfbærra samgöngu- og orkukerfa. Líkanið af orkukerfi Kenía einblínir á rafmagnsframleiðslu og samspil notkunar jarðvarma og vatnsafls. Líkanið metur áhrif þessa samspils og eðli auðlindanna á skipulagningu raforkukerfa. En ein af undirstöðum þess að þróun orkukerfis Kenía stuðli að sjálfbærri þróun er talin góð skipulagning raforkukerfa. Niðurstöður þessarar rannsóknar sýna að þrátt fyrir ólíkar aðstæður í löndunum tveim, þá mæta þau svipuðum áskorunum vegna hvikuls eðlis endurnýjanlegra auðlinda. Í báðum tilvikum leiðir mikil eftirspurn eftir rafmagni til ósjálfbærrar nýtingar á jarðvarmaauðlindum. Afleiðing þess er minni framleiðslugetu og þar með hærra verðs og kostnaðar við framleiðslu á rafmagni úr jarðvarma. Þó eru afleiðingarnar fyrir sjálfbæra þróun orkukerfanna einnig mismunandi milli landanna tveggja. Þessi rannsókn sýnir að mikilvægt er að skilja eðli jarðvarmaauðlindarinnar, hvort sem nýting er komin skammt eða langt á veg. Nauðsynlegt er að taka til greina hvikult eðli jarðvarmaauðlinda við skipulagningu orkukerfa sem eiga að stuðla að sjálfbærri þróun. Einnig sýna þessar niðurstöður hversu miklu máli það skiptir að taka tillit til aðstæðna þegar unnið er að sjálfbærri þróun orkukerfa í mismunandi löndum.

L'abstrait

Une compréhension holistique des dynamiques sous-jacentes du développement de systèmes énergétiques durables et de ses effets socioéconomiques et environnementaux dans différents contextes nationaux est nécessaire pour améliorer la prise de décision en matière de planification de systèmes énergétiques durables. Dans cette thèse, l'approche systémique (p.ex. des diagrammes de boucles causales) est premièrement appliquée à l'exploration des dynamiques générales du développement durable de systèmes énergétiques, incluant notamment les retours et leviers promouvant ou restreignant ce développement. Dans un deuxième temps, le paradigme énergétique émergent (p.ex. l'énergie durable) et les questions liées à ses enjeux sont définies. Une évaluation approfondie de la mesure dans laquelle les modèles de systèmes énergétiques existants peuvent fournir des réponses aux questions soulevées par le paradigme énergétique actuel est présentée. Cela permet d'identifier les forces et faiblesses des modèles de systèmes énergétiques. Une des lacunes identifiées dans ces modèles est la représentation simplifiée des réalités physiques des ressources renouvelables, particulièrement dans le cas de ressources géothermales. Par conséquent, la troisième étape consiste à développer un modèle de dynamique des systèmes qui appréhende l'évolution de ressources géothermales lorsqu'elles sont utilisées pour la production d'électricité. Ce modèle peut capturer les effets des dynamiques de ressources géothermales sur les capacités d'expansion, la disponibilité des ressources, le niveaux de production ainsi que le développement et coûts de production unitaires aux niveau de systèmes nationaux. Basé sur l'observation que les coûts estimés augmentent considérablement lorsque la dynamique des ressources géothermales est considérée tout en affectant leur disponibilités, le modèle de dynamique des ressources géothermales élaboré évalue les effets des dynamiques de ressources géothermiques en Islande et au Kenya. Pour le Kenya, un modèle de systèmes d'électricité qui inclut les dynamiques de la géothermie et de l'hydroélectricité est construit. Ce modèle explore les effets des dynamiques de ressources renouvelables (p.ex. la géothermie et l'hydroélectricité) sur la planification de systèmes d'électricité, perçue comme un élément central du développement de systèmes d'énergie durable au Kenya. Concernant l'Islande, le modèle de dynamiques de ressources géothermales a été relié au modèle de système d'énergie et de transports islandais (UniSyD_IS). Cela permet l'investigation de l'importance des dynamiques de ressources géothermales dans la transition du pays vers un système d'énergie et de transport durable à faible émissions de carbone. Les résultats montrent que malgré le contexte distinct des deux pays (p.ex. Nord-Sud), ils font face à des défis similaires qui découlent des caractéristiques des dynamiques de ressources renouvelables. Dans les deux cas, une forte demande d'électricité mène à une utilisation non-soutenable de ressources géothermiques. Cela résulte en une baisse de ressources disponibles, augmentant de ce fait le coût de l'électricité géothermique (de développement et de production individuelle). Les implications sur le développement de systèmes (énergétiques) durables pour les deux pays sont distinctes. Cette recherche montre que comprendre les implications des dynamiques de ressources géothermales sur le développement de systèmes énergétiques durables dans des pays qui exploitent, ou prévoient d'exploiter des ressources géothermiques à grande échelle est important. De plus, cette recherche souligne le besoin d'une compréhension plus poussée des dynamiques contextuelles du développement de systèmes énergétiques durables pour parvenir au développement de systèmes énergétiques renouvelables dans différents pays.

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Paper II: Chapter 3

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

Paper III: Chapter 4

Spittler, N., Shafiei, E., Davíðsdóttir, B., & Juliusson, E. (2019). Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs. Energy, Submitted.

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1 Introduction

As the Earth is not an isolated but rather a closed system, it is limited in resources and its sink capacity. Source and sink limits relate to the biophysical limits within which our society and economic systems are embedded (Boulding, 1965; Kerschner, 2010). Despite biophysical limits being under discussion for more than four decades, our economy and society is still moving towards and beyond those limits (Donella H Meadows, Meadows, Randers, & Behrens, 1972; Rockström et al., 2009; Seppelt, Manceur, Liu, Fenichel, & Klotz, 2014). One of the main reasons for this has been the development of the current energy system and its reliance on fossil fuels (Steffen et al., 2005). However, not only fossil fuels but also renewable energy resources increasingly come into focus when talking about resource limitations of the energy system. This acknowledges that renewable energy resources cannot be exploited in an unlimited and ever growing manner as either their regeneration rate might pose a limit, they are temporally or geographically limited, or the materials (i.e. rare earth metals) needed for technologies to harvest renewable energy are limited (Gudni Axelsson, Stefansson, Bjornsson, & Liu, 2005; Davidsson, Grandell, Wachtmeister, & Höök, 2014; de Vries, van Vuuren, & Hoogwijk, 2007; Juliusson et al., 2011; Tao, Jiang, & Tao, 2011). Furthermore, limits with regards to the sink capacity of the environmental system, especially those concerning climate change (i.e. CO_2 emissions), are analyzed and under discussion when talking about current and possible future energy systems (Hong, Bradshaw, & Brook, 2015; IPCC, 2000; Kesicki & Anandarajah, 2011; Steffen et al., 2015, 2005; van der Zwaan & Gerlagh, 2006). At the same time, modern energy is essential for economic development and therefore, increasing energy consumption is seen as prerequisite for improved standards of living (Modi, McDade, Lallement, & Saghir, 2005; Pasternak, 2000; Steinberger & Roberts, 2010). The links within the energy system and all its components are often bi-directional, influencing each other and are part of a complex, dynamic system (Huang, Hwang, & Yang, 2008; Stern & Great Britain. Treasury., 2007). The main objective of this thesis is to investigate the dynamics of sustainable energy system development in the global north and the global south. This objective is divided into answering the following research questions:

- What are the dynamics for achieving sustainable energy system development (SED)?
- How has sustainable energy system development been addressed so far?
- How do renewable resource dynamics affect energy systems development in the global north and the global south?

1.1 Research focus and structure

This thesis discusses SED by revealing dynamics and leverage points important to SED. Additionally, it explores how SED has been addressed in energy systems models and pathways of national (sustainable) energy system development are investigated in the context of the global north and the global south. To explore different possible pathways and future developments of national energy systems, models for two case studies were developed and used. The two chosen case studies are Iceland and Kenya. In both cases a particular focus is put on the role of renewable resource dynamics, focusing on geothermal energy and their implications for sustainable development. Due to the interdisciplinary nature of questions concerning sustainable development, the topic of sustainable energy system development is investigated from social, economic, technical and environmental perspectives. The following research objectives were fulfilled in five journal articles: (i) literature review on sustainable (energy) development (Paper I) ; (ii) literature review on the social, economic, environmental and technical components of (sustainable) energy systems (Paper II); (iii) model review of energy system models (Paper II); (iv) conceptualization and modelling of geothermal resource dynamics for energy system models (Paper III); (v) developing and modelling Kenyan case (Paper IV); (vi) exploring possible Icelandic energy system developments when accounting for geothermal resource dynamics (Paper V).

Numerous definitions of sustainable development and interpretations of it exist (Hopwood, Mellor, & O'Brien, 2005). Therefore, the first paper of this thesis commences by exploring the meaning of sustainable development in relation to the energy system. Based on the idea that sustainable development means staying within planetary boundaries as well as fulfilling human needs (Raworth, 2012, 2017), a conceptualization of a sustainable energy system is carried out. The current sustainable development debate is rooted in the concept of environmental limits to today's human system (IPCC, 2011; D H Meadows, Randers, & Meadows, 2004; Donella H Meadows et al., 1972; Rockström et al., 2009; Steffen et al., 2015) in general and source and sink limits of the energy system in particular (IIASA, 2012; Riahi & Roehrl, 2000; Rosen & Dincer, 2001). The acknowledgement of environmental limits was extensively discussed before current sustainability and sustainable development debates originated. This can be referred to as ecological and biophysical economics (e.g.(Boulding, 1965; Georgescu-Roegen, 1975)). Georgescu-Roegen pointed to the importance of considering the second law of thermodynamics and the concept of entropy when studying the link between energy and the economy (Georgescu-Roegen, 1975). Therefore, economic theory should depart from its solely mechanistic explanation of economic processes and acknowledge the law of entropy by recognizing limits as well as making a qualitative distinction between resources, inputs and products. Ayres built on this more biophysically based approach to understanding the energy-economy relationship and, for example, investigated economic growth from a new perspective by focusing on the relationship between useful work (i.e. services provided), exergy inputs and efficiency for the last century in the U.S. (Ayres, 2003). He found that thermodynamic efficiency improvements (i.e. at the conversion and equipment level) have been almost exhausted in the 1960s. Since then, mostly system optimization and end use efficiency improvements have led to further energy system efficiency increases (Ayres, 2003). The understanding that indefinite economic growth is not possible because of biophysical constraints led to alternative concepts on how to build an economic system that remains within those limits. One of those alternative economic theories is the foundation of Daly's steady state economics (Daly, 1974). Several authors have found that the use of energy and economic growth are closely linked (e.g.(Banks, 2000; Jackson & Victor, 2016)). Energy is often seen as part of the economic system. However, the structure of current energy systems is one of the main reasons for today's environmental problems (Steffen et al., 2005). Hence, in Paper I it is argued that the energy system itself should be analyzed. The energy supply cannot grow indefinitely, which has implications for economic growth and its need to become more environmentally and socially sustainable by staying within planetary limits and contribute to human well-being (Rao & Baer, 2012; Steinberger & Roberts, 2010), a sustainable energy system is conceptualized in Paper I. The developed concept of a sustainable energy system is based on Daly's steady state economics and explores the feedbacks and controversies arising when achieving a steady state of energy. By applying systems thinking and leverage points analysis, opportunities and challenges for achieving a sustainable energy system development are identified in the context of a steady state of energy.

The emergence and role of energy in the sustainable development debate is reviewed in Paper II. This, in combination with a detailed review of the aspects of critical elements (e.g. material scarcities, social components), is to be considered when aiming for the development of a sustainable energy system, which leads to a definition of the current understanding of the role of energy. In Paper II this is referred to as the current energy paradigm. From this understanding of the role of the energy system a number of questions arise, which are important to be addressed when aiming to design sustainable future energy systems. As energy system models are one of the main tools for planning future energy systems (Pfenninger, Hawkes, & Keirstead, 2014), they need to be able to answer the above-mentioned research questions. An assessment of whether and how relevant energy system models answer the questions arising from the current energy paradigm is carried out.

Resulting from the analysis of the different model categories (i.e. bottom-up, top-down, hybrid) and their ability to answer the questions arising from the current energy paradigm, issues relating to technical, environmental and social components of the energy system that need to be addressed further are identified. Among those issues is the simplified representation of renewable resources in many energy system models, which does not address many of the concerns raised in energy research literature (Ebinger & Vergara, 2011; Júlíusson & Axelsson, 2018; Moss, Tzimas, Kara, Willis, & Kooroshy, n.d.; Simmons, 2011). Hence, the focus of the third paper is on the dynamics related to renewable resources, especially the ones most relevant for the selected case studies, namely geothermal resource dynamics. The specific geothermal resources dynamics and effects arising from them have been addressed by individual reservoir studies but rarely at a systems level (Gudni Axelsson, 2012; de Boer & van Vuuren, 2017; Júlíusson & Axelsson, 2018; Juliusson et al., 2011; Mondal, Bryan, Ringler, & Rosegrant, 2017; Shmelev & Van Den Bergh, 2016; Stefansson & Axelsson, 2005). Therefore, a model that captures the connection between geothermal resource dynamics and the economics of geothermal plant construction is developed. This enables the exploration of the effects of geothermal resource dynamics on resource utilization, resource availability, unit production cost and total system cost. Unlike purely physical models this model can easily be connected to energy systems models, which capture energy system development and assessment on a national level. This model is presented in Paper III. Renewable resource dynamics are then explored further in Paper IV, in a case study of the Kenyan energy system. This paper assesses the implications of renewable resources dynamics (i.e. hydro and geothermal) for electricity system planning. The model developed in Paper III is integrated into a broader national electricity system model. Additionally, the impacts of climate change on hydro resource dynamics are also considered in the demand-driven bottom-up electricity model presented in this paper. Based on the results of certain energy system parameters, including geothermal resource availability, production capacity of geothermal wells and power plants and electricity unit production cost, several implications for other sustainable development goals are drawn.

1.2 Understanding energy in the context of sustainable development

In 1972, The Limits to Growth (Donella H Meadows et al., 1972) was published and the United Nations Conference of the Human Environment was held in Stockholm. While this conference can be referred to as the first of the most important policy conferences related to sustainable development (Najam & Cleveland, 2003), The Limits to Growth presented the first global sustainability assessment model (i.e. WORLD3). This model linked economic, environmental and social systems, pointing to the unsustainable nature of the economic system. Those two events together are often mentioned as the starting point of the sustainability debate, in which energy was scarcely discussed. In The Limits to Growth, energy is not modelled or analyzed as a separate sector, but is included in the overall category of resources (Bhattacharyya & Timilsina, 2010a). However, the publication of Limits to Growth sparked a discussion on the dependence of the economy on resources, including that of energy (Bhattacharyya & Timilsina, 2010a). One of the concepts that emerged from this discussion and is still used to assess and compare sustainability of different energy options is the one of energy return on investment (EROI) (Cleveland, Costanza, Hall, & Kaufmann, 1984). The higher the EROI of a particular energy source the better, because more energy can be recovered. Already in 1984, Cleveland et al. identified declining EROI values for all principal fuels in the US. A more comprehensive discussion and modelling of the connection between energy and the economy was published after The Limits to Growth Study in "Modelling Energy-Economy Interactions: Five Approaches" (Hitch, 1977).

As the title of the Stockholm Conference suggests, the environment was at the center of the debates. At this point in time, energy system development received little attention in the public debates as energy was only considered as an important input factor and economic resource or a pollution factor that put pressure on the environment. Measures to better understand the energy system from the resource and environmental perspective were recommended. Recommendation 59 of the Report of the United Nations Conference on the Human Environment states that "[it] is recommended that the Secretary-General take steps to ensure that a comprehensive study be promptly undertaken with the aim of submitting a first report, at the latest in 1975, on available energy sources, new technology, and consumption trends, in order to assist in providing a basis for the most effective development of the world's energy resources, with due regard to the environmental effects of energy production and use [...]" (UN, 1972). Two decades later, at the United Nations Conference on Environment and Development in Rio, also referred to as Earth Summit, energy was not addressed in the declaration (Najam & Cleveland, 2003). However, in Agenda 21, which was one of the outcomes of the Earth Summit in 1992, energy received some attention. Despite the fact that there was no separate chapter on energy, energy became a relevant part of other chapters. In particular, energy played an important role in Chapter 9 - "Protection of the atmosphere". It was also mentioned as a contributing factor in the following chapters: Chapter 4 - "Changing consumption patterns"; Chapter 7 - "Promoting sustainable human settlement development"; and Chapter 14 - "Promoting sustainable agriculture and rural development". While these chapters only touch upon the contribution of energy to the issue at hand (i.e. social and economic development), energy is vital in the chapter on the protection of the atmosphere. Hence, energy was still mainly seen as a driver of climate change to be avoided rather than an integral aspect necessary for the achievement of sustainable development. The suggested solutions therefore included economic (e.g. pricing) and technological innovation (e.g. increasing efficiency). (UNCED, 1992)

Although mainly centered around economic and emissions aspects, requests for developing indicators and methodologies to understand and assess the energy system in a more holistic manner were already brought forward in conference documents (i.e. Report of the United Nations Conference on the Human Environment, Agenda 21), which were outcomes of the two conferences mentioned above (UN, 1972; UNCED, 1992).

Nonetheless, only at the end of the 1990s, did the International Atomic Energy Agency (IAEA), together with the International Energy Agency (IEA) and others, develop indicators for sustainable energy development, which went beyond simple growth and emissions indicators but tried to capture the development of the energy system and its interaction with the socio-economic and environmental dimension in a more holistic manner (Ivan Vera & Langlois, 2007). At the beginning of the 21st century not only energy and environmental organizations dealt with the energy topic, but also more socio-economic institutions started addressing these issues. In 2000, the UNDP published the book “World Energy Assessment - Energy and the Challenge of Sustainability” (UNDP, 2000). In this book, Jefferson talks about the need for a new energy paradigm and contrasts the traditional with the emerging paradigm. Jefferson defines the following aspects for the emerging paradigm, which are significant for defining today’s energy paradigm: “(i) greater consideration of social, economic and environmental impacts of energy use; (ii) acknowledgement of limitations on the assimilative capacity of the earth and its atmosphere; (iii) emphasis on developing a wider portfolio of energy resources, and on cleaner energy technologies; finding ways to address the negative externalities associated with energy use; (iv) understanding of the links between economy and ecology, and of the cost-effectiveness of addressing environmental impacts early on; (v) recognition of the need to address environmental impacts of all kinds and at all scales (local to global) (vi) emphasis on expanding energy services (i.e. by increasing useful energy for consumers and reducing losses), widening access, and increasing efficiency; (vii) recognition of our common future and of the welfare of future generations” (Jefferson, 2000, p. 418).

In 2001, in their ninth session report, the UN Commission on Sustainable Development states that “Energy is central to achieving the goals of sustainable development” (UN Commission on Sustainable Development, 2001, p. 1). For the first time, officially and explicitly, energy became central to the delivery of sustainability and was recognized in a holistic manner rather than just as a part of another problem (e.g. climate change).

One year later in the Johannesburg Declaration, which was an outcome of the World Summit on Sustainable Development held in 2002, energy was put on the international policy agenda as one of the themes central to be addressed in order to achieve sustainable environmental, social and economic development (Najam & Cleveland, 2003; United Nations, 2002).

In 2005, the IAEA together with the IEA, UN Department of Economic and Social Affairs (UNDESA), Eurostat and the EEA (European Environment Agency), presented the Energy Indicators for Sustainable Development, which was the final outcome of the work that was started in 1999. This set of indicators includes 30 indicators in three dimensions (social, economic and environmental) (Ivan Vera & Langlois, 2007). Each of the dimensions is composed of different themes. The themes in the social dimension are equity and health, the themes in the economic dimension are use and production patterns as well as security, and the themes in the environmental dimension are atmosphere, water and land. The indicators might belong to more than just one dimension and can comprise several measures necessary to calculate each particular indicator. Each theme is then broken further into sub-themes, where e.g. sub-themes within equity are accessibility, availability and affordability and the atmosphere theme is broken into climate change and air quality. Indicators are then developed for each of the sub-themes, and thereby they reflect the broad spectrum of relevant elements of the energy system to be considered and need to be assessed in the context of each country.

In 2015, “Affordable and Clean Energy” became number 7 of the Sustainable Development Goals (SDGs). The goal aims to “Ensure access to affordable, reliable, sustainable and modern energy for all”. Hence, energy access needs to be ensured for “present and future generations, in an environmentally sound, socially acceptable and economically viable way”, as stated in the ninth session report of the UN Commission on Sustainable Development (UN Commission on Sustainable Development, 2001). When considering future generations, the question about resource availability and potential future climate change also needs to be addressed. More recent research in the energy literature also considers potential material scarcities for harvesting renewable energy (Moss et al., n.d.; Simmons, 2011; WWF, 2014), as well as the climate impact on energy resource availabilities and the overall energy system (Ebinger & Vergara, 2011; Schaeffer et al., 2012).

The above shows that in the sustainability and sustainable development debate the focus of energy linked analysis changed from it solely being a resource availability (as an economic input factor) and emission problem to being an essential component of future development, which is central to all three dimensions of sustainability (environmental, social and economic). Clearly, the energy system encompasses social, economic and environmental factors.

Today, sustainable energy and sustainable energy system (development) are terms often used in academic, political and energy policy as well as sustainable development discourses. Despite the prominence of those terms they are ambiguous and no one definition of sustainable energy (system) exists. SDG 7 is supposed to "ensure access to affordable, reliable, sustainable and modern energy for all" (United Nations, 2018) but does not define the term 'sustainable energy'. Based on the findings of this thesis and particularly the analysis carried out in Paper I and II, the following definition of sustainable energy system is adopted in this thesis: A sustainable energy system ensures the well-being of people today and in the future. This means the energy system provides sufficient and affordable energy services, while respecting biophysical boundaries.

1.3 Understanding sustainable energy systems in the national context

Energy plays a major role in shaping global and national (sustainable) development as it is one of the key factors for achieving socio-economic development but at the same time is currently one of the main drivers of climate change (Pachauri, Rao, Nagai, & Riahi, 2012; Rao, Riahi, & Grubler, 2014; Steffen et al., 2005; Steinberger & Roberts, 2010). Thereby, the energy system encompasses environmental, social and economic components, which need to be considered when referring to sustainable energy system development. While sustainable energy system development is a universal goal, the prioritization of the different targets and ways of achieving them can vary. For example, Vera and Langlois (Ivan Vera & Langlois, 2007) developed energy indicators for sustainable development, which capture all three (social, economic, environmental) components of the energy system. They argue that the performance of the energy system should be measured according to the ends a country wants to achieve by building up or transforming its energy system. Whereas in the global north environmental and economic impacts such as climate change might be most important, providing access to affordable and modern energy to everyone is seen as a primary concern in the global south (Paper II). Despite the varying prioritization of different goals, it is always the case that several goals and their achievement in the short- and long-term need to be considered when planning future energy systems' development. To understand renewable resource dynamics and their role for sustainable energy system development in the context of the Global North, Iceland was chosen as an example, and Kenya was chosen as an example of the Global South. The challenges these two countries face differ. Iceland has already built their electricity systems and enabled access to all, the system is currently being built in Kenya. Both countries, however, mainly rely on geothermal and hydropower resources.

1.3.1 Iceland

Iceland is a Nordic island country. In 2017, the nation's total population was around 340 thousand, of which 92.5% lived in urban and 7.5% lived in rural areas (World Bank, 2018). Since 2012, GDP has on average grown by 3.9% per year (World Bank, 2018). To guide decision-making in the power sector a master plan assessing economic, social and environmental impacts of potential power projects has been developed. It strives to ensure the most feasible utilization of geothermal and hydro resources in Iceland from a multi-dimensional perspective (Orkustofnun - National Energy Authority, 2018c). An overview of the Icelandic energy system is provided in the following subsections.

Institutions and structure of Iceland's energy sector

Fig. 1 provides an overview of Iceland's energy system structure. Due to the research focus and the fact that geothermal resource dynamics are only relevant for the electricity sector, the structure of the heating sector is not displayed in as much detail as the other two (i.e. fuel and electricity).

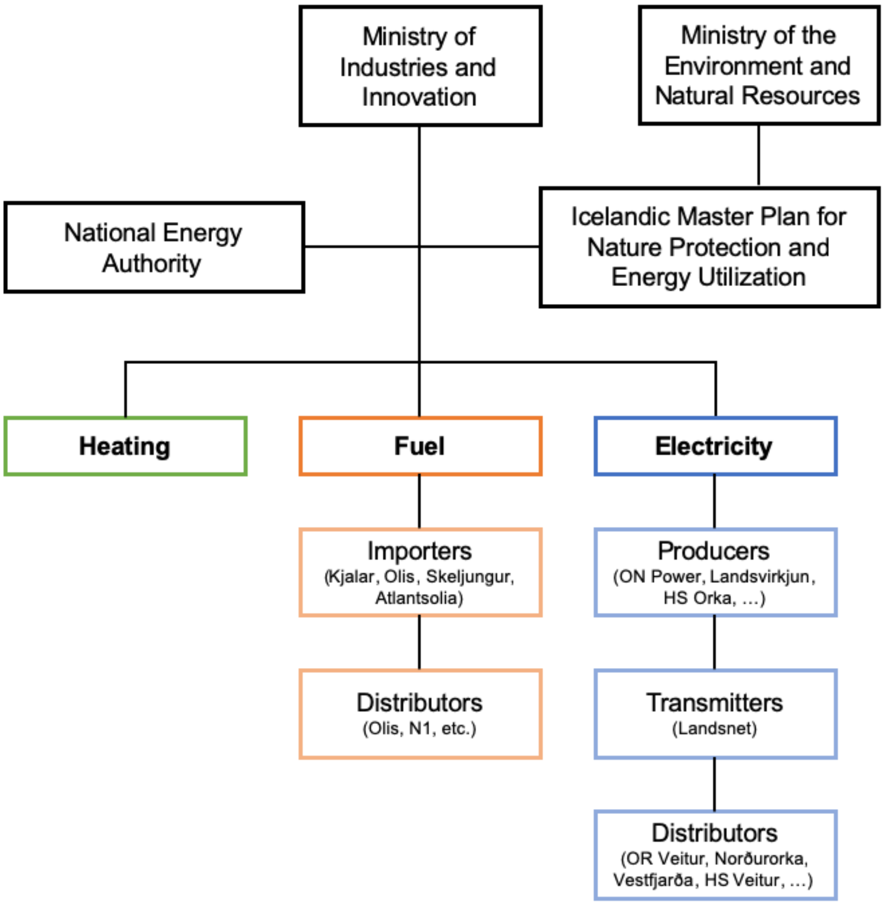

Figure 1: Institutional structure of Iceland's energy system

Several institutions and actors on different levels exist within the Icelandic energy sector. On the policy and legislation level two ministries are mainly relevant for this sector, the Ministry of Industries and Innovation, and the Ministry of the Environment and Natural Resources. These two ministries oversee several institutions, which concern different aspects of the Icelandic energy system. For the Ministry of Environment and Natural Resources, those are: Environment Agency of Iceland, Icelandic National Planning Agency and Icelandic Geo Survey (ISOR). The National Energy Authority (Orkustofnun) is the most important institution that reports to the Ministry of Industries and Innovation. The National Energy Authority, for example, is responsible for the licensing of geothermal resource utilization and electrical power plant construction including hydro, wind and geothermal (Orkustofnun - National Energy Authority, 2018b). The Ministry of the Environment and Natural resources is in charge of the Icelandic Master Plan for Nature Protection and Energy Utilization. The objective of the plan is to bring together the interests of nature conservation and energy utilization on a national scale and thereby, secure sustainable development of the energy system in Iceland. The work on the first Master Plan began in 1999 and it is currently in its fourth phase, which will finish in 2021 (Orkustofnun - National Energy Authority, 2018c).

Structurally, the supply side of the Icelandic energy system can be divided into heating, fuels and electricity. The fuels used in the country are mainly imported fossil fuels, which is done by four main companies (Kjalar, Olis, Skeljungur and Atlantsolia). Other types of fuels used include hydrogen and biofuels, which are producible in Iceland (Askja Energy Partners, 2018; Shafiei, Davidsdottir, Leaver, & Stefansson, 2015). Distribution of fossil fuels is done by several companies, of which some are the importers themselves. The electricity sector is divided into power generation, transmission and distribution. The three largest electricity generators in Iceland are Landsvirkjun, Orkuveita Reykjavikur (OR) and its subsidiary ON and HS Orka. Landsvirkjun is entirely state-owned and produces close to 75% of Iceland’s electricity (Askja Energy Partners, 2018; Landsvirkjun, 2018) from hydropower and geothermal plants. Most of the electricity is sold to energy intensive industries (80%) via long-term contracts, while the rest is sold to Landsnet, the Icelandic publicly owned transmission system operator (Askja Energy Partners, 2018). The second largest electricity producer in Iceland, Reykjavik Energy and its subsidiaries, is a public company that also provides other services, such as heating, water and sewage services. It mainly relies on geothermal energy for heat and electricity production. In total, it provides electricity and heat to around 67% of the population (Askja Energy Partners, 2018; Orkuveita Reykjavikur, 2018). HS Orka previously was a public company but is co-owned by Magma Energy Sweden A.B. and a group of Icelandic pension funds. It is the third largest electricity producer in the country and relies on geothermal power. Other small electricity producers that utilize geothermal, hydro or wind resources exist. Distributors of electricity are OR Veitur, Rarik, Norðurorka, Orkubu Vestfjarða, HS Veitur, and Rafveita Reyadarfjardar. Although the structure of Iceland’s energy system is divided on several levels, many connections between them are present.

Current status, challenges and future goals of energy system in Iceland

In 2017, Iceland’s total primary energy use equaled 5985 ktoe (Orkustofnun - National Energy Authority, 2018d). Fig. 2 displays the shares of total primary energy use by fuel type. The largest share of Icelandic primary energy use comes from domestic renewable resources, which account for more than just 81% in 2017. Only around 19% of total primary energy use were fossil fuels, which were entirely imported (Orkustofnun - National Energy Authority, 2018d).

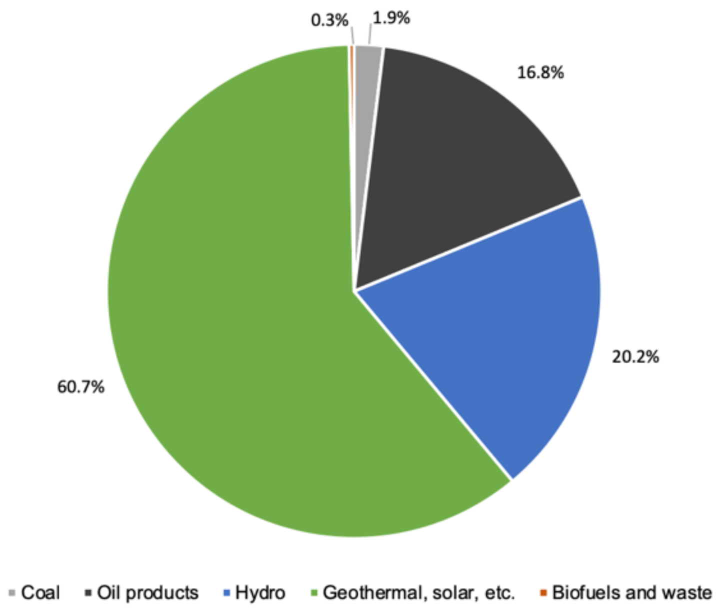

Figure 2: Shares of total primary energy use by source in Iceland

In 2016, around 50% of total final energy consumption (i.e. 2990 ktoe) was electricity (OECD/International Energy Agency, 2018a). As displayed in Fig. 3, close to 99% of all electricity in Iceland was produced from renewable resources, where the largest share of electricity was produced from hydro resources, and slightly more than a quarter of electricity derived from geothermal resources in 2017 (Orkustofnun - National Energy Authority, 2018a). In total, about 19 TWh of electricity were consumed, which translates into an average electricity consumption of 56 MWh per person (Orkustofnun - National Energy Authority, 2018a). However, in 2016, the major share (83%) of electricity was consumed by energy intensive industries (Orkustofnun - National Energy Authority, 2017). A total of 1.6 Mt of CO_2 were emitted from fuel combustion in 2016, which equates to 6 t CO_2 per person (Hellsing et al., 2018).

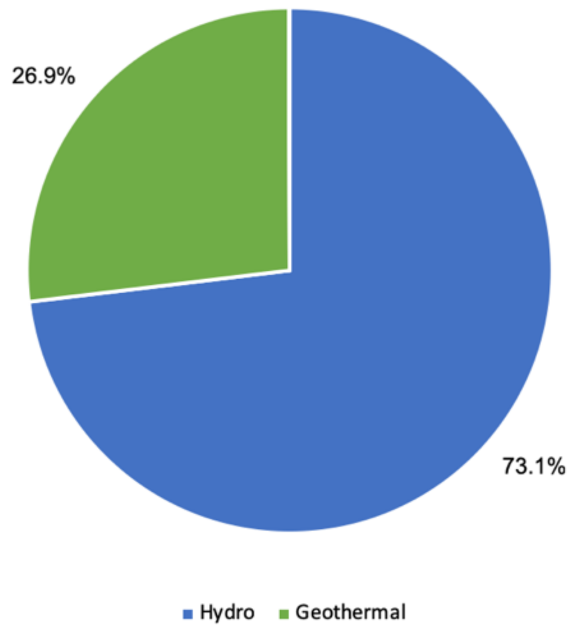

Figure 3: Shares of total electricity production by source in Iceland

When examining the structure of the Icelandic energy system in the context of sustainability, it is clear that Iceland has a modern energy system and infrastructure, which mostly relies on renewable resources for electricity generation and heat. Iceland also performs well in terms of energy access and affordability but faces some challenges in terms of equity, security, environmental, efficiency, and its contribution to well-being and economic aspects (Shortall & Davidsdottir, 2017). For the contribution to well-being, Icelanders would want to have a more democratic decision-making process in the energy sector. When it comes to equity, a concern is pricing differences between industry and households, even if both prices are comparatively low at the moment (Shortall & Davidsdottir, 2017). Despite Iceland's abundant energy resources, more efficient use of energy is recommended – for example, by increasing the energy efficiency of buildings (Shortall & Davidsdottir, 2017). Energy security can refer to short-term (e.g. disruptions of electricity supply due to problems with the transmission system) and long-term (e.g. supply of imported fuels due to a tense geopolitical situation) security (Kucharski & Unesaki, 2015). Both short and long-term perspectives need to be addressed in Iceland. The most relevant short-term security concern in Iceland is grid stability. Long-term security issues in Iceland include the fossil fuel dependency of the transport sector and industry as well as the potentially excessive use of geothermal energy resources due to its significant role in the energy system and the geographical proximity of many of the nation's power plants, which makes the electricity system vulnerable to volcanic eruptions or earthquakes (Drouin et al., 2017; Jousset et al., 2010; Juncu, Árnadóttir, Hooper, & Gunnarsson, 2017). The fishing industry and transport sector are the two sectors largely reliant on fossil fuels (Shafiei et al., 2018). Hence, to continue the shift to renewable energy and to significantly reduce GHG emissions, these two sectors need to transition towards renewable energy. This could be partially accomplished by electrifying the light duty vehicle fleet (Shafiei et al., 2018; Shafiei, Davidsdottir, Leaver, & Stefansson, 2014).

In summary, the most important sustainability aspects of the Icelandic energy system are to ensure security by ensuring sustainable use of geothermal resources, eliminating the use of fossil fuels and reducing GHG emissions by electrifying road transport, and to ensure equity in terms of price and securing access across the country. All these factors are influenced by renewable resource dynamics, including the dynamics of the geothermal resources when used for electricity production (Gudni Axelsson et al., 2005; Shortall, Davidsdottir, & Axelsson, 2015; Stefansson & Axelsson, 2005) (also see section 1.4.1).

1.3.2 Kenya

Kenya is located at the equator and overlies the East African Rift Valley. In 2017, the total population was around 50 million, of which 73.4% and 26.4% lived in rural and urban areas, respectively (World Bank, 2018). Since 2012, GDP has on average grown by 5.4% per year (World Bank, 2018). As outlined in Kenya's Vision 2030, the government aims at transforming Kenya into "a newly-industrializing, middle income country providing a high quality of life to all citizens in a clean and secure environment" (Government of Kenya, 2018; Government of the Republic of Kenya, 2007). Energy is an important foundation of the vision (Gainer, 2015). An overview of the Kenyan energy system is presented below. A special focus is put on the electricity sector, because it is the focus of the energy system development plan of the Kenyan Government.

Institutions and structure of Kenya's energy sector

As a result of several reforms, institutions of the Kenyan energy sector were divided into individual entities on different levels as depicted in Fig. 4. Despite the differentiation of different institutions, close connections among the individual actors and to the government still exist (Lahmeyer International, 2016).

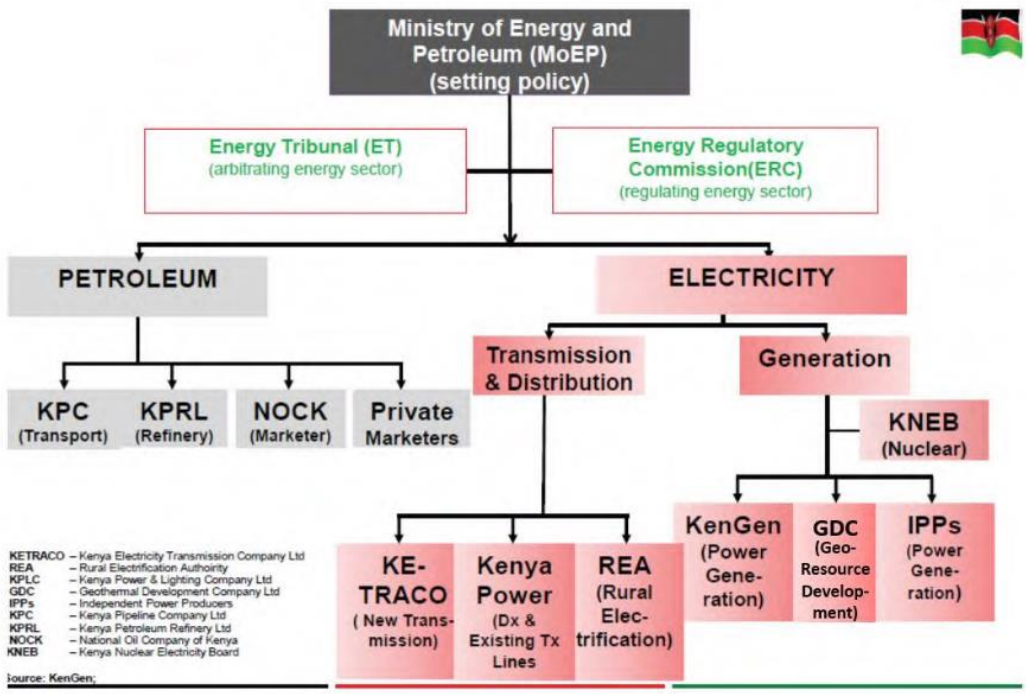

Figure 4: Institutional structure of Kenya's energy system

Enactment of the Energy Act of 2006 followed several reforms and developments in Kenya's energy policy. The aim of the Act was to ensure the regulation and development of all energy resources in Kenya. Through this, the Energy Regulatory Commission (ERC) and the Rural Electrification Authority (REA), Kenya Electricity Transmission Company (KETRACO) and Geothermal Development Company (GDC) were established (Lahmeyer International, 2016).

While the ERC together with the Energy Tribunal were established as state independent regulatory bodies to coordinate as well as advise the Ministry of Energy, KETRACO and GDC are 100% state owned. KETRACO is responsible for Kenya's high voltage electricity transmission infrastructure. Currently, Kenya Lighting and Power Company (KPLC), which is in charge of existing transmission infrastructure, supports the more recently established KETRACO with maintaining and operating their infrastructure (Lahmeyer International, 2016). KPLC is governed by the State Corporations Act and is the buyer of all power from all generators. It ensures that the purchase of electricity as negotiated in the respective Power Purchase Agreements (PPAs) for on-grid plants. Additionally, its role is to negotiate the prices for and ensure the transmission, distribution and supply to customers (Lahmeyer International, 2016). Together with KPLC, REA's main task is to implement the Rural Electrification Programme. GDC's mandate is to explore geothermal energy potential and fields. This task is partially shared with Kenya's Electricity Generating Company (KenGen), which is the largest electricity generator in the country. KenGen is 70% governmentally and 30% privately owned. Other relevant actors in Kenya's electricity sector include the Kenya Nuclear Electricity Board (KNEB) and Independent Power Producers (IPPs).

Based on the new constitution of 2010 and Kenya's Vision 2030, the Energy Bill 2015 was passed (Lahmeyer International, 2016). Its role is "to consolidate the laws relating to energy, to provide for National and County Government functions in relation to energy, to provide for the establishment, powers and functions of the energy sector entities; promotion of renewable energy; exploration, recovery and commercial utilization of coal and geothermal energy; regulation of midstream and downstream petroleum activities; and the production, supply and use of all energy forms; and for connected purposes" (Kenya Ministry of Energy and Petroleum, 2015, p. 10). The Planning Team, which is supervised by the ERC and the Ministry of Energy and Petroleum (MOEP), handles the major power sector plans for future development and collaborates with other power sector topics. Despite the large share of biofuels in Kenya's primary energy supply (see next section), no entity specifically concerned with this exists.

Current status, challenges and future goals of energy system in Kenya

In 2016, Kenya's total primary energy supply equaled 25,992 ktoe (OECD/International Energy Agency, 2018b). Fig. 5 displays the shares of TPES by fuel type. The share of biofuels, primarily traditional fuels (i.e. firewood and charcoal), and waste constitute the largest share (i.e. 64.8%) of overall primary energy supply.

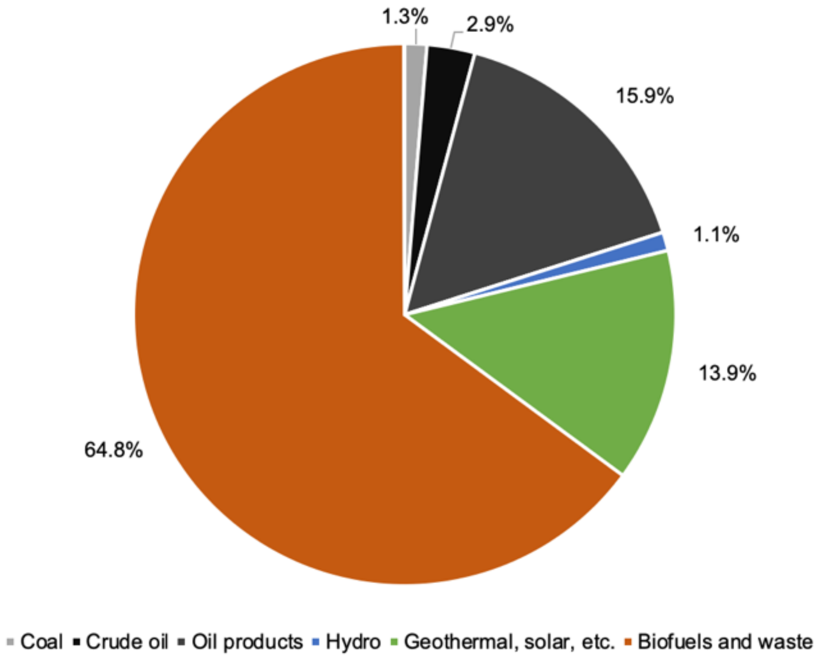

Figure 5: Shares of total primary energy supply (TPES) in Kenya

In total final consumption, biofuels and waste also account for two thirds of the total yet only 4% was electricity (OECD/International Energy Agency, 2018b). Fig. 6 shows that over 43% of electricity was produced from geothermal resources, followed by approximately 34.4% from hydropower (OECD/International Energy Agency, 2018b). In total, 8 TWh of electricity were consumed, which translates into an average electricity consumption of 0.16 MWh per person (OECD/International Energy Agency, 2018b).

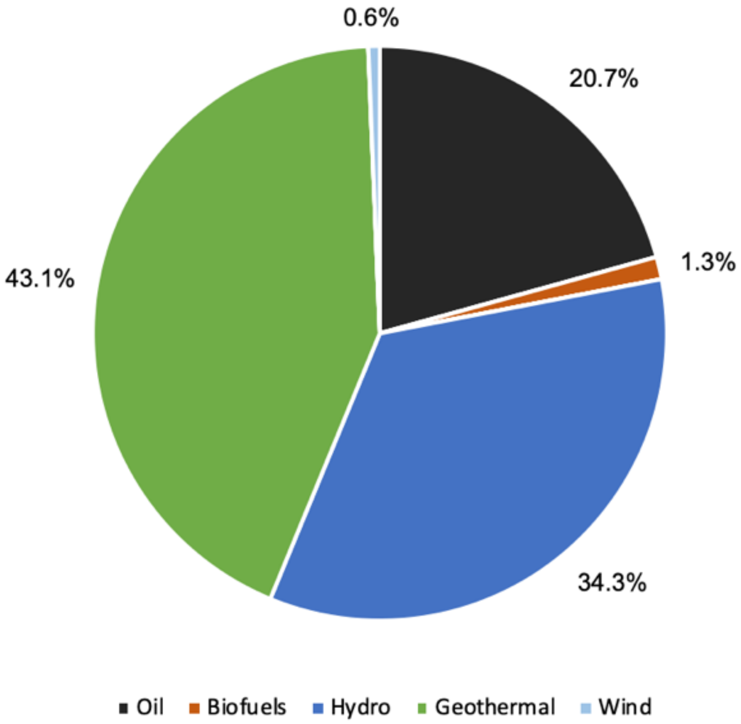

Figure 6: Shares of total electricity production by source in Kenya

A large share of TPES, final consumption as well as electricity production, is derived from renewable resources (OECD/International Energy Agency, 2018b). However, the large share of biofuels and waste in TPES stems from the fact that many households still rely on traditional fuels (i.e. firewood and charcoal) for cooking, which is associated with a number of issues such as emissions that negatively affect public health and the environment (Bailis, Ezzati, & Kammen, 2005; Mohammed, Mustafa, & Bashir, 2013; Ogola, Davidsdottir, & Birgir, 2011; Smith et al., 2000). Additionally to the effects on women's health, the collection and burning of fuelwood can contribute to deforestation and unsustainable use of biomass (Modi et al., 2005; Smith et al., 2000; Tanner & Johnston, 2017). In 2016, Kenya's CO_2 emissions from fuel combustion was 32 Mt of CO_2, which amounts to 0.32 t CO_2 per person (OECD/International Energy Agency, 2018c). As emissions have risen faster than the population, both those values have grown over the last 15 years.

Kenya's current energy system has a long way to go towards sustainability apart from the share of renewable energy, as shown by Shortall and Davidsdottir (2017). Kenya is performing well when it comes to the share of renewables, not only in TPES but also for electricity production. Kenya is endowed with a large amount of renewable resources for power production including hydro, geothermal, solar and wind. Historically, hydropower has been the main source for electricity in Kenya. Due to droughts causing shortfalls, geothermal power was added for providing a stable base load (Lahmeyer International, 2016). Despite having significant solar and wind potentials, these resources are not harvested on a large scale yet but might play a role in Kenya's future energy system. So far, biofuels are only utilized to a very limited extent when assessing pathways of Kenya's energy system (Lahmeyer International, 2016).

Kenya needs to improve to move its system towards sustainability include energy access, affordability, equity, well-being, security, environmental, efficiency and economic aspects, as outlined by Shortall and Davidsdottir (2017). The main strategy of tackling the above-mentioned sustainability issues is to construct an energy system which relies on modern infrastructure and resources enabling access to electricity by all. According to the Least Cost Power Development Plan 2017-2037 the average electricity access rate was 73% and according to the Energy Progress Report it was 65% in 2016 (International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank Group, & World Health Organization, 2019; Republic of Kenya, 2018). In both cases, electricity increasing electricity access is necessary. By focusing on electricity access, well-being is simultaneously addressed as access to modern energy (especially electricity) and is correlated with several other positive impacts, such as reducing poverty, combating deforestation, and improving health (Ogola et al., 2011; Shortall & Davidsdottir, 2017; Sustainable Energy for All, 2018; Tanner & Johnston, 2017; United Nations, 2018). Further electricity capacity expansions are also needed for promoting socio-economic development, which is linked to realizing infrastructure and other industrial projects in line with the Kenya Vision 2030 (Lahmeyer International, 2016; Republic of Kenya, 2018). In 2016, most electricity (53%) was consumed by industry, followed by the residential sector (32%) and the smallest share was consumed by commercial and public services (15%) (OECD/International Energy Agency, 2018b; Republic of Kenya, 2018). Expansion of the grid and electricity production capacity does not only address the issue of electricity access but also tackles short-term security (Republic of Kenya, 2018). In terms of long-term security, Kenya currently is relying on fossil fuel imports but domestic oil reserves were recently found and might be exploited in the future (Lahmeyer International, 2016; Republic of Kenya, 2018).

In summary, the largest energy related sustainability challenges for Kenya is to ensure access to secure and high quality and affordable energy such as electricity, and at the same time limit environmental impact. As renewable resources currently and in the future are expected to account for the largest share of electricity generation in the country, realizing renewable resource dynamics is required when planning for the future.

1.3.3 Similarities and differences in the cases

As stated above, it is important to always consider the country-specific context when discussing and designing future energy pathways. Iceland and Kenya are at different stages in terms of their economic and energy system development. Hence, each country faces distinct challenges with regards to its future energy system development. Table 1 summarizes the similarities and differences between the two countries in terms of sustainable energy system development by displaying the score for each of the indicators of SDG7 (International Energy Agency et al., 2019) plus CO2 emissions (OECD/International Energy Agency, 2018c).

Table 1: Sustainable Energy System Indicators

Indicator	Unit	Iceland	Kenya
Proportion of population with access to electricity	%	100	65
Proportion of population with primary reliance on clean fuels and technology	%	100	13
Renewable energy share in the total final energy consumption	%	78	72
Share of geothermal energy in electricity mix	%	43	27
Energy intensity measured in terms of primary energy and GDP	MJ per US$ PPP 2011	14.5	7.7
CO2 emissions from fuel combustion	Mt of CO2	1.6	32
CO2 emissions from fuel combustion per person	t CO2 per person	6	0.32

While Kenya is still building up a modern energy system with a main priority to provide modern energy to all, Iceland is facing two main challenges: securing supply in a system already built and transforming sectors from one modern energy type to another to reduce environmental impact. As stated by the World Economic Forum (2015), “there is no universally applicable formula for energy reform; each country must develop and implement policies that address its own unique circumstances”. Despite the differing challenges Kenya and Iceland face, they have two important aspects in common: the reliance on renewable energy, in particular geothermal and hydro resources for electricity production, and the focus on electricity system development. In Kenya, the goal is to build up the electricity system and to transition from traditional fuels to a modern electricity-based energy system to improve access and well-being. In Iceland, the goal is to strengthen an already built electricity system to ensure equitable access and the nation’s ability to fulfill increasing demand, and to switch away from the use of fossil fuels in fisheries and transport where in the latter the aim is to switch to electrified transport. Demand increases are expected e.g. from industrial development, the possible installation of an undersea cable to the UK and electrified transport. Thereby, sustainability challenges in both countries center on the electricity system, and the reliance on renewable resources for electricity production. Like all renewable resources, geothermal and hydro resources have specific physical characteristics from which certain dynamics arise. These affect the sustainability of the energy system.

1.4 Renewable resource dynamics

As mentioned previously, renewable energy faces resource limitations. These limitations are a result of the dynamics and physical realities of renewable resources. Each renewable resource has specific features where some can be viewed as stock-based resources (e.g. geothermal or biomass) and others as flow-based (Serensen 1991; Mercure & Salas 2012; German Advisory Council on Global Change 2003; UNDP 2000; IPCC 2011). Flow-based renewables are more or less temporarily available in unlimited yet intermittent quantities. However, some harvesting technologies of flow-based renewable resources depend on scarce or critical materials, which may limit the potential of flow-based renewable energy harvesting with currently available technology (Ali et al., 2017). For stock-based renewables, the rate of use is an important aspect, because if an energy resource is harvested beyond its recovery rate, it can be, at least temporarily, depleted. In terms of climate change, renewable resources affect and are affected by climate change. As stated by the IPCC, many renewable resources are not carbon neutral (Edenhofer, Pichs Madruga, & Sokona, 2011). Furthermore, many renewable resources with the exception of geothermal energy resources, are weather and climate dependent. This means that the availability of renewable resources, including, hydro, biomass, wind and solar, and thereby, renewable energy production from those resources is affected by climate change (Fant, Adam Schlosser, & Strzepek, 2016; Hisdal et al., 2007; Pryor & Barthelmie, 2010). The characteristics of renewable energies are often only considered in a simplified manner in current energy system models, such as by externally defined limits or fixed supply curves, not endogenously accounting for resource dynamics (de Boer & van Vuuren, 2017; Lan, Malik, Lenzen, McBain, & Kanemoto, 2016; Mondal et al., 2017; Ou et al., 2018; Shafiei et al., 2014; Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2017, 2015b; Shafiei, Leaver, & Davidsdottir, 2017; Shmelev & Van Den Bergh, 2016). Recently, efforts have been made to address and represent the physical characteristics of renewable resources. Those include more accurate representation of intermittent resources (Després, Hadjsaid, Criqui, & Noirot, 2015; Després et al., 2017) and the effects of climate change on hydro resources (de Queiroz, Marangon Lima, Marangon Lima, da Silva, & Scianni, 2016; Shafiei, Davidsdottir, Leaver, Stefansson, & Asgeirsson, 2015a; Tanner & Johnston, 2017). So far, only little attention has been paid to geothermal resource dynamics in energy system models, even in countries which heavily rely on geothermal resources (e.g. (Shafiei et al., 2018; Shafiei, Leaver, et al., 2017).

1.4.1 Geothermal resource dynamics

Geothermal resources, unlike other renewable resources, can be almost depleted temporarily, if they are utilized excessively beyond their regeneration rate for electricity production (G Axelsson & Stefansson, 2003; Dayan & Ambunya, 2015). Some studies have dealt with the management of individual reservoirs and optimization of the exploitation of the reservoir from which several conclusions could be drawn. Stefansson and Axelsson (2005) found that despite the fact that larger geothermal plant developments are often viewed as more economically advantageous, the Icelandic case has shown that stepwise development, in which capacity is added in steps rather than all at once, can be more beneficial from an economic and resource perspective. As the data and experience of the development in the first steps allows for a better utilization of the resource, more stable electricity production levels and lower long-term production cost can be achieved (Stefansson & Axelsson, 2005). This increases the likelihood of sustainable use of the resource. Sustainable geothermal resource management occurs if energy production can be maintained for a long period of time (100-300 years). Once a geothermal resource has been used excessively and utilized close to depletion, in some case, geothermal regeneration can take up to a century or more (Juliusson et al., 2011). This effect occurs due to pressure drops in the geothermal reservoir (Rybach, 2007). The production capacity of a geothermal power plant depends on the reservoir capacity, which is determined by parameters such as its temperature, pressure, volume and permeability, and is influenced by the extraction rate of the geothermal fluid. The connection between geothermal resource utilization and changes in the reservoir capacity depends on the characteristics of the reservoir such as temperature and pressure and how it responds to extraction (Rybach, 2007). If the geothermal resource is utilized beyond its sustainable harvesting rate, the production level of the associated power plant decreases over time. In general, geothermal production losses can be compensated up to a certain level by drilling additional wells into the reservoir (Juliusson et al., 2011). As a result, a geothermal resource can be studied as a stock and flow system. Hence, system dynamics modelling is seen as an appropriate method for the simulation of geothermal resources.

System dynamics is a method that can be used for understanding complex systems and has been widely used in energy research and especially energy system modelling (e.g.(Ahmad & Tahar, 2014; Shafiei et al., 2018, 2014; Siegel et al., 2018; Sterman, 2000)). System dynamics encompasses qualitative tools, such as Causal Loop Diagrams (CLDs), as well as quantitative, such as differential equation-based stock-flow models. CLDs are a "qualitative diagramming language for representing feedback-driven systems" (Schaffernicht, 2010, p. 653). By mapping variables and their connections, it becomes possible to understand the structure and feedbacks of the system and to investigate its behavior and arising dynamics (Sterman, 2000). Based on the understanding gained from mapping the system, quantitative system dynamics models can be developed. Those models make structural differences between stocks and flows and allow for the incorporation of feedback between different variables (Hannon & Ruth, 1994; Sterman, 2000). Given these characteristics, system dynamics is seen as a suitable method for studying geothermal resources. On the one hand, it provides a tool (i.e. CLDs) for understanding and conceptualizing geothermal resource dynamics in the context of the broader energy system development. On the other hand, the non-linear differential equation-based modelling approach is well-suited for capturing the stock-like behavior of geothermal resources. The modelling approach is able to to capture the most important characteristics of the resource in a simplified manner. Because several system dynamics energy system models already exist (Shafiei et al., 2018; Siegel et al., 2018), using the same modelling approach for geothermal resource dynamics can support the incorporation of geothermal resource dynamics into larger system models. This then facilitates an investigation of the effects of geothermal resource dynamics arising from the feedbacks in the context of national energy systems (Paper IV and V).

1.5 Summary of methods and results

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

1.5.1 Paper I[1]

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

The insights gained during the literature review on sustainable development aspects related to energy systems and alternative economic theories, aiming to stay within planetary boundaries, motivated the first paper to develop a concept of what a sustainable energy system can look like. In order to understand what constitutes a sustainable energy system, which stays within planetary as well as social boundaries, Daly's steady state theory is applied to the energy system. Despite being a purely theoretical concept, by using a systems thinking approach, the analysis becomes more dynamic and allows for new insights in terms of gathering better understanding of the opportunities and challenges of sustainable energy system development.

In this paper, the following research questions were addressed:

- 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?

To answer those research questions, an overview is given of the relevant literature of sustainable development related to energy systems. First, the biophysical limitations are introduced. This covers the source (i.e. availability of resources) and sink (e.g. climate change) limits for fossil as well as renewable energies. Second, the link between socio-economic development aspects (i.e. GDP and human development) and the energy system are briefly presented. Third, alternative economic theories dealing with planetary limits are touched upon. From this, the motive for conceptualizing and exploring a steady state energy system is established.

The tool used for conceptualizing and enabling a dynamic analysis of a steady state energy system is called Causal Loop Diagrams (CLDs). This tool from the field of system dynamics allows the depiction of the causal links and feedbacks among variables, from which the

1 The main role of the doctoral student (Nathalie Spittler) in this paper was to carry out the conceptualization of the Steady State of Energy and conduct the related research. Ganna Gladkykh's main role was to conceptualize the leverage points in the latter part of the paper. Professors Brynhildur Davíðsdóttir and Arnaud Diemer guided the doctoral student and Ganna Gladkykh during the research activities and writing process.

system's dynamics arise. This, in connection with Donella Meadow's Leverage Points approach, facilitates the identification of the implications of the steady state of energy for sustainable energy system development, including challenges and opportunities.

The conceptualization of the steady state of energy system departs from Daly's steady state theory and what he refers to as ultimate efficiency, which is often seen as one of the main solutions for achieving a sustainable energy system. Ultimate resource efficiency is defined as minimizing the service-throughput-ratio. This equation represents the basis for a first simple CLD, which is expanded and transformed into a bigger and more detailed CLD of a steady state energy system. The main balancing and reinforcing feedbacks of such a system are uncovered. A steady/sustainable energy system development would need to ensure that the service-throughput-stock relationship stays within biophysical boundaries, by keeping it at a constant or overall decreasing level. From the analysis it can be found that efficiency increase, one of the central elements often addressed in the steady state and sustainable energy system debate, has a rather limited leverage. Other leverages on the national and global level are analyzed and contrasted with current energy policies.

The analysis made it possible to better understand the sustainability challenges of the energy system in the short- and long-term and to rank the identified leverages for achieving a more sustainable energy system. Leverages considered to have a higher impact are technological transfer, shifting to high quality energy resources, energy sufficiency and energy justice. Among the leverages of lower impact are energy efficiency, shifting to renewable energy sources, pollution and waste material reduction.

1.5.2 Paper II[2]

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

Building on the latest research on sustainability relevant aspects of the energy system and international documents defining the international sustainable development agenda, a new energy paradigm can be defined. This paradigm covers economic, environmental and social aspects related to energy system development. From this a number of questions are formulated with regards to future (sustainable) energy system development. As energy system models represent one of the main tools for understanding and designing energy system development, the paper investigates in what way those questions are addressed and answered in current energy system models, which is connected to decision-making.

The research questions of this paper are the following:

- How is the new energy paradigm defined?

2 The main role of the doctoral student (Nathalie Spittler) in this paper was to carry out the conceptual framework analysis to define the current energy paradigm, analyze bottom-up and hybrid models. Ganna Gladkykh's main role was to define model categories based on the investigation of model reviews and carry out model analysis of top-down and other models. Professors Brynhildur Davíðsdóttir and Arnaud Diemer guided the doctoral student and Ganna Gladkykh during the research activities and writing process.

- What are the main questions arising from the new energy paradigm?
- To what extent do existing energy system models used for decision-making answer or address the questions arising from the new energy paradigm?

This paper commences by defining the new energy paradigm following the procedure of conceptual framework analysis as laid out by Jabareen in 2009. Therefore, the reviewed literature covers a broad range of text types and disciplines. For the discussion of the role of paradigms, Kunh's theory of paradigms is discussed.

Based on the insights gained from reviewing international documents dealing with energy in the context of sustainable development and studies on energy relevant to the broader energy system, the new energy paradigm is defined, from which the following consequential aspects arise: (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; (iii) resource limitations for fossil fuels, nuclear and for renewable energies need to be accounted for. Hence, the question arising from the new energy paradigm is: "How do different energy system pathways impact the (sustainable) development of the energy system and overall (sustainable) development globally and nationally?". This question is split into 11 sub questions that are relevant for energy system models.

To assess how those questions are addressed by energy system models, a review of recent energy reviews covering a total of 55 models was carried out. Following this initial review, 13 models were reviewed in detail and categorized into: into top-down, bottom-up and hybrid models. Additionally, alternative sustainability/integrated assessment models were considered that contain a substantial energy module. It was assessed how each of the model categories addresses or answers the questions arising from the new energy paradigm and presented a detailed description about how some chosen representative models address or answer the question and related sub-questions.

Although all sub-questions are addressed by at least one type of energy modeling category and by at least one of the presented models, it does not mean that the model is able to answer that particular question. While some questions could be easily answered by the models because no extensive additional data or structure would be necessary, other questions might need to rely different approaches to receive an answer.

1.5.3 Paper III[3]

Spittler, N., Shafiei, E., Davidsdottir, B., Juliusson, E., 2019. Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs. Energy 116407. https://doi.org/10.1016/j.energy.2019.116407

[3] The main role of the doctoral student (Nathalie Spittler) in this paper was to carry out research on geothermal resource dynamics and develop the related system dynamics model. During the model building and paper writing process the doctoral student collaborated with Ehsan Shafiei, who provided support for the development of the model (especially on the economic and plant construction module) and feedback to the paper. Professor Brynhildur Davíðsdóttir guided the doctoral student during the research and modelling activities and writing process.

In order to study the possible future developments of the contribution of geothermal energy to sustainable energy system development, it is important to understand the dynamics and complexities on the supply and demand side of the energy system. In recent years, geothermal resource utilization has increased significantly. Globally, geothermal power production grew by 16% between 2010 and 2015. Geothermal resources are renewable, have relatively low emission rates and production is unrelated to weather conditions making them suitable for providing base load electricity and independent of changes in climatic conditions. Due to those characteristics, further expansion of geothermal resources is expected. However, geothermal resources, unlike other renewable resources, can be (almost) depleted if they are utilized excessively beyond their regeneration rate for electricity production.

The research questions investigated in this study are:

- How can geothermal resource dynamics be conceptualized for (national) energy system modelling?
- What are the implications (e.g. cost, resource availability) of geothermal resource dynamics for expanding geothermal electricity production?

The connection between the geothermal resource utilization and changes in the resource's availability depends on the characteristics of the reservoir. If a geothermal resource at a plant site is utilized beyond its regeneration rate, the capacity of the plant decreases significantly over time. In general, geothermal capacity losses can be compensated up to a certain level by drilling additional wells. Because of these characteristics, it has been argued that the geothermal resource can be studied as a stock and flow system.

While geothermal resources have been modelled and investigated for individual reservoirs or plants, their influence in the context of energy system modelling has not been assessed in a similar manner. Hence the model introduced in this study captures the dynamics of geothermal resources occurring during its utilization for electricity production on a system's level (i.e. national level), incorporating an economic structure, which makes it possible to connect it to an energy system's model such as the UniSyD_IS model.

The presented model follows a System Dynamics approach and consists of three main sectors: "geothermal resource dynamics", "geothermal plant construction", and "geothermal economics". In order to test the model structure, it is applied to Iceland. Four different scenarios are assessed, which vary with regards to their level of resource utilization and the consideration of the feedback from the geothermal resource dynamics to the other sectors.

The results show that including geothermal resource dynamics into the model structure makes it possible to estimate capacity installation cost as well as production cost per unit more accurately. With regards to assessing future resource availability, and therefore energy supply security, including the feedback between resource dynamics, the economic and plant construction sector, allows for an improved distribution of resource utilization between fields.

1.5.4 Paper IV[4]

Spittler, N., Davidsdottir, B., Shafiei, E., & Diemer, A. (2019). The implications of renewable resource dynamics for energy system planning : The case of geothermal and hydropower in Kenya. Energy for Sustainable Development, Submitted.

This paper is based on the understanding and findings that renewable resource dynamics, explicitly hydro and geothermal ones, can affect short- and particularly long-term energy system development. Building on the previous paper, which focused on conceptualizing and modelling geothermal resource behaviour and its connection to geothermal resource utilization for electricity production and the cost of system development, this paper investigates geothermal and hydropower resource dynamics connected to national electricity system planning. To assess the relevance of these resources' behavior in the context of a system, which is still transitioning from traditional to modern energy, an analysis of Kenya's electricity system is conducted.

The research questions explored by this paper are:

- What are the implications of renewable resource dynamics for short- and long-term (sustainable) electricity system planning?
- What synergies and trade-offs occur when considering renewable resource dynamics in the short- and long-term?
- What are the implications of renewable resource dynamics on other sustainable development goals related to energy system planning?

Kenya's government aims at transforming the country into a "newly-industrializing, middle income country providing a high quality of life to all its citizens in a clean and secure environment". In order to achieve this goal, significant developments and expansions in the energy sector need to take place. While in 2016, electricity accounted only for 4% of total final energy consumption, ambitions to reach an electricity rate of 100% by 2030 will increase the importance of electricity in the country's energy mix. In 2016, almost 80% of the Kenya's current electricity production came from renewables, mainly relying on hydro (34%) and geothermal (43%) resources. Hence, understanding the dynamics of these two important resources is necessary when it comes to future electricity system planning.

The dynamics of geothermal resources arise from its stock-based nature. If geothermal resources get over-utilized they can be temporarily (almost) depleted and recovery can take up to several centuries. Hence, any utilization of the resource for electricity production affects resource availability, production capacity, unit production cost and overall system development cost. In the case of hydro resources, the dynamics are a result of climate change, which affects runoff. Thereby, it impacts on production capacity and unit production as well as system cost.

The presented demand driven bottom-up model represents the most prevalent technologies of Kenya's future electricity system (i.e. Multi Speed Diesel (MSD), Gas Turbine (GT), Hydro) Geothermal, Combined Cycle Gas Turbine (CCGT), Nuclear, Coal, large scale Wind, large

4 The main role of the doctoral student (Nathalie Spittler) in this paper was to carry out research on Kenya's energy system and develop an electricity system model for Kenya. Ehsan Shafiei and professors Brynhildur Davíðsdóttir, Arnaud Diemer and Peter Victor guided the doctoral student during the research and modelling activities and writing process.

scale PV). The decision-making and technology choice is based on a cost minimization approach. To be able to evaluate the impact of resource dynamics in different contexts, eight scenarios are run that differ in level of demand (i.e. high, low) and to what extent resource dynamics are considered (i.e. no consideration of hydro or geothermal dynamics, consideration of geothermal dynamics, consideration of hydro dynamics).

Results show that that integration of the renewable resource dynamics of hydro and geothermal for electricity generation affects electricity supply patterns as their behaviour is represented more realistically. In the long-term, more installed capacity is necessary when geothermal and hydro resource dynamics are considered because of losses in production capacity. Additional installed capacity does not translate into more production. This causes higher estimated system cost than when no resource dynamics are considered. Other parameters relevant to sustainability, such as GHG emissions, are affected by the resources' dynamics. They are especially relevant when planning for high demand growth and when looking at short- and long-term developments of the electricity system as a whole, certain parameters within it, or implications for sustainable development.

1.5.5 Paper V[5]

Spittler, N., Davidsdottir, B., Shafiei, E., Leaver, J., Stefansson, H., Asgeirsson, E. I., & Diemer, A. (2019). The role of geothermal resources in sustainable power system planning in Iceland. Renewable Energy, Submitted.

This paper explores geothermal resource dynamics for sustainable energy and transport system development in Iceland. By connecting the geothermal model to Iceland's energy and transport system model (UniSyD_IS), it investigates the effects of geothermal resource dynamics on different energy and transport system pathways in Iceland as well as the effects of different energy and transport system pathways on geothermal resource dynamics. Iceland is currently trying to achieve sustainable energy system development by reducing its emissions, especially from the transport sector. Hence, the paper focuses on understanding the relevance of geothermal resource dynamics in the context of an energy system that is currently aiming to transition from one modern fuel to another.

The research questions discussed in this paper are:

- How do geothermal resource dynamics affect sustainable energy system development on a national level?
- How do different energy system pathways influence geothermal resource development?
- What are the implications of geothermal resource dynamics for sustainable energy system development in Iceland?

Although Iceland is endowed with a large quantity of indigenous renewable resources, it faces several challenges for achieving a fully sustainable energy system remain. The challenges investigated in this paper relate to economic, environmental and resource aspects. Therefore, the geothermal resource model developed in Paper III was linked to the Icelandic energy and transport system model UniSyD_IS. By linking the two models, the supply module of

[5] The main role of the doctoral student (Nathalie Spittler) in this paper was to connect the geothermal energy model to Iceland's energy and transport system model and carry out related research. Ehsan Shafiei and professors Brynhildur Davíðsdóttir and Arnaud Diemer guided the doctoral student during the research and modelling activities and writing process.

UniSyD_IS is amended and geothermal resource dynamics replace the cost-supply curve of geothermal power. To investigate the relationship between geothermal resource dynamics and sustainable energy system development, sixteen scenarios that vary with regards to consideration of geothermal resource dynamics, rate of GDP growth and number of EVs.

Results show that geothermal resource dynamics do not alter estimated emissions but calculated unit production cost, which will probably affect electricity prices and are higher when geothermal dynamics are accounted for. In terms of production capacity, only small differences between scenarios with and without resource dynamics occur, however, it can be expected that these grow in the long-term. An aspect, previously not explored when modelling energy and transport system development, is geothermal resource potentials and availability. All scenarios with a GDP growth of larger than 2% use geothermal resources excessively, which already leads to significant drawdowns in some reservoirs.

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

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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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0301-4215/

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

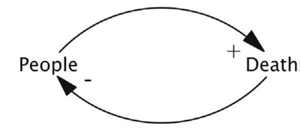

Fig. 1. Example of a CLD.

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:

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

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

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

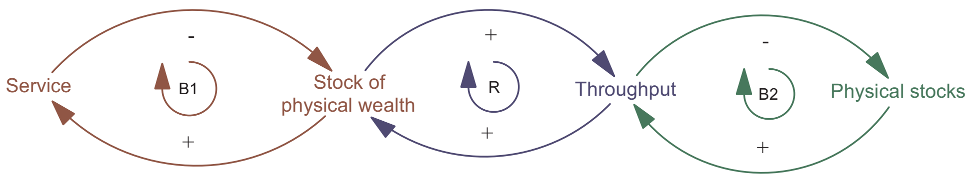

Fig. 2. CLD of Daly's equation.

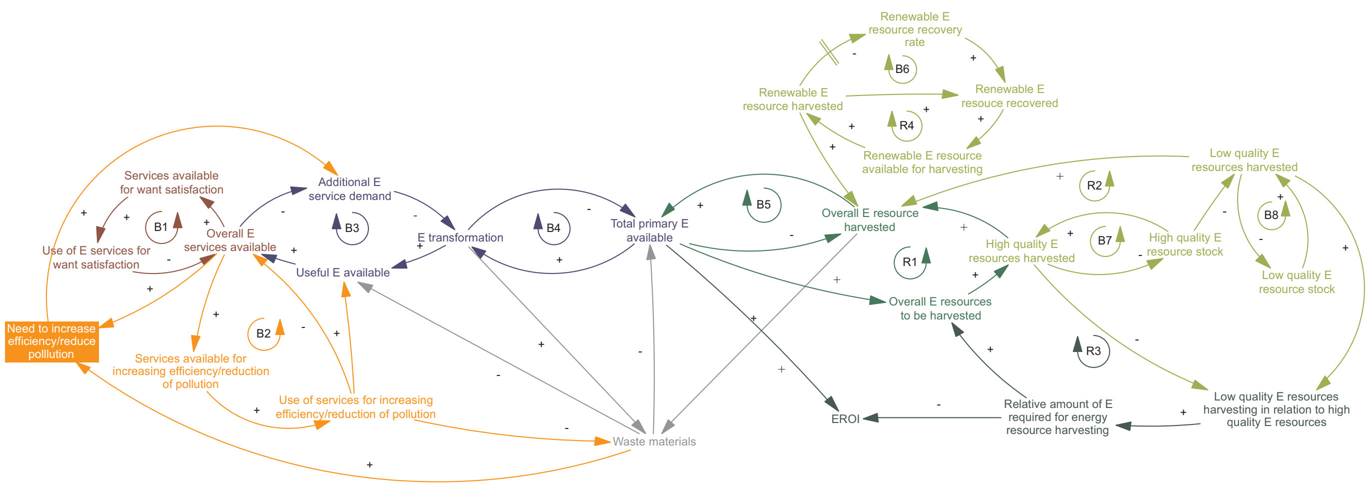

Fig. 3. CLD of steady state of energy based on Daly's equation.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4. Leverage points

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

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

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

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

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

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

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

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

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

4.1. Leverage 12. Constants, parameters, numbers

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

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

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

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

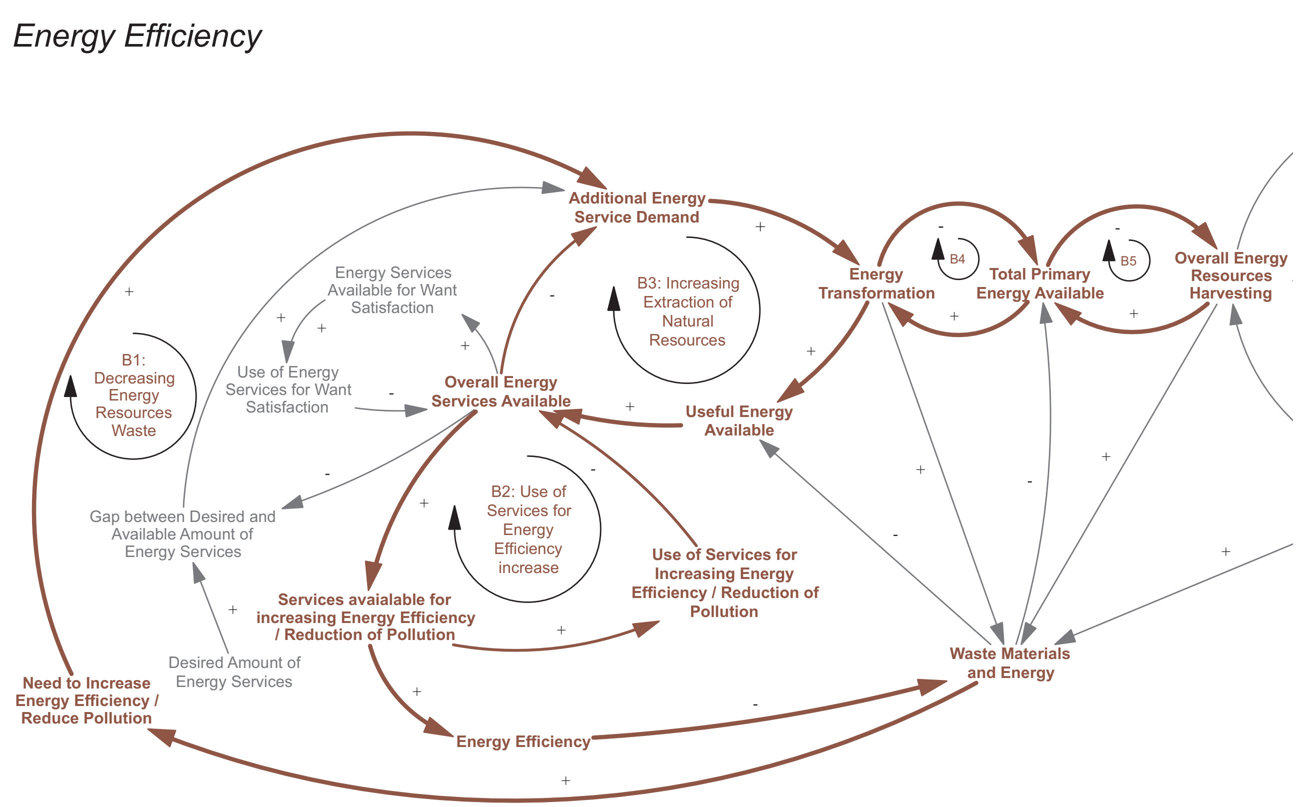

Fig. 4. Energy efficiency leverage point.

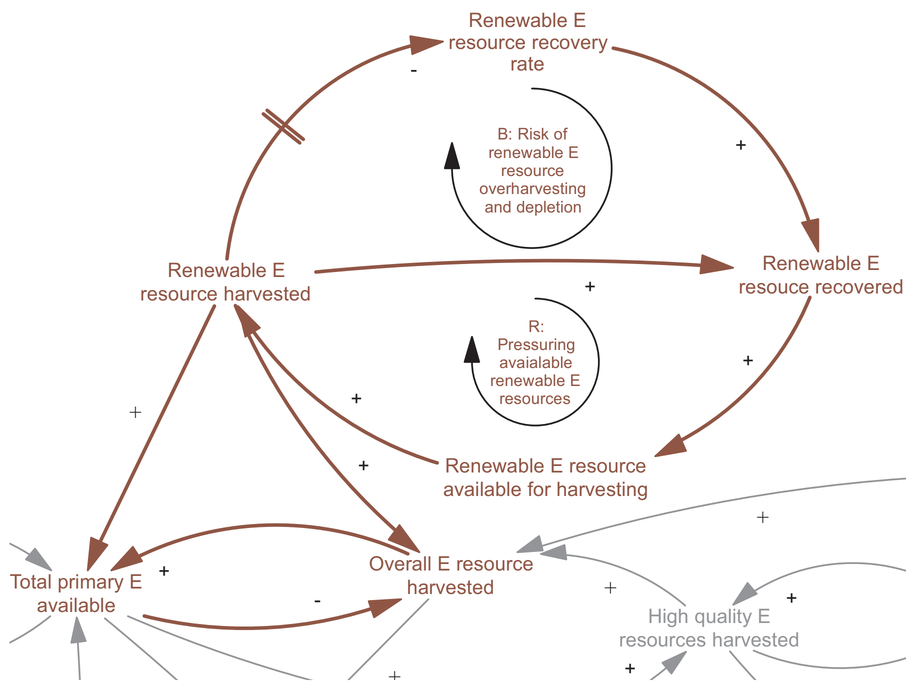

Fig. 5. Shifting to renewable energy sources leverage point.

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

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

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

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

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

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

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

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

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

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

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

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

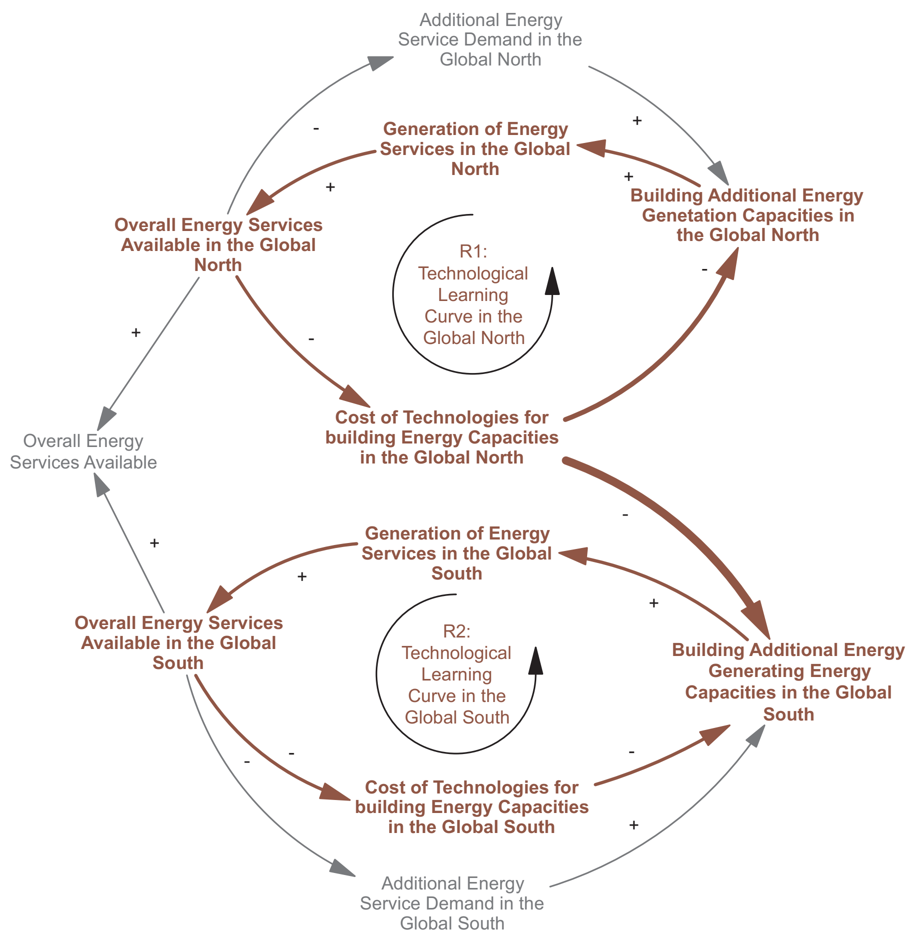

Fig. 6. Technological transfer leverage point.

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

4.5. Leverage 6. The structure of information flows

4.5.1. Technological Transfer

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

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

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

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

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

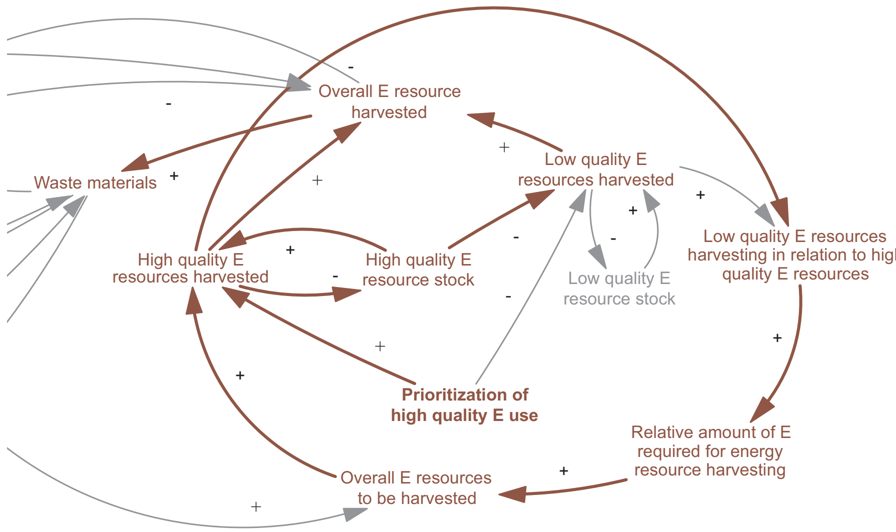

Fig. 7. Shifting to high quality energy leverage point.

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

4.6. Leverage 3. The goals of the system

4.6.1. Energy sufficiency

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

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

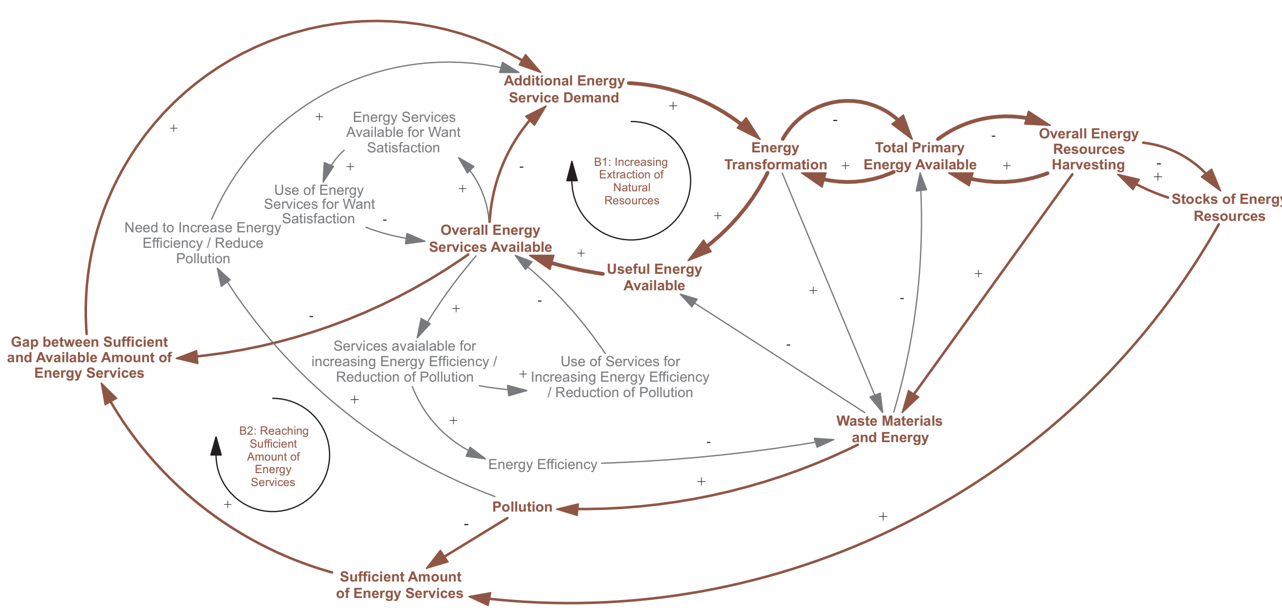

Fig. 8. Energy sufficiency leverage point.

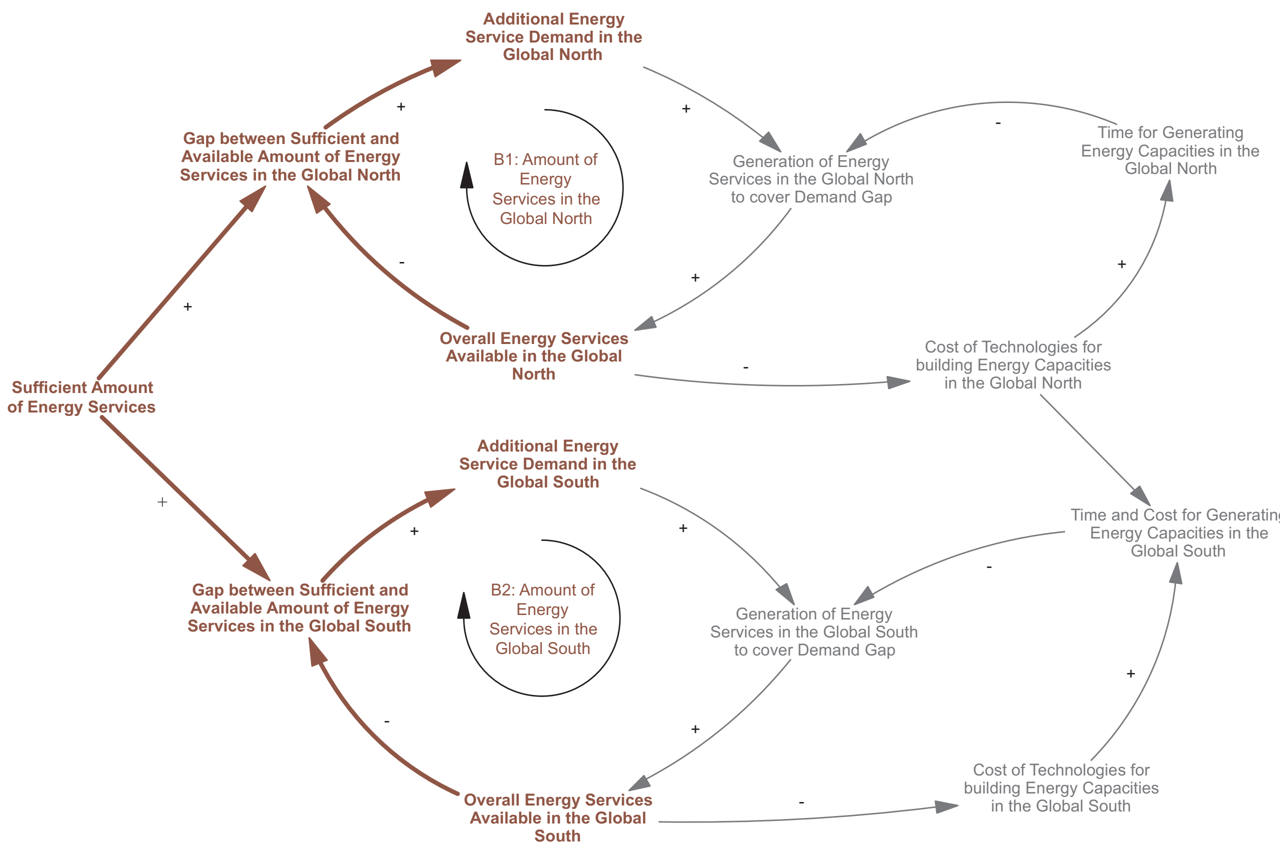

Fig. 9. Energy justice leverage point.

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

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

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

4.7.1. Energy justice

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

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

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

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

4.8. Leverage 1. The power to transcend paradigms

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

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

5. Conclusion

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

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

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

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

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

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3 Paper II: Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development

energies

Review

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

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

Keywords: energy paradigm; sustainability; energy system models

1. Introduction

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

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

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

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

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

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

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

2. Method

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

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

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

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

Bottom-up

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

Top-down

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

Hybrid

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

Other assessment models

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

3. The Current Energy Paradigm and Arising Questions

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

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

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

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

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

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

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

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

Table 2. Questions arising from the current energy paradigm.

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

4. Model Analysis

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

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

4.1. Bottom-Up Models

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

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

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

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

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

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

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

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

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

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

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

4.2. Top-Down Models

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

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

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

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

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

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

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

4.3. Hybrid Models

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

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

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

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

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

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

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

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

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

4.4. Energy in Other Assessment Models

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

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

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

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

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

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

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

5. Discussion

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

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

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

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

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

Table 3. Strengths and weaknesses of different model types.

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

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

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

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

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

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

6. Conclusions

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

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

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

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

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

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

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

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Acronyms and Abbreviations

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

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

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4 Paper III: Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs

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Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs

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ABSTRACT

If geothermal resources are utilized excessively for electricity production, the reservoir can be temporarily (almost) depleted. Regeneration of an overutilized resource can take a long time. This paper presents a System Dynamics model for geothermal power plant expansion considering the dynamics of geothermal resources on a system's level. The model consists of three main modules: resource dynamics, plant construction, and geothermal economics. Thereby, it captures the following dynamics: The geothermal field stock decreases due to utilization for electricity production and increases through natural recharging. Changes in geothermal stock, and thus in well production capacity, lead to additional well requirements to maintain electricity production levels. This influences the unit cost of electricity. To show the effect of geothermal resource dynamics on a national system's level the model is applied to Iceland's geothermal resources. Four main scenarios are simulated and compared based on the level of resource utilization, assuming high and low demand growth (i.e. 2% and 4.4%), and whether geothermal resource dynamics are incorporated or not. Sensitivity analysis is performed with respect to well capital cost and natural recharging rates for geothermal fields. The findings indicate that geothermal resource dynamics significantly increase costs because of the well drilling activities that are required to maintain production.

1. Introduction

To study the possible future contribution of geothermal energy to sustainable energy system development, it is important to understand the dynamics and complexities of the supply and demand sides of the energy system. In recent years, overall geothermal resource utilization has been growing significantly. Globally, geothermal power production grew by 16% between 2010 and 2015, and further expansion of geothermal resources is expected [1]. It is expected that in 2050 approximately 161 GW of geothermal power is installed globally, resulting around 1266 TWh of electricity produced per year [2].

However, geothermal resources, unlike other renewable resources, can be almost depleted temporarily if they are utilized far beyond their regeneration rates [3,4]. Once a geothermal resource has been utilized close to depletion, full recovery can take a century or more [5]. This is due to both pressure and temperature drops in the geothermal reservoir [6]. The connection between geothermal resource utilization and changes in the reservoir capacity depends on the characteristics of the reservoir, such as temperature, pressure, reservoir flow boundaries and other parameters [6,7]. When a geothermal resource is utilized, the production level of wells decreases over time. Geothermal production losses can be compensated by drilling additional wells [5]. The economic performance and sustainable (i.e. not exceeding natural recharge) use of geothermal resources for electricity production has been emphasized by previous research (e.g. Refs. [8–11]). Dynamics of geothermal resource utilization are usually calculated for individual reservoirs using detailed and complicated physical models (e.g. Refs. [12–15]). However, in Ref. [16] a novel and simplified approach for modelling geothermal resource behaviour, treating it as a stock and flow system, has been developed. This new

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Nomenclature

Symbols

A	plant capital cost [$/MW]
B	well capital cost [$/well]
C	reservoir well production capacity [MW]
E	well operation and maintenance cost [$/MWh]
F	levelized cost of original wells [$/MWh]
G	levelized cost of power plant [$/MWh]
h	operating hours [h/yr]
I	plant installation [MW/yr]
i	power plant index
l	lifetime of power plant and wells [yr]
M	make-up well construction per year
N	number of wells
O	original well construction per year
P	installed capacity [MW]
R	natural recharge rate [MWh/yr]
R_{max}	maximum natural recharge rate [MWh/yr]
r	discount rate
S	field stock [MWh]
S_{max}	maximum field stock [MWh]
t	time [year]
V	production cost signal [$/MWh]
w	well capacity [MW/well]
w_{max}	maximum well capacity [MW/well]
Y	plant operation and maintenance cost [$/MWh]
α	recharge coefficient [1/MWh]
β	extraction rate [MWh/yr]
γ	well productivity change [MW/yr]
ε	capacity factor [share]
$	US dollars

approach has only been applied to a specific reservoir. Thus, the impact of geothermal resource dynamics on the energy system, such as the impact on development cost or resource availability, has not been examined.

Some energy system models have dealt with renewable energy resources as constraints on their availability to evaluate the implications of exogenously defined bounds on resource potentials. For example, this was performed in a study assessing the Ethiopian power sector development using the energy system model MARKAL [17]. Also, a study carried out by Ref. [18] used this approach to identify the optimal renewable energy mix in the UK. In Ref. [19], exogenously defined limits for the potential of renewable resources for assessing low-carbon pathways in the US were applied. By endogenizing resource dynamics, energy-system optimization models encounter significant computational complexities, which prevent a proper representation and specification of resource behaviors. Enhanced modelling approaches have incorporated renewable resource patterns by means of so-called resource supply-cost curves that relate the cost of resources to cumulative utilization. This was the case in the study by Ref. [20], which deals with a representation of variable renewable energy sources in the energy system model TIMER. Other examples are the assessments of the cost of reducing greenhouse gas emissions in Iceland [21] and New Zealand [22]. For these the energy and transport system model UniSyD was used, which also employs resource supply-cost curves. In Ref. [23], the authors suggest the introduction of a new typology for energy system models based on how renewable resources are integrated, arguing that combining the advantages of energy and power system models can help to improve the modelling of renewable energies in the long-term. Many studies have investigated how to integrate renewables, especially variable renewables, into energy systems, using different approaches and levels of detail [24]. While the complexities of some renewables such as wind, solar and biomass are increasingly considered, the effects of geothermal resource dynamics have not been explicitly addressed in the energy system modelling literature. The aim of this paper is to bridge this gap by capturing the physical realities of geothermal resources. Hence it addresses the links between resource stock change, production capacity change, and total system costs to provide a sound analysis of geothermal resource utilization in the context of energy system models.

A System Dynamics model of geothermal resource utilization is introduced in this paper. The novelty stems from linking the nonlinear geothermal resource dynamics that are usually only considered for individual reservoirs, power plant construction, and geothermal economics. So far, the interplay between these aspects of geothermal development has not been explored in the literature. By connecting these components, the interaction between different geothermal fields can be analyzed from an energy system's perspective.

The model structure is applied to Iceland's geothermal resources available for electricity production. Four scenarios are run, which differ in their level of resource utilization and consideration of geothermal resource dynamics. This allows for investigating the relevance of geothermal resource dynamics for energy system modelling. The model is developed on a national level, which makes it possible to connect it to other energy system models such as the UniSyD model (e.g. Refs. [22,25]). The findings are not only relevant to the geothermal energy community but also to the energy system modelling community and policy makers.

The remaining sections describe the research steps undertaken. In section 2 the geothermal resource utilization model is explained. This includes a description of the main structures, a detailed presentation of the Stock-Flow structure and the underlying mathematical formulations of the model. Section 3 presents the assumptions and description of the Icelandic case for testing and validating the model. Section 4 introduces the scenarios for simulating the Icelandic case study. Section 5 presents and discusses the main findings of the scenario runs as well as the sensitivity analysis. Section 6 summarizes the main results and provides concluding remarks.

1.1. *Geothermal resource utilization model*

The proposed structure of the geothermal resource utilization model captures feedbacks between the resource and economic components of the system and incorporates a plant construction module. The System Dynamics approach has been used to develop the model. System dynamics is a stock-flow based modelling approach that provides advantages for modelling geothermal resource dynamics. Since it is differential equation-based modelling, it enables the combination of the stock-like behavior of the geothermal resource with feedbacks from the economic module and vice versa [26]. Additionally, it accounts for structural differences between stocks and flows, and it is appropriate for addressing delays [26].

The modelling software used was STELLA Architect [27].

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1.2. Stock-flow structure

The geothermal resource utilization model consists of three main modules: resource dynamics, plant construction, and geothermal economics. The structure and fundamental mathematics of each module are presented as follows.

1.3. Geothermal resource dynamics

The mathematical formulations for geothermal resources dynamics follows the system dynamics method presented in Ref. [26], because it is suitable for modelling the stock-like behavior of the resource as well as feedback loops between different variables. As depicted in Fig. 1, the geothermal resource dynamics module encompasses two main stocks: field stock and well capacity.

The field stock ($S_{i,t}$) defines how much energy can be extracted from an area of a specific geothermal power plant (i) at a certain point in time (t). As displayed in Fig. 1 and shown in Eq. (1), the field stock increases due to the natural recharge rate and decreases according to the extraction rate ($\beta_{i,t}$). Electricity production translates into the extraction rate, which is calculated in the power plant construction module (see section 2.1.2).

$$S_{i,t} = S_{i,t-1} + R_{i,t} - \beta_{i,t} \tag{1}$$

As the available field stock decreases, the natural recharge rate ($R_{i,t}$) increases. The natural recharge rate can be defined as an exponential function as presented in Eq. (2). It is based on available field stock, maximum stock ($S_{max,i}$), recharge coefficient (α_i), and the maximum recharge rate ($R_{max,i}$) [16].

$$R_{i,t} = R_{max,i} \cdot [exp(\alpha_i \cdot (S_{max,i} - S_{i,t})) - 1] \tag{2}$$

If the extraction rate is beyond the natural recharge rate, the available field stock declines significantly and recharge to the maximum field stock will take longer.

Well capacity ($w_{i,t}$) represents the average capacity per well in the area of a specific power plant. According to Eq. (3), it is a function of the preceding well capacity and well productivity changes ($\gamma_{i,t}$).

$$w_{i,t} = w_{i,t-1} - \gamma_{i,t} \tag{3}$$

Well capacity is at its maximum when field stock is at its maximum too. Well productivity change is related to maximum well capacity ($w_{max,i}$) and field stock changes as expressed in Eq. (4).

$$\gamma_{i,t} = w_{i,t} - w_{max,i} * (S_{i,t} / S_{max,i}) \tag{4}$$

Reinjection is a method increasingly used to artificially recharge the field to prevent declines of field stock due to overutilization [6,28]. However, due to lack of reliable data to model reinjection in this manner, this model does not consider reinjection.

1.4. Geothermal plant construction

The geothermal plant construction module, as displayed in Fig. 2, includes stocks of installed capacity as well as the build-up flows of new capacity. It distinguishes between surface (i.e. power plant infrastructure) and sub-surface (i.e. wells) elements. Additionally, the stock of remaining approved geothermal capacity influences the structure of this module.

Future electricity demand determines the future geothermal capacity that is needed. If future geothermal capacity need is higher than available installed capacity, additional plants are constructed. Based on the remaining approved geothermal capacity by field and the production cost signal, which is calculated in the geothermal economics module, the decision is made concerning which plant to construct. The constructed plant has to be at least the size of the minimum capacity possible or multiples of it, depending on the future capacity requirements. If the decision on which plant to build and its size has been made, this capacity size is subtracted from the respective remaining approved capacity. After an assumed construction time of three years, the capacity turns into installed capacity and remains there until the power plant's lifetime has been reached, then it gets replaced with new investment costs (i.e. plant replacement).

Number of wells refers to all wells per plant (original and make-up wells). Hence, number of wells ($N_{i,t}$) is a function of original well construction ($O_{i,t}$) and make-up well construction ($M_{i,t}$). The accumulation of wells is explained in Eq. (5).

$$N_{i,t} = N_{i,t-1} + O_{i,t} + M_{i,t} \tag{5}$$

Original well construction happens when plant installation takes place. As explained in Eq. (6), it is a function of plant

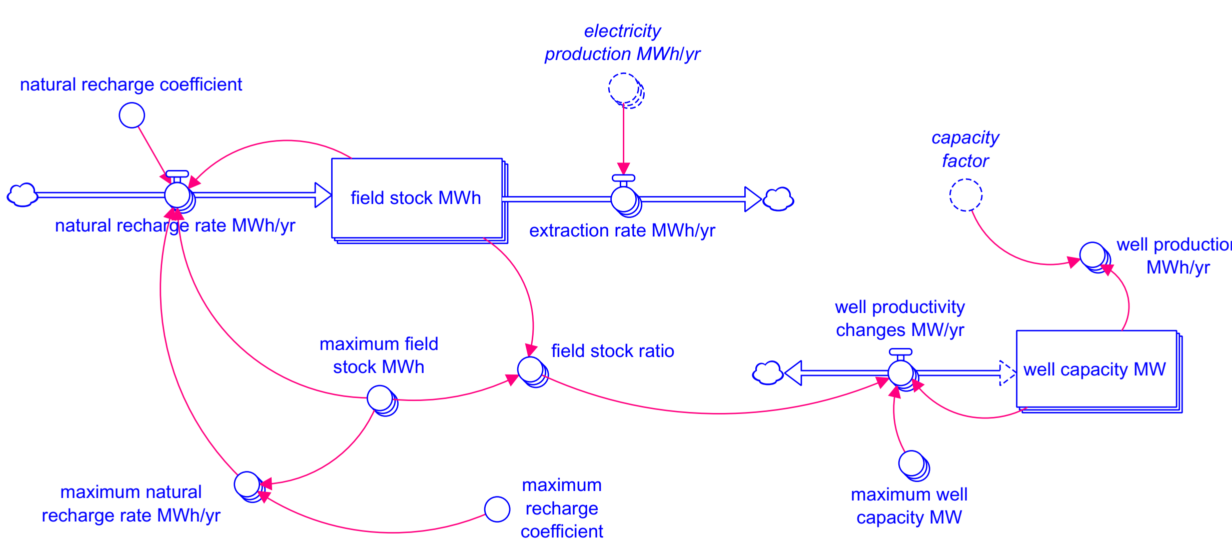

Fig. 1. Stock and flow structure of geothermal resource dynamics.

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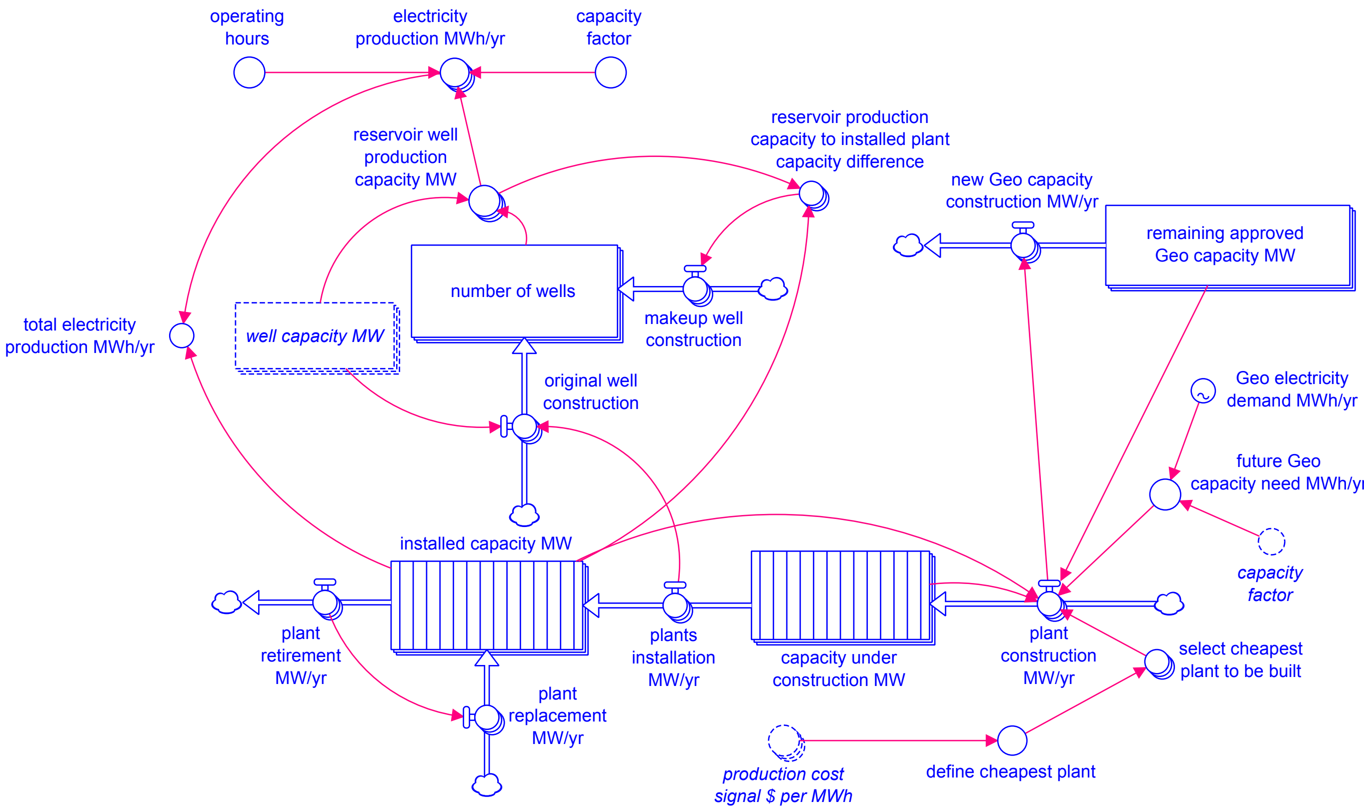

Fig. 2. Simplified stock and flow structure of geothermal plant construction.

installation ($I_{i,t}$) and well capacity ($w_{i,t}$). The ROUND function returns the nearest integer value.

$$O_{i,t} = \mathrm{ROUND}(I_{i,t} / w_{i,t}) \tag{6}$$

Unlike for original wells, make-up well construction is not connected to new plant installation but to reservoir well production capacity and total installed plant capacity. Reservoir well production capacity ($C_{i,t}$) is defined as the total number of wells times the well capacity and has to match the installed plant capacity ($P_{i,t}$). If well capacity decreases, due to the dynamics presented in Eqs. (1)–(4), reservoir well production capacity goes down. When the difference between field well production and installed plant capacities grows, make-up wells need to be constructed. Eq. (7) explains make-up well construction, which takes place to maintain the intended level of electricity production.

$$M_{i,t} = \mathrm{Max}(0\ ,\ \ \mathrm{ROUND}(P_{i,t} / w_{i,t}) - N_{i,t}) \tag{7}$$

Actual electricity production is constrained by reservoir well production capacity as well as installed capacity considering the capacity factor.

1.4.1. Geothermal economics

Fig. 3 shows the stock-flow diagram for the geothermal economics module. The costs of all plant components are calculated in this module as well as total cost and unit cost for the surface and subsurface elements of each geothermal plant. This module is connected to the other two modules. The costs of plants and wells are influenced by already installed plant and related well capacity. The production cost signal calculated in this module influences the decision on future plant development in the plant construction module.

As depicted in Fig. 3, total annual cost per plant is the sum of annualized capital costs and operation and maintenance costs. Three types of capital costs are distinguished: i) capital cost for power plants including production infrastructure and turbines, ii) capital cost for original wells that are drilled at the time of new power plant installations, and iii) capital cost for make-up wells that are drilled to compensate for well capacity losses.

Annualized capital cost for plants includes the cost of newly installed as well as replaced power plants. It is calculated based on annualized capital cost per MW times the capacity size, which is added to the already annualized cost from previous installations. This cost remains until the plant retires.

New power plants can either be installed as additional capacity in an already utilized field or in a new field. In the case of the former, reductions in cost are assumed due to the absence of a need for exploration and existing knowledge about the field, as well as there being some plant and well infrastructure already in place.

The annualized capital cost for original and make-up wells is determined based on the annualized well capital cost times the number of constructed wells. This annualized cost is added to the already annualized well cost from previous drillings. Once the lifetime of original or make-up wells has been reached they have been paid off. This means that the annualized cost of those wells is subtracted from the annualized capital cost of original or make-up wells. When the power plant's lifetime has been reached, a reinvestment to maintain already existing wells is assumed in line with the replacement of the power plant.

Although the calculations for original and make-up well construction follow the same steps, a differentiation is made between them in the model structure. This enables us to trace the effect of modelling resource dynamics, because make-up wells only get drilled when reservoir well production capacity declines. Unlike

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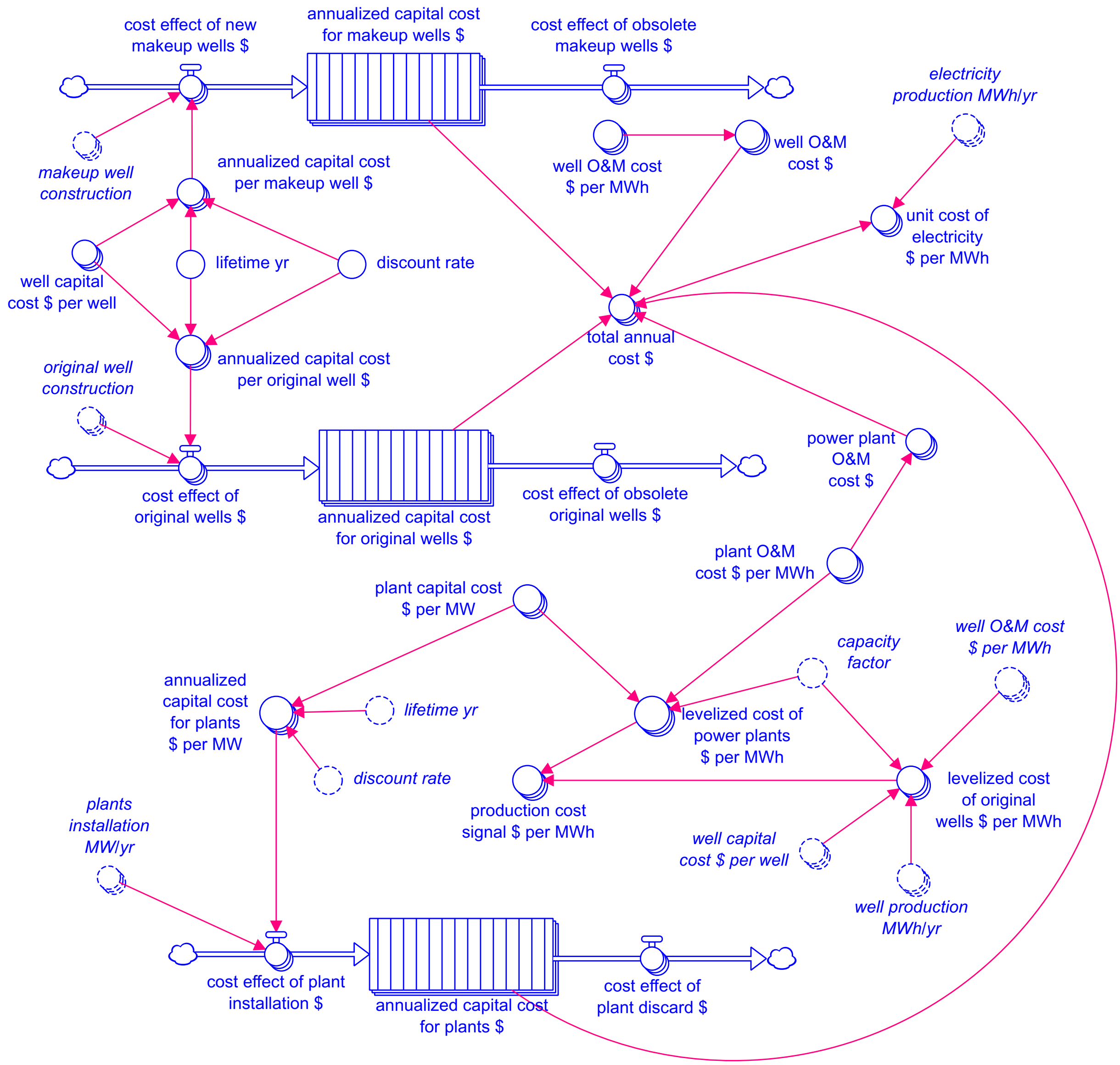

Fig. 3. Simplified stock and flow structure of geothermal economics.

power plants, wells are not discarded once their economic lifetime has been reached. However, they are economically counted as fully depreciated. Operation and maintenance costs are separately considered for power plants and wells (see Table 3).

The production cost signal, as well as the unit cost of electricity, are calculated in the geothermal economics module. While the former is an indicative value that only considers levelized cost, the latter represents actual cost, at which electricity is produced at a certain point in time. The production cost signal ($V_{i,t}$), as displayed in Eq. (10), is the sum of levelized cost of power plants ($G_{i,t}$) and levelized cost of original wells ($F_{i,t}$). As described in Eq. (8), the levelized cost of power plants is estimated based on the plant capital cost ($A_{i,t}$), plant operation and maintenance cost ($Y_{i,t}$), capacity factor ($\varepsilon_{i,t}$), discount rate (r), its lifetime (l) and the hours of operation (h). According to Eq. (9), the estimation of the levelized cost of original wells considers hours of operation (h), lifetime (l), discount rate (r), well operation and maintenance cost ($E_{i,t}$), well capital cost ($B_{i,t}$), well capacity ($w_{i,t}$), and the capacity factor ($\varepsilon_{i,t}$). Well capacity needs to be considered in the calculation because well production is dependent on well capacity, which changes over time due to resource dynamics. As the production cost signal is a sum of both levelized costs (plants and original wells), it also changes over time in fields where geothermal resources are already utilized for electricity production. Because of the short construction time, the effects of construction time on annualized capital cost has been ignored.

$$G_{i,t} = Y_{i,t} + A_{i,t} \Big/ \sum_{t=1}^{l} \frac{h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \tag{8}$$

$$F_{i,t} = E_{i,t} + B_{i,t} \Big/ \sum_{t=1}^{l} \frac{w_{i,t} \cdot h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \tag{9}$$

$$V_{i,t} = G_{i,t} + F_{i,t} \tag{10}$$

Unit cost of electricity is the actual cost, at which electricity is produced including the cost of make-up wells. Consequently, the unit cost of electricity can be higher than the production cost signal as it is composed of total annual cost (i.e. sum of the annualized plant capital cost, annualized original well capital cost, and annualized make-up well capital cost) divided by actual electricity production. The average production cost is the weighted average of unit costs of electricity production across all plants.

2. Assumptions and description of Icelandic case

The model is adapted to Icelandic geothermal resources. Different scenarios are run for a simulation period from 2015 to 2050. Globally, Iceland is among the leading countries in electric power generation from geothermal resources [29]. According to the Icelandic National Energy Authority, currently 97% of the electricity produced in Iceland either comes from geothermal (25%) or hydropower (72%) resources [30,31]. Further expansion of geothermal and hydro electricity production is planned. The Icelandic Master plan for Nature Protection and Energy Utilization currently considers seven fields available for geothermal electricity production [32]. Currently, six geothermal power plants are operating in five fields. Each field can comprise a number of power plants. The power plants are distributed between fields in the following way (plants marked with * were considered installed before or in the year 2015):

1. Krafla: A*
2. Svartsengi: B*, G
3. Hengill: C*, D*, K, I, J
4. Reykjanes: E*, H
5. Namafjall: F
6. Krysuvik: N, M, L
7. Theistareykir: O

Due to the very limited utilization of plant F in the past (3.2 MW), it has not been considered as installed capacity in the model. Therefore, F is treated as undeveloped. Due to the calculation method employed [16], it is assumed that despite plants being located in the same field, they do not draw from the same geothermal resource stock. Hence, each plant operates in isolation without influencing other reservoirs' production capacity. The reservoir area, including the influence area that a plant is operating in, is referred to as plant area in this paper. Hence the field stock, which is calculated individually for each plant, refers to the power plant and its respective area. This results in a total of 15 different field stocks, one for each plant area. The data and main assumptions are presented in the following sections.

2.1. Geothermal resource data

The most important parameters of this module, which influence the results, are maximum field stock ($S_{max,i}$), maximum well capacity ($w_{max,i}$), natural recharge coefficient (α_i), and maximum recharge rate ($R_{max,i}$). In Table 1, these parameters are presented for each plant area.

For existing power plants, the maximum stock in each area has been defined using the method described by Ref. [16]. The maximum field stock and maximum recharge rate are determined by using historical data for actual electricity production and number of wells in place. By fitting a curve for actual production based on estimated values of recharge rate, extraction rate, number of wells and maximum field stock, the aforementioned values are specified [16]. For areas that have not been utilized so far, the estimated field stocks for each area were obtained from Refs. [32,33].

Based on the values found for calibrated historic data (available for plants A, C, D), the maximum recharge rate coefficient for all plant areas is assumed to be 0.1 of the maximum field stock. The maximum recharge rate is the product of multiplying the maximum field stock with the maximum recharge rate coefficient. This means that the field would fully recharge within 75 years if it was (almost) depleted and not utilized until it has been recharged. The recharge coefficients ($\alpha_{i,t}$) presented in Table 1 have been obtained from Eq. (12). It has been derived from the exponential function in Eq. (2) based on the fact that the recharge rate reaches its maximum value ($R_{max,i}$) when the field stock ($S_{i,t}$) is completely depleted [16].

$$\alpha_i = \ln(2)/S_{max,i} \tag{12}$$

For the existing plants, for which historical data on the number of wells was obtainable, maximum well capacity has been calculated by dividing installed capacity with the initial number of wells. The maximum well capacity for those plant areas, for which no historical data was available, has been chosen based on average well capacities in Iceland [28]. For plants that were utilized before the year 2015, values for field stock, actual well capacity and

Table 1
Assumptions on key parameters in the geothermal resource dynamics module.

Power plant	Maximum field stock [TWh]	Field stock in 2015 [TWh][c]	Maximum well capacity [MW][d]	Well capacity in 2015 [MW][c]	Number of wells in 2015[c]	Recharge coefficient [1/TWh]
A	190[a]	189	4.0	3.9	16	0.0036
B	34[b]	29	5.5	4.7	16	0.0204
C	170[a]	162	6.0	5.7	21	0.0041
D	134[a]	122	9.0	8.3	37	0.0052
E	28[b]	23	6.0	5.0	20	0.0250
F	116[a]	116	10.2	10.2	0	0.0060
G	22[b]	22	6.5	6.5	0	0.0315
H	22[b]	22	6.3	6.3	0	0.0315
I	20[b]	20	6.7	6.7	0	0.0351
J	39[b]	39	6.0	6.0	0	0.0176
K	39[b]	39	5.9	5.9	0	0.0176
L	44[b]	44	6.1	6.1	0	0.0158
M	44[b]	44	5.8	5.8	0	0.0158
N	44[b]	44	7.0	7.0	0	0.0158
O	66[b]	66	6.0	6.0	0	0.0105

[a] Based on the number of wells, actual production per power plant [34–48], maximum field stock and maximum recharge rate and calibration according to the method presented in Ref. [16].
[b] Based on the estimations in the report of Evaluation of Iceland Geothermal Energy [33].
[c] Values for the year 2015 have been derived by running the simulation for the period from 1969 to 2015.
[d] Based on average well capacity in Iceland for plants where data was not available [28].

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number of wells were calibrated for the year 2015 by running the model for the period 1969–2015 (also see section 3.4).

2.2. Geothermal power plants

Future electricity demand is based on the forecast by Iceland's National Energy Authority (a more detailed description is presented in Section 4) [49]. The maximum remaining approved capacity for each of the plant areas is based on the Masterplan [32]. The capacity factor is assumed to be constant at 90%, which is based on the average of historical capacity utilization. The values for installed plant capacities [34] and approved capacities [32] in the year 2015 can be seen in Table 2.

2.3. Geothermal economics module

Due to the lack of detailed and plant specific data, cost values are assumed to be the same for all plants. The cost components displayed in Table 3 have been derived by relying on cost data presented in Ref. [50]. In order to trace the cost effects of individual plant elements, which is needed to understand the effect of decreased well capacity and make-up well drilling, it was necessary to break down the cost accordingly. Based on [51–53], the percentages for calculating the cost for wells and power plants (see Table 3) were defined in the following way: 25% for drilling, 15% for surface infrastructure, 10% for exploration, and 50% for the power plant (i.e. 25% of the total original investment cost is used for well construction and 65% for plant construction).

Once a power plant has been built in an area, the cost for exploration becomes obsolete. Other plant infrastructure that is already installed leads to a decrease in cost in a previously developed field. Hence, it is assumed that capacity additions to existing plants is 10% cheaper than building new plants in not yet utilized areas [51].

2.4. Validation

Due to a lack of historical cost data, it was not possible to

Table 2
Assumptions on key parameters in the geothermal plant construction module.

Power plant	Approved plant size [MW][a]	Installed plant capacity in 2015 [MW][b]
A	150	60
B	76	76
C	120	120
D	303	303
E	100	100
F	90	0
G	50	0
H	50	0
I	45	0
J	90	0
K	90	0
L	100	0
M	100	0
N	100	0
O	200	0

[a] Based on the approved capacities presented in the Icelandic master plan [32].
[b] Based on the data from Orkustofnun – the Icelandic Energy Authority [34].

Table 3
Assumptions used in the geothermal economics module for cost calculations.

	Investment cost[a,b]	Operation & Maintenance cost[a,b]	Economic lifetime
Power plant	2870 $/kW (new plants)	0.0114 $/kWh	30 years
Wells	7.08 M$ per well[c]	0.005 $/kWh	30 years

[a] Based on the values presented for a 100 MW power plant in Ref. [50] and distributed on percentages derived from Refs. [51–53].
[b] Based on the EUR – USD exchange rate of 1:1.24.
[c] Personal communication with Orkuveita Reykjavikur 5th of December 2017.

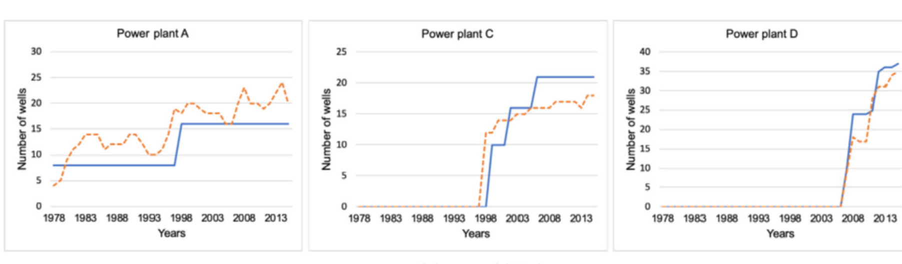

Fig. 4. Validation results for the number of wells by plant.

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simulate past plant construction. However, the number of wells and electricity production were chosen to validate the model. As historic data availability was limited, the validation for the number of wells could be carried out for three of the six existing areas, and the production per field could be validated for five of the fields.

Fig. 4 shows that the simulated results for the number of wells follow similar trends as historical data. Deviations occur because the model uses average well capacity values instead of differing values for individual wells. This, in combination with the rounding function for well construction (see Eqs. (6) and (7)), also contributes to differences between the historical and modelled number of wells. Due to a delay in data availability, the validation can only be run until 2015. Regardless, the patterns for plant D illustrate that the model is able to capture make-up well construction after the power plant has been built. This is an indication for well capacity and related field stock declines due to excessive electricity production.

As displayed in Fig. 5, the historical and modelled production patterns are in line with each other. In particular, plant E shows that the model is able to effectively reproduce the varying production patterns due to declining well capacities. The number of wells and related production levels can be influenced by a number of other factors, for example real historic demand and generation scheduling, which are beyond the scope of this analysis.

3. Scenarios

The scenarios are defined based on the level of resource utilization and whether geothermal resource dynamics are incorporated or not. The following four scenarios are run to test the model for the Icelandic case:

Low utilization: Geothermal electricity demand is assumed to grow at a yearly rate of 2% and approved capacity is according to the one defined in the Master Plan (see Table 2).

High utilization: Geothermal electricity demand is assumed to grow at a yearly rate of 4.4%, which means that the entire Icelandic electricity demand as forecasted by Ref. [49] can be satisfied through geothermal electricity by 2050. The corresponding approved capacity for each field is twice as much as the one defined in the Master Plan, which is necessary to be able to fulfil the higher demand.

The inclusion of feedback from geothermal resource dynamics

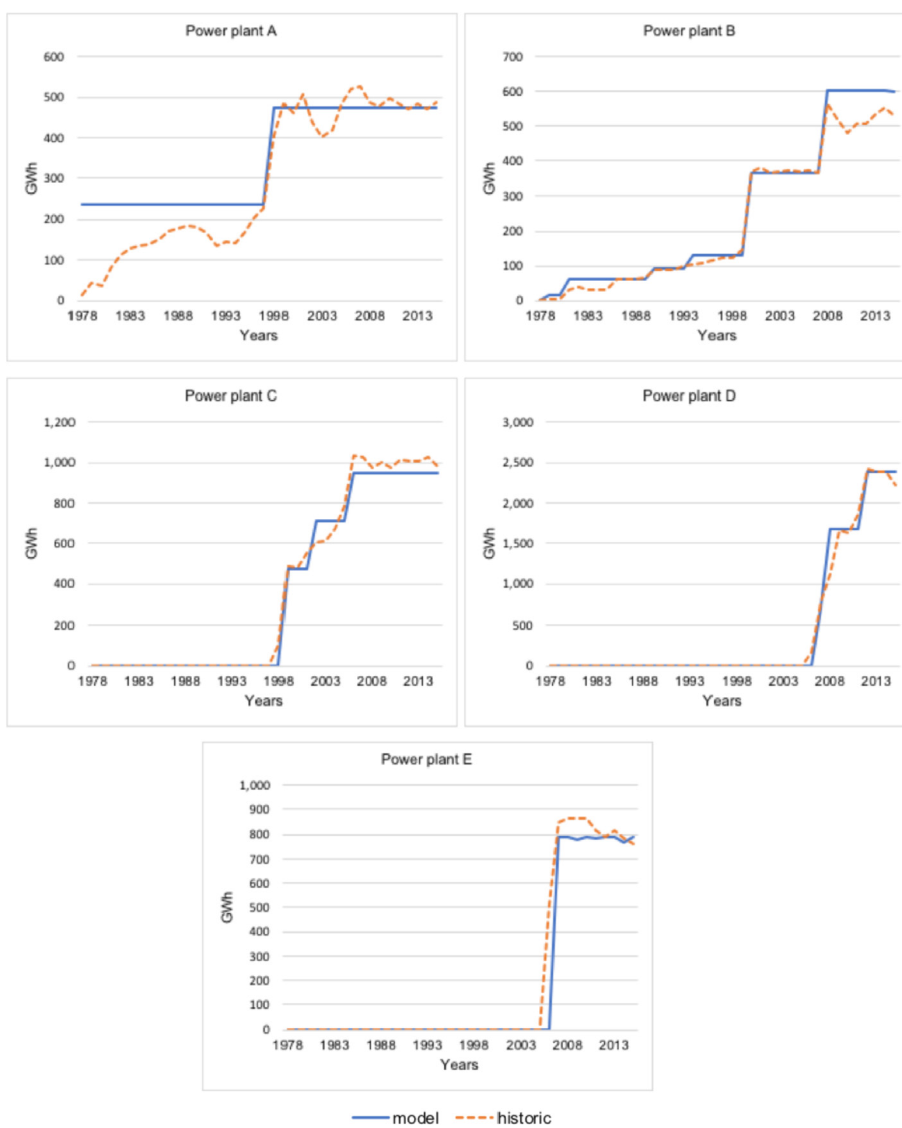

Fig. 5. Validation results for production per field.

can be distinguished between feedback dynamics and no feedback dynamics as explained below:

Feedback: When the feedback of resource dynamics is taken into account, the effects of the geothermal plant construction module on geothermal resource dynamics are considered. On the one hand, it incorporates the impact of the resource utilization (i.e. electricity production) on resource patterns (i.e. changes in field stock and well capacity). On the other hand, it accounts for the feedback from the geothermal resource dynamics module to the geothermal economics and plant construction modules. This is reflected through the effect of make-up well construction and associated changes in cost due to changes in well capacity (see section 2.1).

No feedback: When the feedback of resource dynamics is taken into account to a limited extent, only the effects of the plant construction module on the resource dynamics module is considered. This means that the utilization (i.e. electricity production) affects the resource module. Therefore, field stock and well capacity can still change, but these effects are not reflected in the other two modules. As a result, well capacity is assumed to be constant (i.e. maximum well capacity) in the plant construction and geothermal economics modules. The reason to include the feedback to the resource module, but not reversely, is to show how resources are influenced, even if its dynamics are not accounted for in the consideration of expanded production.

In summary, the combinations of cases represent four main scenarios: i) Feedback—Low utilization, ii) Feedback—High utilization, iii) No feedback—Low utilization, and iv) No feedback—High utilization. The main reason for focusing on demand in defining the scenarios is that a higher demand leads to a higher extraction rate of geothermal resources, which, in turn, influences the remaining resource potential and sustainable utilization of resources.

4. Results and discussion

In this section, results from the simulation of the four scenarios and sensitivity analysis are presented and discussed with regards to the implications of geothermal resource dynamics. Due to the effects of initial conditions and the inclusion of already planned plants as capacity under construction, the patterns are almost the same for all scenarios up to 2020. Results are presented in two ways: i) the resulting absolute values of one or several scenarios are displayed in one chart, and/or ii) percentage changes in selected results due to the consideration of resource "Feedback" or "No feedback" occurring in the "Low or High utilization" cases.

4.1. Well construction

Resource utilization leads to reductions in electricity production capacity that need to be compensated by make-up well construction. Fig. 6 shows that well capacity decline lead to more well construction in scenarios that consider feedback from geothermal resource dynamics. Additionally, it is shown that a large number of wells are constructed in the case of high resource utilization. This is in line with findings in Ref. [5], in which the optimal extraction rate of an individual reservoir was assessed by determining a simplified relationship between the resource, well construction and economic parameters. It was found that any departure from the optimal size, which would be the case in the "High utilization" scenario, leads to a higher well construction because of decreased well capacities. High resource utilization results in approximately 35% more constructed wells in the year 2050 in the "Feedback – High utilization" scenario than in the "No feedback – High utilization" scenario. The latter scenario has the same level of resource utilization as the former but ignores the effects of resource dynamics in the construction and economics modules. When these effects are ignored, no additional make-up wells need to be drilled. Hence, if new power plant capacity is added to an already exploited field, the well capacity for calculating the cost signal at any point in time equals its maximum capacity.

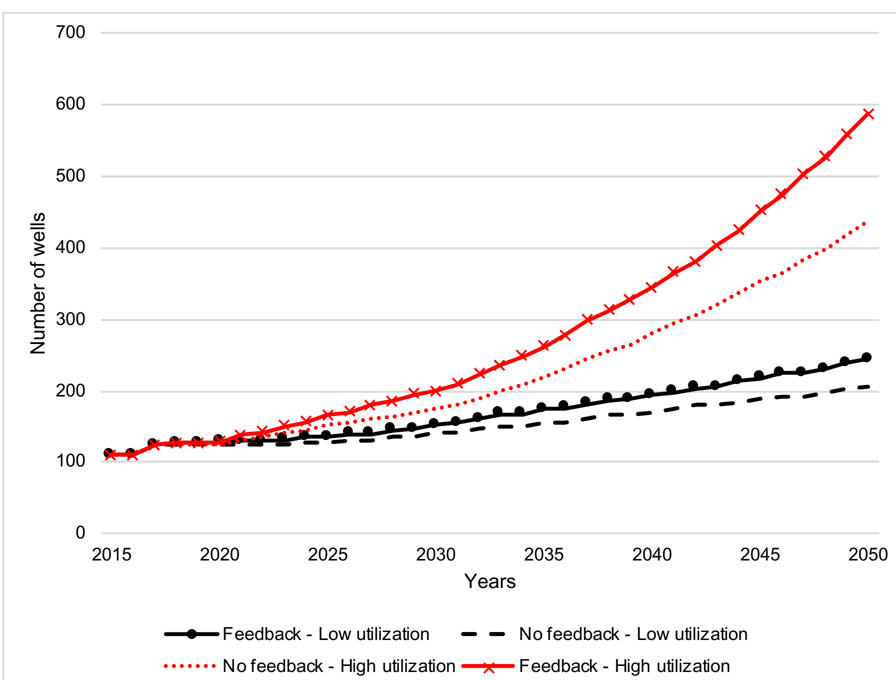

Fig. 6. Comparison of total number of wells in different scenarios.

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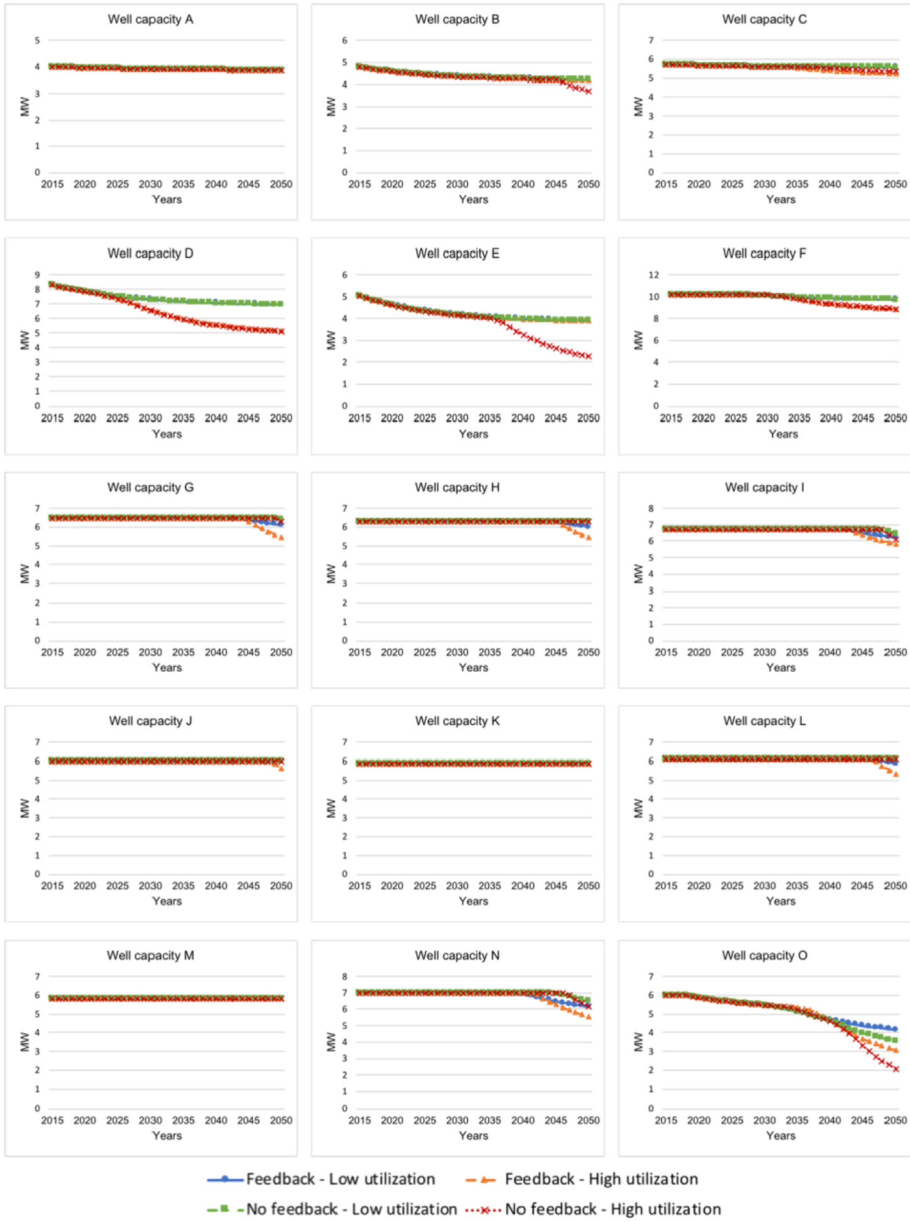

Fig. 7. Well capacity by plant and by scenario.

4.2. Well capacity

Fig. 7 draws attention to the resource dynamics of each field in each scenario by displaying well capacities of individual plants. The level of individual well capacity depends on the level of resource utilization in a specific field.

In terms of resource utilization levels, the lowest well capacities can be found in both of the “High utilization” scenarios (i.e. “Feedback—High utilization” and “No feedback — High utilization”). Regarding the effects of resource dynamics, generally in the “No feedback” scenarios the well capacities of some (i.e. B, E, O) plants are significantly lower than in the scenarios considering the feedback effect. When the feedback is considered, the capacity expansion of plant B and E are lower than in the case of “No feedback” because costs are higher for those plants. The implication of including the feedback is thus a redistribution to and earlier exploitation of other fields that are less expensive, namely, G, H, N and I. Hence, their well capacities are lowest in the scenario of “Feedback-High utilization”. This effect is not present in the case of “No feedback”. Ignoring the impact of resource dynamics on wells leads to the installation of capacity in a smaller number of fields. Thus, higher levels of exploitation and an inaccurate lower unit cost of electricity in those fields will occur. Therefore, including feedback dynamics leads to better informed economic decisions in terms of cost as well as resources in the longer term. These findings can be compared to those in Ref. [9]. The authors connected an economic decision model to a reservoir engineering model to define the optimal level of resource utilization. However, the approach in Ref. [9] was not dynamic and the modelling was not carried out on a systems level. The authors in Ref. [9] found that economic considerations would overrule considerations with regards to the sustainability of the resource. Taking a system level perspective showed that considering the resource dynamics influences decision making that leads to a more sustainable

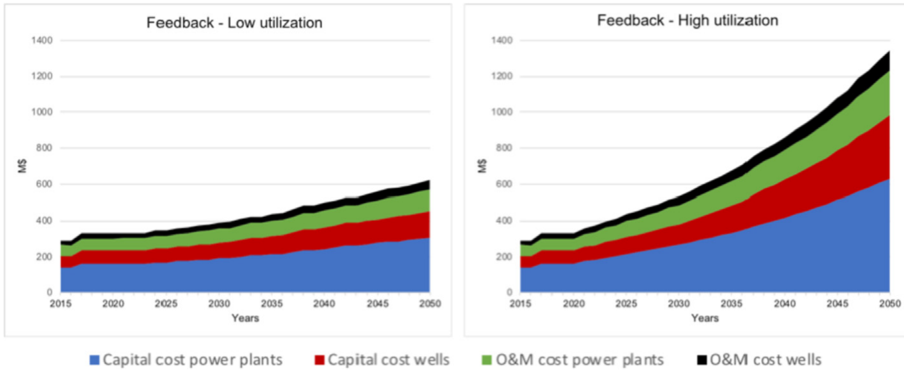

Fig. 8. Comparison of geothermal capacity expansion cost.

distribution of resource extraction to different fields. This is because the feedback between the geothermal resource dynamics and the utilization economics are assessed at a system level. Nonetheless, Fig. 7 shows that in the high demand scenarios, excessive utilization of some resources still occurs, even if less than when resource dynamics are not accounted for.

4.3. Geothermal development cost

Fig. 8 displays the total annualized cost of the geothermal electricity production system for low utilization and high utilization cases when the feedback of resource dynamics is considered.

Fig. 9 shows the changes in total cost that occur when resource dynamics are accounted for. In the case of low utilization, including resource dynamics leads to an increase of 6% in total estimated cost, which equals to M$40 in the year 2050. In the case of high utilization, the estimated cost difference due to incorporating the feedback is around 8%, equivalent to M$102 by 2050. The changes in estimated cost occur due to two reasons: i) when new capacity is added to an already developed field with already decreasing well capacity, more original wells need to be drilled, and ii) more make-up wells need to be drilled in order to sustain the intended production levels.

Fig. 10 displays the changes in unit production cost of electricity due to the effects of resource dynamics. This value refers to cost per unit at which electricity is actually produced. The differences in estimated unit cost due to resource dynamics appear higher in the case of high utilization due to larger changes in production, which are caused by well capacity reductions and delays in make-up well construction. These larger production changes mean lower production levels when resource dynamics are considered due to drawdown than when they are not. Hence the unit cost of electricity production is higher. While the changes in the unit production cost of electricity can be captured by supply-cost curves as it is for example the case in Refs. [54,55], these are based on simplified assumptions about the relationship between cumulative geothermal utilization and cost increase. The unit production cost of electricity in these studies does not rely on the geothermal resource dynamics as it is the case in the model presented in the current paper. Therefore, the unit production cost more accurately captures the effects of different levels of utilization of the resource.

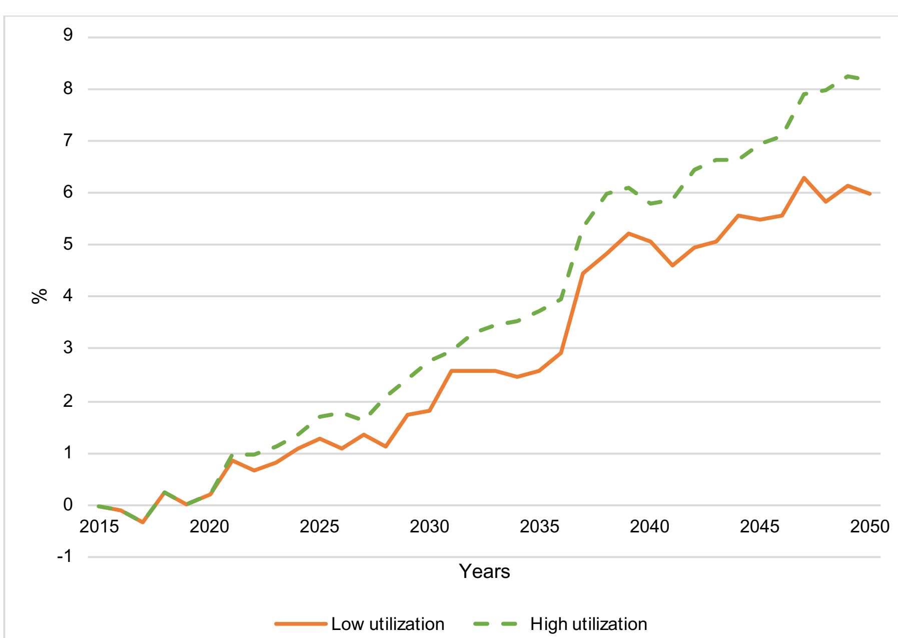

Fig. 9. Impact of resource dynamics modelling on estimated total cost for geothermal capacity expansion.

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4.4. Sensitivity analysis

Sensitivity analyses were carried out on two key parameters which influence the results significantly: i) the maximum recharge rate coefficient in the geothermal resource dynamics module, and ii) well capital cost ($B_{i,t}$) in the geothermal economics module. In both cases positive and negative percentage changes in the baseline values were evaluated. For the well capital cost, the changes range from −100% to +100%. For the maximum recharge rate an increase and decrease of up to 75% were tested. This means that at the lowest tested maximum recharge coefficient (−75%), the recharging of an (almost) depleted reservoir would take around 300 years. For the highest case (+75%), the recharge of a reservoir would take about 30 years. Despite the relation between the field stock and the natural recharge, it is still relevant to run a sensitivity analysis with regards to the maximum recharge coefficient without adjusting the field stock. This is because it tests the sensitivity to different recharging times, for which the values in the literature range from less than 100 years up to 300 years. The results for the sensitivity of changes in average unit production cost to resource dynamics (as in Fig. 10) and additional well construction are presented as they show the main effects of including feedback in each module.

4.4.1. Well capital cost change

Fig. 11 shows the sensitivity of average unit production cost changes with respect to well capital cost. Notably, the cost difference never drops to zero, even if well cost is reduced by 100% (meaning no well capital cost). The main reasons are: i) operation and maintenance cost of wells still differs, and ii) production levels are lower in the scenarios incorporating feedback dynamics (according to Fig. 6), which increases the cost per unit.

Fig. 12 displays the sensitivity of additional well requirements arising from the resource dynamics with respect to the well capital cost. The number of additional wells increases in the case of well capital cost reduction as it influences levelized cost, resulting in different plant construction choices. This is due to the fact that additional wells do not affect the actual production cost or the production cost signal. Therefore, fields that are already utilized are cheaper and seem more economic as the effect of increasing well cost is missing compared to the case of high well capital cost. Hence, fields that are already developed become further exploited, because the only limiting factor constraining exploitation of a field is the remaining approved capacity. This leads to lower field stock and results in lower well capacities. As well capacity determines the number of wells necessary, the significantly higher number of wells indicates an excessive extraction and overuse of the resource in some fields. In the scenarios that include the feedback of geothermal resource dynamics, this leads to around 27% more wells in the case of low utilization and 70% more wells in the case of high utilization compared to when the feedback is not considered.

4.5. Maximum recharge coefficient changes

Fig. 13 depicts the sensitivity of changes in average unit production cost to changes in the maximum recharge rate. The findings indicate that higher maximum recharge rates do not significantly impact changes in production cost. However, lower maximum recharge rates can increase unit production cost significantly by 2050, up to 20% in the case of low utilization and more than 27% in the case of high utilization.

In the low utilization case, sharp growth is observed in 2035. This is especially true for low maximum recharge rates. The reason is that plant replacement stimulates original well investment, without adding new production capacity.

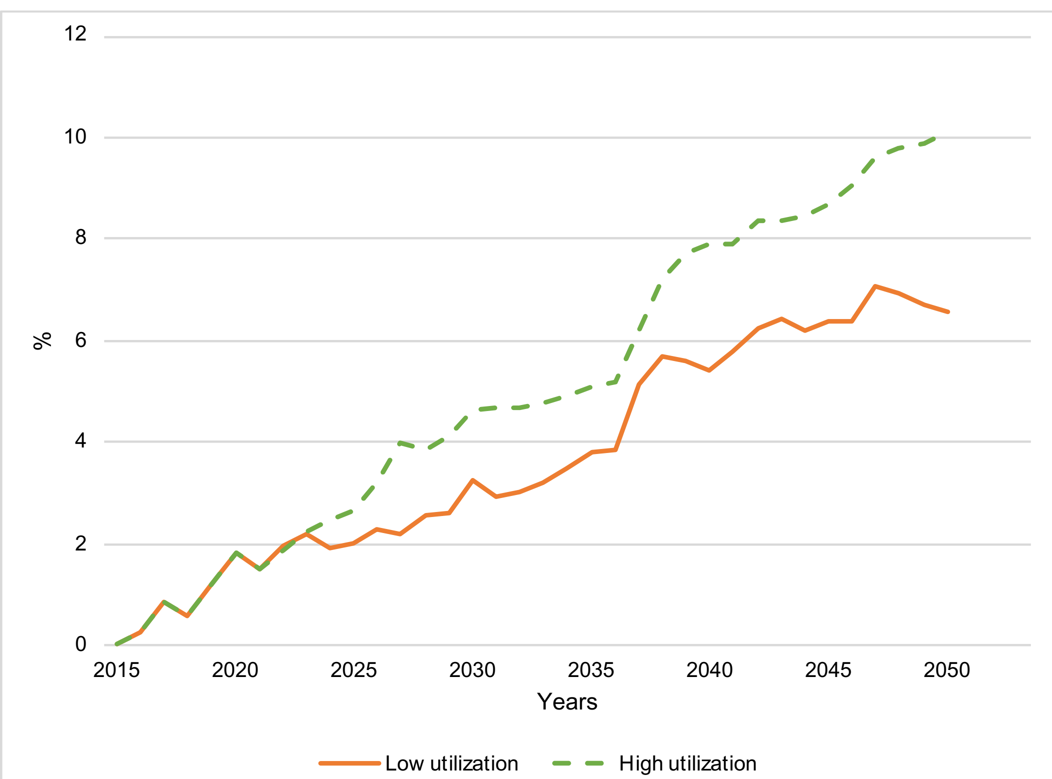

Fig. 10. Impact of resource dynamics modelling on estimated average unit production cost of geothermal electricity.

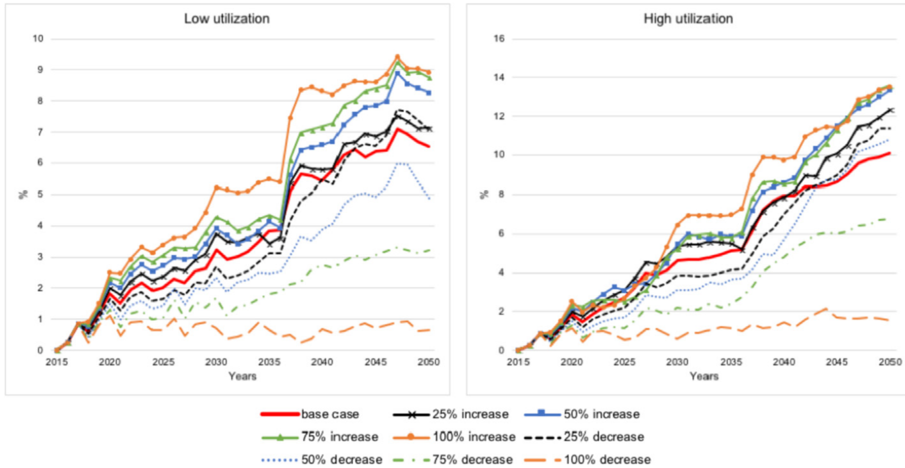

Fig. 11. Sensitivity of unit production cost changes (due to resource dynamics) with respect to well capital cost.

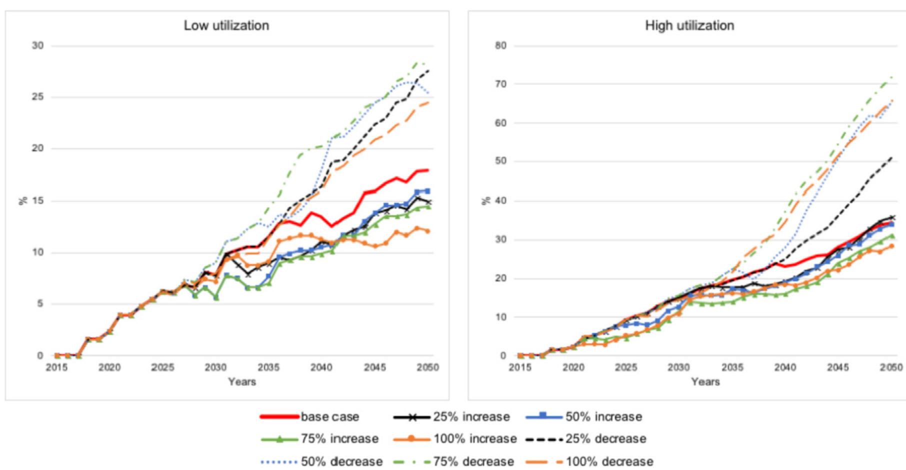

Fig. 12. Sensitivity of additional well construction (due to resource dynamics) with respect to well capital cost.

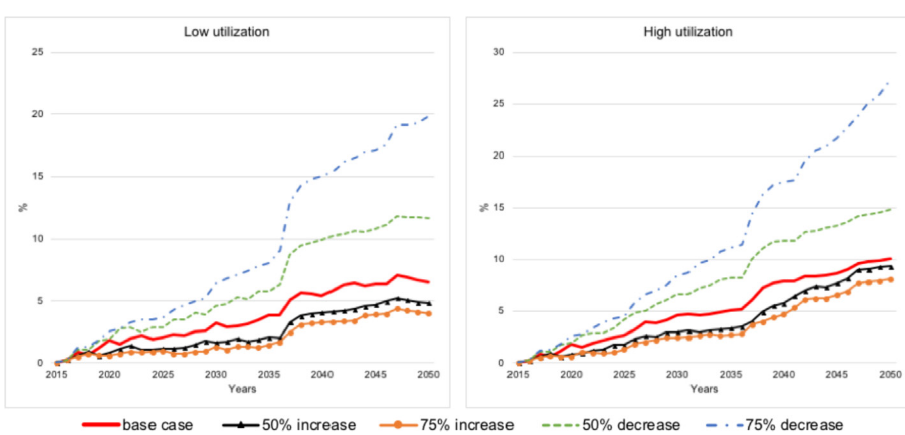

Fig. 13. Sensitivity of changes in unit production cost (due to resource dynamics) with respect to maximum recharge rate.

Fig. 14 demonstrates the sensitivity of total number of well changes with respect to R_{max}. It is evident that the sensitivity is higher for lower R_{max} values. As the number of wells is dependent on well capacity, a higher number of wells indicates that some fields may be over-utilized. Therefore, well capacity and field stock are significantly lower than in the base case.

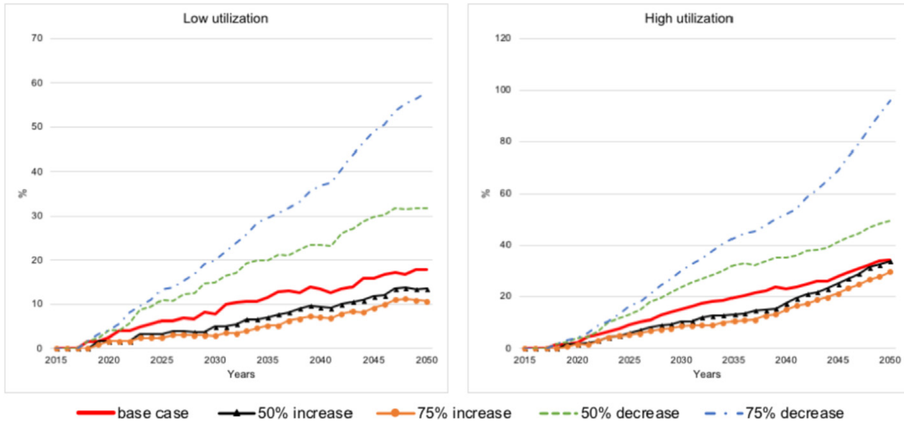

Fig. 14. Sensitivity of additional well construction (due to resource dynamics) with respect to well capital cost.

5. Conclusions

In this paper a System Dynamics model was introduced that combines geothermal resource dynamics, geothermal economics, and geothermal plant construction. It was demonstrated that applying a System Dynamics approach is useful, as it is able to represent the stock-like dynamics of the geothermal resource and feedbacks between various system components. While the same modelling approach can be taken to model other renewable resources, especially biomass, the presented equations and parameters are specific to the dynamics of geothermal resource dynamics. In the presented model the effect of electricity production on the geothermal resource and changes in the cost of electricity were captured. Applying this structure to the Icelandic case has shown that due to the more accurate representation of the dynamics of the geothermal resource, a more precise cost estimation for total as well as unit cost is possible. The results indicate that when resource dynamics are not included, the model underestimates the need for drilling makeup wells, and thus the production cost is artificially lower. This implies that excluding geothermal resource dynamics from energy system models results in greater emphasis on the utilization of geothermal resources than perhaps is warranted. Additionally, including the dynamics resulting from reinjection (i.e. artificial recharge) could further enhance the accuracy of results and should be assessed in further research.

The accuracy of results can be influenced by uncertainties associated with resource potential and resource parameters, as well as future trajectories for technology costs. The parameters assumed for the calibration of the resource behavior function may be imprecise, because real experimental data is not available. To improve the accuracy of the results, we have performed a comprehensive sensitivity analysis on the important parameters, as presented in Section 5. It was shown that despite uncertainties regarding the natural recharge rates, average unit production costs fall less significantly with a decrease in the maximum recharge coefficient than they grow with an increase in the maximum recharge coefficient of the same order. Additionally, sensitivity analysis has demonstrated that higher well capital costs do not only lead to higher cost (total system cost and unit production cost), but also to a more economic utilization of the geothermal resource, which is more sustainable in the long-term.

Additionally, results could be improved by defining a higher temporal resolution for the model to simulate the system in shorter time increments (e.g., hourly, daily, or seasonal). However, a higher temporal resolution would require more detailed data, such as power demand load curves, and mechanisms for generation scheduling (taking into account the role of other power plants such as hydro and wind) to be synchronized with a fluctuating demand. This is out of the scope of the current paper, which focuses on a new approach when presenting the dynamics of geothermal resources and their expansion in the longer term.

In this analysis, no feedback between supply and demand is considered. Including this feedback would enable an estimate of the potential of geothermal energy under specific market price scenarios. Additionally, incorporating the current model into a national energy system model would facilitate an assessment of the prospects of geothermal power and its competitiveness compared to other resources, in the short- and specifically long-term, under different demand scenarios. Therefore, it is planned to connect the presented model to the Icelandic national energy system model, in order to assess the implications of including geothermal resource dynamics for energy system development on a national scale.

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5 Paper IV: The implications of renewable resource dynamics for energy system planning: The case of geothermal and hydropower in Kenya

Implications of renewable resource dynamics for energy system planning: The case of geothermal and hydropower in Kenya

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ABSTRACT:

In 2016, almost 80% of Kenya's current electricity production came from renewables, mainly relying on hydro (34%) and geothermal (43%) resources. Both of those resources are subject to dynamics, which may affect utilization. In the case of geothermal resources excessive utilization can lead to production capacity losses. In the case of hydro resources climate change can reduce their availability. This paper investigates what the implications of the dynamics of those two renewable resources are for short- and long-term (sustainable) electricity system planning in Kenya. A demand driven bottom-up model representing the most prevalent technologies of Kenya's future electricity system is developed, including hydro and geothermal dynamics. With this a total of eight different scenarios, varying in electricity demand and which resource dynamics are considered, are run. Results show that in the long-term more installed capacity is necessary when geothermal and hydro resource dynamics are considered because of losses in production capacity. However, additional installed capacity does not translate into more production but leads to higher system and unit cost. This not only reflects the decreasing hydropower availability due to climate change but also geothermal drawdown due to unsustainable use of the resource. Renewable resource dynamics are especially relevant when planning for high demand growth.

Keywords: renewable resource dynamics; electricity system planning; Kenya; sustainable planning; System Dynamics

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Nomenclature

c	construction time [year]
ε	capacity factor [share]
A	power plant specific capital cost [$]
B	well capital cost [$/well]
c	construction time [year]
D	actual fuel cost [$/MWh]
E	well operation and maintenance cost [$/MWh]
F	levelized cost of original wells [$/well]
G	expected LCOE [$/MWh]
h	operating hours [h/year]
i	power plant
J	unit production cost [$/MWh]
K	lower limit of capacity factor [share]
l	lifetime [year]
r	discount rate [1/year]
S	expected average fuel cost [$/MWh]
t	time [year]
V	expected LCOE for geothermal [$/MWh]
w	well capacity [share]
Y	O&M cost [$/MWh]

1 Introduction

The aim of United Nations Agenda 2030 Sustainable Development Goal 7 (SDG7) is to "ensure access to affordable, reliable, sustainable, and modern energy for all" (United Nations, 2018). Thereby, it acknowledges the importance of energy in shaping global and national (sustainable) development as it is one of the key factors for achieving socio-economic development but also is one of the main drivers of climate change (Pachauri et al., 2012; Rao et al., 2014; Steffen et al., 2005; Steinberger and Roberts, 2010; United Nations, 2018). Hence, the challenge is to develop an energy system that supports socio-economic development and mitigates climate change. This is also the case for Kenya, since its government aims at transforming the country into a "newly-industrialising, middle income country providing a high quality of life to all its citizens in a clean and secure environment" as it is stated in Kenya Vision 2030 (Government of Kenya, 2018). While no specific goals for the energy system are defined, its development is a part of the foundation for being able to achieve the goals defined in the economic, political and social pillar of Kenya Vision 2030 (Gainer, 2015). Despite not being part of Kenya Vision 2030 government addresses energy related issues and defines related goals in the Least Cost Power Development Plan (e.g. (Lahmeyer International, 2016; Republic of Kenya, 2018)), which is published bi-annually.

In 2016, electricity accounted for 4% of total final energy consumption in Kenya. In 2015, 94% of urban population and 14% of rural population had access to electricity (Ogeya et al., 2018). The Kenyan government sees development of the electricity system as one of the key elements in Kenya's future development strategy. On the one hand, 100% electrification by 2030 is defined as one of the main goals in the Sustainable Energy for All – Kenya Action Agenda and is one of the key scenarios of future electricity expansion plans (Lahmeyer International, 2016; Republic of Kenya, 2018; SE4ALL, 2016). On the other hand, electricity expansion is prerequisite for a number of flagship projects in Kenya Vision, which are supposed to boost economic development (Government of the Republic of Kenya, 2007; Lahmeyer International, 2016; Republic of Kenya, 2018).

Kenya is endowed with significant renewable resources (Republic of Kenya, 2018). In 2016, almost 80% of the country's electricity production came from renewables, mainly hydro (34%) and geothermal (43%) resources (OECD/International Energy Agency, 2018). Although those renewable resources have several advantages over fossil fuels for electricity generation (e.g. less GHG emissions, locally available, and no direct fuel cost), they are subject to variations in resource availabilities, which can influence their sustainability in the long run. Yet, the impact of renewable resource dynamics on the electricity system is not fully represented in many existing power system planning models, which have been used for assessing and designing future national, regional and global energy plans (de Boer and van Vuuren, 2017a; Mondal et al., 2017; Shafiei et al., 2016; Shmelev and Van Den Bergh, 2016). Energy and electricity system models applied to Kenya dealt with assessing low carbon pathways and macro-economic effects of different scenarios (e.g. (Carvallo et al., 2017; Ogeya et al., 2018; Willenbockel et al., 2017)) or investigated what the optimal combination of on- and off-grid electrification was in Kenya (e.g.(Moksnes et al., 2017; Zeyringer et al., 2015)). While all of the studies follow the least cost optimization strategy, which is also endorsed by the Kenyan government, not all of them consider the effects on cost caused by specific characteristics of renewable resources. Some of the models are able to capture individual effects of the specificities of renewables, such as the variability of solar radiation, water or land constraints. However, geothermal resource dynamics are usually not considered explicitly in the models applied to the Kenyan case and only few consider the characteristics of hydro. Considering the current and anticipated large share of hydro and geothermal resources in total electricity generation in Kenya, it is important to capture the dynamics of those renewable resource and their impact on the sustainability of the electricity system, when planning for the future (Lahmeyer International, 2016). Hydro resources are highly climate dependent and geothermal resources can exhibit drawdown if utilized excessively for power production (Juliusson et al., 2011; Tarroja et al., 2016; Turner et al., 2017).

The focus of this paper are the effects of hydro climate change dynamics and geothermal resource utilization dynamics, which will be referred to as either resource dynamics, for both of them, or hydro/geothermal resource dynamics, when referring to them individually. The main research question of this paper is: What are the implications of hydro and geothermal resource dynamics for short- and long-term (sustainable) electricity system planning in Kenya? This question is answered by exploring the effects of hydro and geothermal resource dynamics on the government’s plans of expanding Kenya’s electricity system and the implications for sustainable development are discussed.

A demand driven least cost optimization bottom-up model representing the most prevalent technologies of the Long-term Least Cost Power Development Plan 2017 (see (Republic of Kenya, 2018)) for the Kenyan power sector is developed. To evaluate the impact of resource dynamics in different contexts, eight scenarios are run that differ in level of demand (i.e. high, medium, low) and to what extent resource dynamics are considered (i.e. no consideration of hydro or geothermal dynamics, consideration of geothermal dynamics, consideration of hydro dynamics). The outcomes for energy system output variables are analysed and implications drawn for the SDG´s.

The remaining part of this paper is structured into 5 sections. In Section 2, the background of renewable resource dynamics focusing on hydro and geothermal resources is presented. In Section 3 materials and methods of the study are provided. This includes a presentation of the electricity system model used to assess the implications of renewable resource dynamics in Kenya, data assumptions and scenario descriptions. In Section 4 the results of the modelling process are presented. In Section 5 the implications of the findings for sustainable development in the short- and long-term are discussed. Finally, Section 6 provides some concluding remarks.

2 Renewable energy resource dynamics

Renewable energy has been defined as: “a flow of energy, that is not exhausted by being used” (Serensen, 1991), including traditional energy sources and new renewables such as modern biofuels, wind, solar, small-scale hydropower, marine, and geothermal energy (UNDP, 2000). Renewable energy as defined in the IPCC report of 2011 includes “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” (IPCC, 2011). The German Advisory Council on Global Change (2003) states that renewables’ “overall potential is in principle unlimited or renewable, and is CO_2-free or -neutral” (German Advisory Council on Global Change, 2003). Together those definitions address general aspects of renewable resources and their characteristics, but at the same time mask the diverse nature of renewable energy resources. For example, not all renewable resources are CO_2-free or –neutral, they are not all inexhaustible and the rate of use can be higher than the natural replenishment. These simplifications also appear in energy modelling where the diverse nature of renewable resources tends to be overly simplified.

In a study for the assessment of global energy resource economic potentials (Mercure and Salas, 2012), energy resources are defined as either "stocks, where energy may be extracted from fixed amounts of geologically occurring materials with specific calorific contents" or "renewable flows, where energy may be extracted from continuously producing onshore or offshore surface areas with wind, solar irradiation, plant growth, river flows, waves, tides or various forms of heat flows" (Mercure and Salas, 2012). According to this definition fossil fuels and nuclear would be characterized as stocks (accumulated over time) and all renewable resources would count as flows (available intermittently), implying continuous flows of energy. Such characterization may be misleading as some renewables can be almost depleted for a period of time, if the stock they are derived from are harvested excessively, and their regeneration rate is slower than their harvesting rate (Juliusson et al., 2011). Thus, it is argued that not all renewable energy sources can be seen solely as flows (flow-based), but rather as a combination of stocks and flows. Stock-based renewable resources can build up and accumulate in a stock (e.g. biomass, geothermal, hydropower reservoir). Once sufficient stock is available, the resource can in principle be used at any time. Flow-based renewable resources are more or less temporarily available in unlimited quantities and energy can be harvested while the flow occurs, but they do not build up and accumulate (IPCC, 2011). Therefore, they cannot be stored without external storage and harvested at a later point in time. At the same time, making use of those flow-based renewable resources does not reduce their availability.

Another important aspect addressed in the literature is renewables' weather and climate dependency. The impact of climate change on renewable resources has increasingly gained attention (de Queiroz et al., 2016; Fant et al., 2016; Hisdal et al., 2007; Pryor and Barthelmie, 2010). A number of studies have investigated climate impacts on the overall energy system (Ebinger and Vergara, 2011; Schaeffer et al., 2012). The effects of climate change can be beneficial or disadvantageous depending on whether change in the climate increases or decreases the availability of a certain renewable resource (e.g. increased runoff for hydropower) or its production capacity (e.g. better growth conditions for biomass) (Hisdal et al., 2007; Schaeffer et al., 2012; Shafiei et al., 2015a; Turner et al., 2017).

Each of the renewable energy resources has specific physical characteristics, including resource potentials and intermittency. So far, many modelers have either dealt with this by defining limits for the resources' availability to assess consequences of those exogenously defined potentials (e.g. (Lan et al., 2016; Mondal et al., 2017; Ou et al., 2018; Shmelev and Van Den Bergh, 2016)) or by applying cost-supply curves that account for the cumulative use of resources (e.g. (de Boer and van Vuuren, 2017b; Shafiei et al., 2017a, 2017b, 2015b, 2014)). Efforts to represent intermittencies of flow-based renewables in energy system models have been made, which should make it possible to create more realistic scenarios on the contribution of renewables to the overall energy system (e.g. (Després et al., 2017, 2015)). Accounting for feedback from using the resource to availability is however rarely done. If geothermal resources are available in the modelled region, their contribution in future energy system scenarios is usually examined in a simplified manner by including exogenous resource constraints or cost-supply curves (e.g. (Hori et al., 2016; Lenzen et al., 2016)), excluding feedbacks or non-linear behaviors. Linking geothermal resource dynamics to resource utilization for electricity production and the implications for unit production cost and production capacity has mainly been dealt with from a technical reservoir management perspective (Axelsson, 2012; Axelsson and Stefansson, 2003; Juliusson et al., 2011; Sigurdsson et al., 1995). The geothermal stock-like characteristic, which leads to a non-linear behaviour, has not been integrated in real cases of power system planning models. Finding ways to represent the geothermal resource as a stock and thereby representing the arising patterns in a simplified manner that allows its integration into energy system models has been dealt with to a limited extent (Júlíusson and Axelsson, 2018). This paper builds on the geothermal utilization model developed in (Spittler et al., 2019).

Possible effect of climate change on renewable energy resources is another feature that commonly is excluded. Geothermal resources are climate independent, but for hydro resources, for example, including the impact of climate change implies changing assumptions of future flow rates and capacities, which are based on forecasted impacts of climate change on resource potential (e.g.(Shafiei et al., 2015a; Tanner and Johnston, 2017a)).

In conclusion, considering the stock and flow dynamics of renewable resources in future energy system planning is important if in particular the electricity supply system is largely reliant on hydro and geothermal resources in addition to biomass.

3 Material and methods

In this section the basic structure and main assumptions of the developed model are presented. Additionally, scenario parameters are defined. The System-Dynamics approach is chosen as the modelling methodology because the resources modelled collectively create a complex system, and their dynamics are characterized by non-linear feedback relationships and delays (Ford, 2009; Sterman, 2000).

3.1 Model description and main assumptions

The system dynamics model for the Kenyan on-grid electricity system consists of a detailed bottom-up structure, which encompasses power plants and economic calculations for each of the electricity generating technologies. The technologies included are: Multi Speed Diesel (MSD), Gas Turbine (GT), Hydro, Geothermal, Combined Cycle Gas Turbine (CCGT), Nuclear, Coal, Large-scale Wind and Large-scale Solar PV. The resource dynamics module captures the behaviour of geothermal resources based on the concepts and approach introduced in (Spittler et al., 2019).

The model follows a demand-driven approach, which means that forecasted electricity demand always needs to be met at the lowest possible cost. Demand is an exogenously defined parameter, which differs in the various scenarios. Associated supply is calculated on a yearly basis. Demand is split between peak- and base-load. Technologies are also distinguished between peak and base-load ones. This means selected plant types fulfil peak demand (i.e. Multi Speed Diesel, Gas Turbine, and Hydro) and others fulfil the base-load demand (Geothermal, Hydro, Combined Cycle Gas Turbine, Nuclear, Coal, large scale Wind, large scale PV) as defined in (Lahmeyer International, 2016). Because of a limited contribution of biomass resources to electricity generation, they are not considered in this study (Lahmeyer International, 2016).

Fig. 1 displays the basic structure of the model. It consists of three main modules (Power plants, Economics and Resource dynamics), and a decision-making algorithm, which are explained in the following sections. The arrows in Fig. 1 show the flow of information between the different modules.

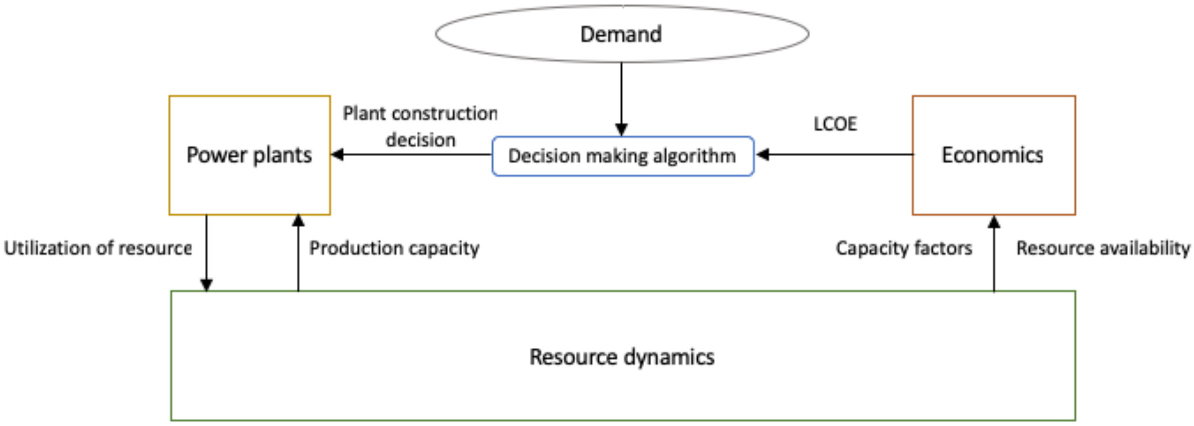

Figure 1: Kenya electricity model structure

3.1.1 Power plant and economics modules

The main decision variables, i.e. levelized cost of energy (expected LCOE) and available capacity are estimated in the power plant and economic modules. Their structure is based on the one presented in (Spittler et al., 2019). Cost calculations are the same for all power plants except for the geothermal plant. This is because plant and well costs are calculated separately and the resource dynamics influence cost calculation of the latter (Spittler et al., 2019).

The two main cost components in this module (i) expected LCOE and (ii) unit cost of electricity, are calculated for each plant individually. Based on expected LCOE, the model choses the cheapest technology to be built (see section 3.1.4 Decision making algorithm for plant construction). As displayed in Eq. 1, expected LCOE ($G_{i,t}$) is a function of the power plant specific capital cost ($A_{i,t}$), plant operation and maintenance cost ($Y_{i,t}$), expected average fuel cost ($S_{i,t}$) over the plant's lifetime (l), capacity factor ($\varepsilon_{i,t}$), discount rate (r), and hours of operation (h). Due to exogenous technological learning PV and wind power capital costs decrease over time, hence the expected LCOEs also decline. Storage technologies are not modelled as they are not considered in Kenya's Least Cost Power Development Plan (Lahmeyer International, 2016).

$$G_{i,t} = S_{i,t} + Y_{i,t} + A_{i,t} / \sum_{t=1}^{l} \frac{h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \qquad (1)$$

In the case of hydro- and geothermal power the resource dynamics influence the expected LCOE of each plant (see section 3.1.2 for Geothermal dynamics and 3.1.3 for Hydro resource dynamics).

Unlike expected LCOE, the unit cost of electricity $(J_{i,t})$ reflects the actual cost at which electricity is produced once plant capacity has been installed. The general calculation for the unit cost of electricity is displayed in Eq. 2:

$$J_{i,t} = D_{i,t} + Y_{i,t} + A_{i,t} / \sum_{t=1}^{l} \frac{h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \quad (2)$$

For nuclear plants and power plants relying on fossil fuels, the unit cost of electricity differs from the expected LCOE because actual fuel prices $(D_{i,t})$ in a certain year (at time t) are used for its calculation (based on predicted fuel cost in (Lahmeyer International, 2016)) instead of expected average fuel cost over the power plant's life time. In the case of geothermal and hydropower plants, unit costs differ when resource dynamics are considered. This is because resource dynamics influence actual production (see section 3.1.2 and 3.1.3), due to changed capacity factors of hydropower and changed capacity factors of geothermal wells (Spittler et al., 2019).

Detailed assumptions about the parameters for cost calculations for all technologies can be found in the Annex.

The structure of the power plant module is the same for all technologies but an additional module for wells is added in the case of geothermal power plants. The two main stocks in this sector are available capacity and installed capacity. Based on (Lahmeyer International, 2016), existing plants are represented by installed capacity and planned plants are counted as capacity under construction. Available capacity refers to remaining capacity that is still possible to be installed. For fossil fuel plants this capacity is in theory unlimited. For renewable resources (stock- and flow-based), this available capacity is constrained for each plant site (see Annex). Once the decision to construct new capacity (see section 3.1.4) has been made, it becomes installed capacity after the construction time has passed. Both capacity under construction and installed capacity are considered as available capacity for the future. The installed capacity times the capacity factor determines electricity production. The capacity factor is assumed to be constant for all technologies except for geothermal and hydro power. Once the economic lifetime of a certain plant has been reached, this capacity is retired or reinvested in, depending on relative costs.

3.1.2 Geothermal resource utilization dynamics

The causal loop diagram (CLD) presented in Fig. 2 depicts the main feedback loops related to geothermal resource utilization for electricity production. Arrows labelled with a “+” mean that cause and effect behave in the same direction (e.g. more original well construction leads to more wells) and arrows labelled with a “–“ indicate that cause and effect move in opposite directions (e.g. the higher the well capacity the less original well construction). A detailed description of the geothermal resource dynamics are discussed in (Spittler et al., 2019). The colour of the lines was chosen to distinguish the loops. The dashed lines refer to connections not represented in some of the scenarios as discussed in section 3.2 Scenario description. The dotted blue lines that are not part of any causal loops in this structure represent important causal links of the resource dynamics to the cost of electricity production.

Geothermal resource dynamics are modelled for each individual geothermal power plant. Each geothermal field stock is reduced through electricity production and grows through natural recharge. Changes in this stock lead to changes in production capacity, which affects the level of well construction and unit production cost (Spittler et al., 2019). The five main balancing loops driving system behaviour are explained in more detail below:

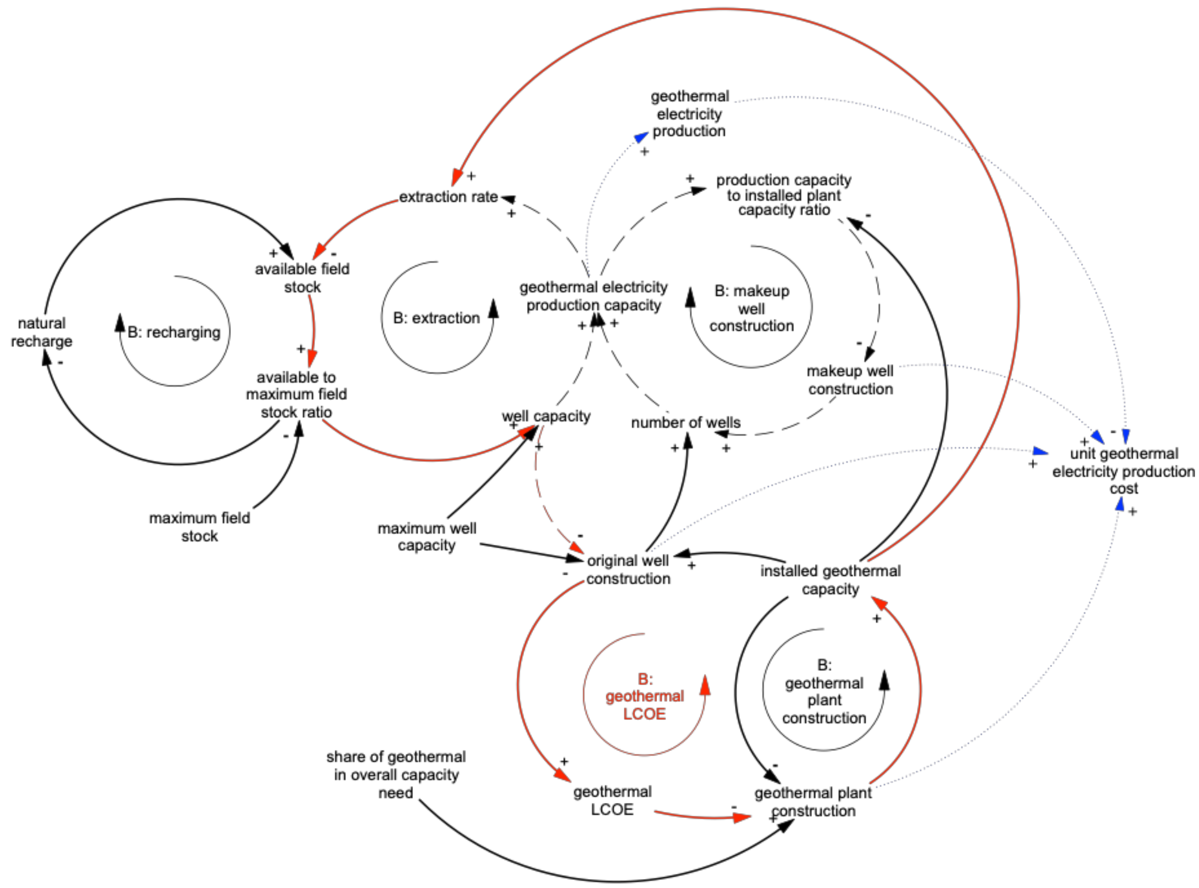

Figure 2: Main feedback loops of the geothermal resource dynamics for electricity production

- ***Geothermal plant construction***

New geothermal plant construction is driven by the share of geothermal capacity in overall capacity needed (see section 3.1.4) to meet the exogenously defined future electricity demand. The feedback from the economic part of the model to geothermal plant construction is represented through the geothermal expected LCOE loop as shown in Fig. 4. Installed plant capacity determines original well construction, which affects the number of wells and unit geothermal electricity production cost. (Spittler et al., 2019)

- ***Geothermal expected LCOE***

The geothermal expected LCOE loop (indicated in red colour in Fig. 4) displays the feedback between the economics of geothermal capacity build-up and the geothermal resource dynamics (Spittler et al., 2019). Increased new geothermal plant construction translates into more installed plant capacity. This leads to an increased extraction rate, which negatively impacts the field stock. A reduction in the field stock ratio (i.e. available to maximum field stock) leads to a lower well capacity ($w_{i,t}$), which means more original wells need to be constructed if at a later point in time additional new geothermal capacity is added to the field. (Spittler et al., 2019) Hence, for additional installed geothermal capacity expected LCOE in that field are higher because total expected LCOE of geothermal electricity produced is the sum of expected LCOE of power plants ($G_{i,t}$) and levelized cost of original wells ($F_{i,t}$). A higher geothermal expected LCOE negatively influences new plant construction. In an undeveloped field, the maximum field capacity determines original well capacity. Only in an already developed field, well capacity influences original well construction. Besides the explained dynamics influencing overall geothermal expected LCOE, also power plant specific capital cost ($A_{i,t}$), plant operation and maintenance cost ($Y_{i,t}$), well operation and maintenance cost ($E_{i,t}$), well capital cost ($B_{i,t}$), well capacity ($w_{i,t}$), capacity factor ($\varepsilon_{i,t}$), discount rate (r), its lifetime (l), the hours of operation (h), and construction time (c) need to be considered. Eq. 3-5 display the calculations of geothermal expected LCOE as also presented in (Spittler et al., 2019):

$$G_{i,t} = Y_{i,t} + A_{i,t} / \sum_{t=1}^{l} \frac{h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \quad (3)$$

$$F_{i,t} = E_{i,t} + B_{i,t} / \sum_{t=1}^{l} \frac{w_{i,t} \cdot h_{i,t} \cdot \varepsilon_{i,t}}{(1+r)^t} \quad (4)$$

$$V_{i,t} = G_{i,t} + F_{i,t} \quad (5)$$

Actual unit production cost differs from LCOE as geothermal drawdown causes additional well construction and reduces production capacity. A more detailed explanation can be found in (Spittler et al., 2019).

- ***Make-up well construction***

Make-up wells are those wells that get drilled in an already developed field in order to maintain production levels when production capacity decreases due to drawdown in the field. More make-up well construction leads to an increased number of wells, which again leads to larger electricity production capacity and geothermal expected LCOE. The higher the electricity production capacity, the higher will be the production to installed capacity ratio, and the less make-up well construction will be necessary. (Spittler et al., 2019) This loop is linked to the balancing loops of plant construction and extraction. The link to the geothermal plant construction loop is through the production to installed capacity ratio; the higher the installed capacity, the lower is the ratio. The link to the extraction loop is through electricity production.

- ***Extraction***

Extraction is driven by installed capacity and well production capacity. The higher the well production capacity and the installed capacity, the higher the extraction rate (i.e. electricity produced by a specific field), and the lower the available stock. The "available to maximum stock ratio" behaves in a way that the smaller that ratio, the lower is well capacity. Lower well capacity leads to less geothermal electricity production capacity, which ends in a decreased extraction rate. This balancing loop is connected to the recharging loop through the available stock and "available to maximum stock ratio" variables. (Spittler et al., 2019)

- ***Recharging***

This loop describes the balancing effect of natural recharge on the available stock, which is linked to "available to maximum stock ratio". Additionally, this ratio is determined by the exogenous parameter of maximum field stock (also see (Spittler et al., 2019))

Albeit not explicitly shown in the CLD, in combination, some loops together create a reinforcing behaviour such as the link between plant construction, make-up well construction and extraction. A possible outcome of these dynamics is that through the installation of new geothermal plant capacity and related original well construction, more extraction can occur. It, in turn reduces the field stock, which reduces well capacity and therefore limits the geothermal production capacity. However, caused by the link to make-up well construction, higher installed plant capacity (i.e. production capacity to installed plant capacity ratio) leads to additional well construction and a higher number of wells. This again allows for increased geothermal electricity production and extraction. The dynamics of these loops are ultimately linked to the unit cost of geothermal electricity production. The unit cost is lower if geothermal electricity production is higher, but it increases through well (original and make up) and plant construction.

3.1.3 Hydro climate change dynamics

The sustainability of hydropower has been assessed by several studies. For example, (Moran et al., 2018) assessed the environmental and social effects of hydropower developments in the 21st century and (Turner et al., 2017) investigated the consequences of climate change on hydropower globally. However, when modelling the future energy system for Kenya, the impacts of climate change on hydropower has only been addressed to a limited extent by (Lahmeyer International, 2016). Building on this Fig. 3 shows the two main loops that describe the utilization of hydropower for electricity generation and the role of climate change in it. Like for Fig. 2 the dashed lines refer to connections not represented in some of the scenarios as discussed in section 3.2 Scenario description and the dotted blue lines display relevant causal links of the dynamics to the cost of electricity production. The dynamics of resources are presented and modelled for each hydropower plant. A distinction is made for hydro resources that are utilized for peak (P Hydro) and those that are utilized for large base (B Hydro) load demand in the model. Hydropower that is utilized for peak demand has smaller capacity factors than base load hydropower. In general, two balancing loops are responsible for the dynamics (Ebinger and Vergara, 2011):

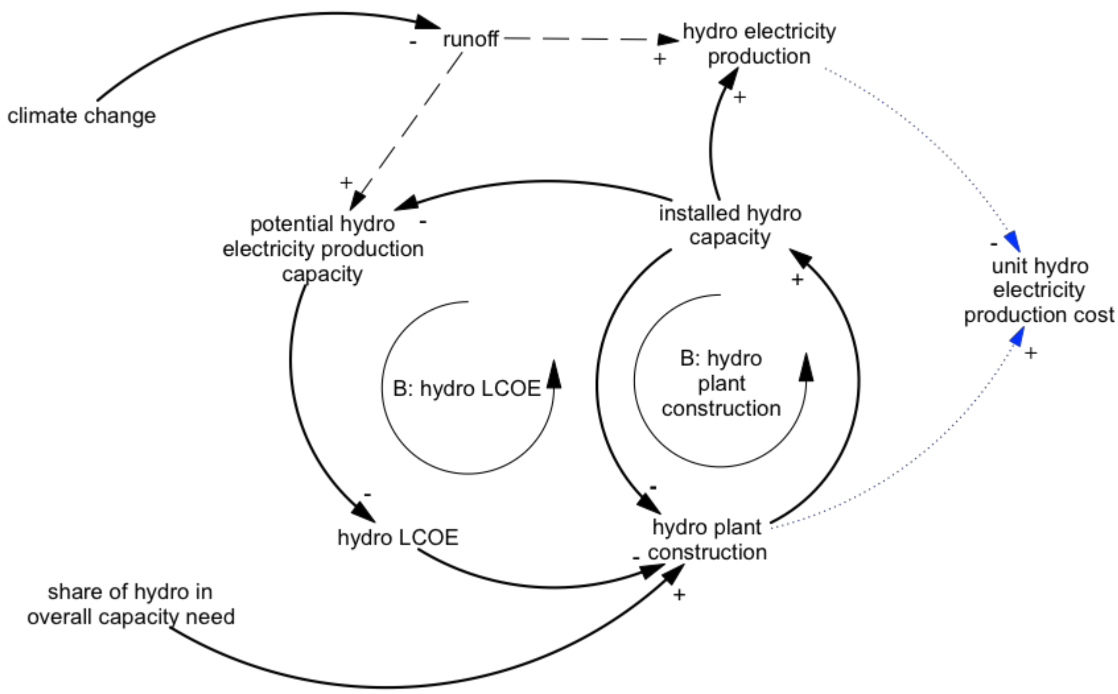

Figure 3: Main feedback loops of the hydro resource dynamics for electricity utilization

- ***Hydro plant construction***

The hydro plant construction loop follows the same logic as the geothermal plant construction loop. The more hydro plant capacity is installed, the less new hydropower plant construction is taking place. The balancing behaviour of this loop is created by the negative connection between installed hydro plant capacity and new hydro plant construction. However, new hydro plant construction is driven by the determined share of hydro capacity in the overall capacity needed to meet the exogenously defined future electricity demand. The feedback from the economic part of the model to hydro plant construction is represented through the hydro expected LCOE loop, which differs from the geothermal loop as the resource dynamics are different. (Ebinger and Vergara, 2011)

- ***Hydro expected LCOE***

The hydro expected LCOE displays the feedback between the economics of hydroelectric capacity build up and the hydro resource capacity. Increased hydro plant construction translates into more installed plant capacity. More installed plant capacity means more potential hydro electricity production, which due to economics of scale reduces expected LCOE of hydro plants and leads to additional hydro plant construction. The potential hydro electricity production capacity is positively related to available runoff, which is negatively influenced by climate change. The calculation of expected LCOE for hydropower is shown in Eq. 1. The capacity factor is assumed to exponentially decline towards its lower limit as defined in (Lahmeyer International, 2016). Due to changing capacity factors an estimate of the average capacity factor over the power plants lifetimes is made when the expected LCOE is calculated. Due to the changing capacity factors unit production cost at a certain point in time differs from expected LCOE.

In this case, climate change is an external driver, which influences the already existing dynamics of hydropower utilization. Historic data has shown that a negative polarity between "climate change" and "runoff" in Kenya exists. This has led to decreasing hydropower potentials (Lahmeyer International, 2016). Hence, climate change leads to higher unit cost for hydro electricity production. This is because a lower capacity factor leads to lower production while total cost stays constant. The calculation for unit production cost depends on the capacity factor of the respective year.

3.1.4 Decision making algorithm for plant construction

Since focus is on how renewable resource dynamics influence short- and long-term electricity system planning, a central element of the model is the underlying decision-making structure for additional plant capacity. This decision is made separately for both load types (i.e. peak and base load). Fig. 4 shows the decision-making algorithm employed in the model to decide what size and type of new capacity gets built and in what order. This algorithm is based on a cost minimization approach as presented in (Lahmeyer International, 2016).

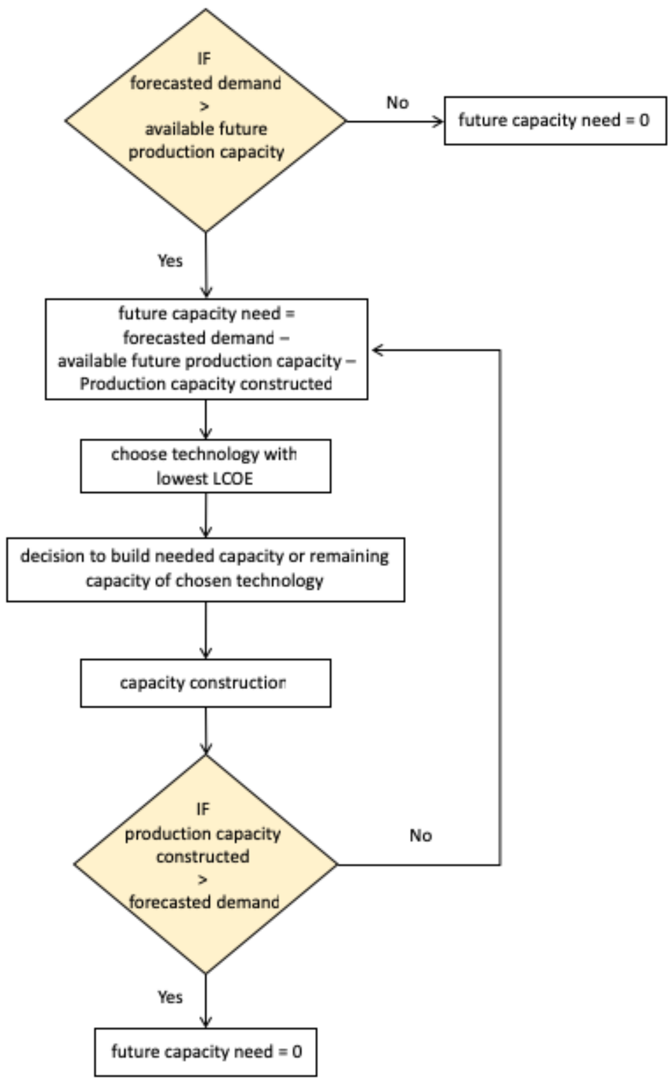

Figure 4: Capacity construction decision-making algorithm

If the forecasted demand is higher than the available future production capacity a future capacity need is identified. Once, this future capacity need is determined the cheapest expected LCOE and the corresponding technology and in the case of geothermal and hydro the corresponding plant is selected. Since capacity construction for plants cannot exceed available capacity, the model has to decide whether it is limited by remaining capacity or if forecasted demand can be fulfilled by the chosen technology or plant. When the decision on capacity construction has been made the model checks if the currently determined production capacity constructed can meet the forecasted demand. If this is not the case, the selection process for additional capacity starts again. The focus lies on production capacity rather than installed capacity because in case of geothermal and hydro, installed capacity can differ from actual production capacity as described in sections 3.1.2 and 3.1.3.

3.2 Scenario description

Eight scenarios are run from 2015 to 2050 and are defined based on the level of demand growth, which can either be high, or low, and whether the hydro and/or geothermal resource dynamics are considered or not. Both demand scenarios start from 9453 GWh for baseload and 1570 GWh for peak load (Lahmeyer International, 2016). A total of eight scenarios are run to unveil the implications of renewable resource dynamics for short- and long-term sustainable energy system planning. The parameters are defined as the following:

- *Low demand:* Peak and base demand are assumed to grow at a yearly rate of 5.7% and 5.6% respectively. This means no flagship projects of Kenya Vision 2030 are implemented and translates into around 70% electricity access (Lahmeyer International, 2016).
- *High demand:* This means a yearly growth rate of 9.6% for base load and 9.8% for peak load. This demand is in accordance with Kenya Vision 2030 and the goal of 100% electricity access (Lahmeyer International, 2016).
- *Geothermal resource dynamics:* When geothermal resource dynamics are taken into account, the effects of geothermal resource utilization on the resource are considered. Hence, it incorporates the impact of resource utilization (i.e. electricity production) on resource patterns (i.e. changes in field stock and well capacity). Additionally, it accounts for the feedback from the geothermal resource to the cost and construction of geothermal power plants. This translates into make-up well construction and leads to changes in cost due to changes in well capacity. All causal connections (dashed and solid) as portrayed in Fig. 2 are considered.
- *Hydro resource dynamics:* The consideration of hydro resource dynamics means that the effect of climate change on the hydro resource is considered, which translates into lower capacity factors and therefore, higher production cost. In this scenario all causal links (dashed and solid) displayed in Fig. 3 are accounted for.
- *No geothermal resource dynamics:* When geothermal resource dynamics are not taken into account, it means that only utilization (i.e. electricity production) affects field stock and well capacity, but this is not reflected in plant or cost calculation modules. As a result, well capacity is assumed to be constant (i.e. maximum well capacity) in the power plant and cost calculation modules. Hence, only causal connections with solid lines, as presented in Fig. 2 are considered.

- *No hydro resource dynamics:* When hydro resource dynamics are not accounted for, the potential influence of climate change on the resource is neglected and a stable capacity factor is assumed. Therefore, only solid lines in Fig. 3 are considered.

In combination this results in the following eight different scenarios (S1-S8) displayed in Table 1:

Table 1: Scenario definition

	Demand level	Geothermal resource dynamics	Hydro resource dynamics
S1	low	no	no
S2	low	yes	no
S3	low	no	yes
S4	low	yes	yes
S5	high	no	no
S6	high	yes	no
S7	high	no	yes
S8	high	yes	yes

Assumptions that are not scenario specific can be found in the Annex.

4 Results

In this section the results regarding power plant capacity, utilization, cost and environmental results from the model are presented. Table 2 displays the numerical results for the relevant parameters for the years 2020, 2030 and 2050.

Table 2: Short- and long-term results for main parameters

		Installed capacity [MW]	Production [GWh]	Average unit production cost [cent/kWh]	Emissions [tCO2]
2020	***S1***	3831	20356	11	1241229
	S2	3831	20204	11	1241229
	S3	3831	19442	11	1241229
	S4	3831	19290	11	1241229
	S5	3831	20356	11	1241229
	S6	3831	20204	11	1241229
	S7	3831	19442	11	1241229
	S8	3831	19290	11	1241229
2030	***S1***	7186	36383	16	3917150
	S2	7186	36140	17	3917150
	S3	8726	37192	18	4488582
	S4	8726	36948	19	4488582

	S5	10070	48245	16	4626678
	S6	10070	48001	17	4626678
	S7	10660	43925	18	4945727
	S8	10660	43681	18	4945727
2050	***S1***	22353	95253	22	7631457
	S2	22353	94237	22	7631457
	S3	22829	94097	24	7721934
	S4	22829	92956	24	7721934
	S5	51807	234759	24	14655307
	S6	51807	233346	24	14655307
	S7	53478	236137	26	15231501
	S8	53478	234791	26	15231501

Table 2 supports the graphical results (i.e. Fig. 7 to 11) described in the following sub-sections by showing the exact values.

4.1 Capacity installation and utilization

Fig. 5 displays total installed capacity by scenario and energy type. In all scenarios, the largest share of peak capacity is MSD, independent of the level of assumed demand growth. In 2050, for base load, the largest share of installed capacity is geothermal for low demand scenarios and nuclear for high demand scenarios. Coal and CCGT are less competitive especially in the long run as renewables are cheaper in the beginning and after a certain demand threshold is reached, nuclear power becomes the cheapest available option. Most capacity for each demand category is installed in the scenarios in which either only hydro or both hydro and geothermal resource dynamics are considered (i.e. S3, S4 and S7, S8). This is because additional capacity needs to be installed to be able to compensate the losses caused by the resource dynamics. In the scenarios in which hydro resource dynamics are not considered (i.e. S1, S2, S5, S6) hydropower contribution is largest for base as well as peak load, for the latter it especially reduces MSD installations. In the low as well as high demand scenarios, wind power installations are the highest when either hydro or both resource dynamics are considered. This is because cost of hydro and geothermal power increases when resource dynamics are included as well as additional installations of electricity production capacity, which are often fossil fuel based. This applies to scenarios S3, S4, S7 and S8. In scenarios of low demand, wind power can compensate for additional installation needs caused by resource dynamics but in scenarios S5 to S8, nuclear becomes the most cost-effective option to satisfy the high demand. Solar PV only accounts for a small share in all scenarios because of cost. This reflects the government’s plans for Kenya’s future electricity system, which does not consider PV as a major source of electricity (Republic of Kenya, 2018).

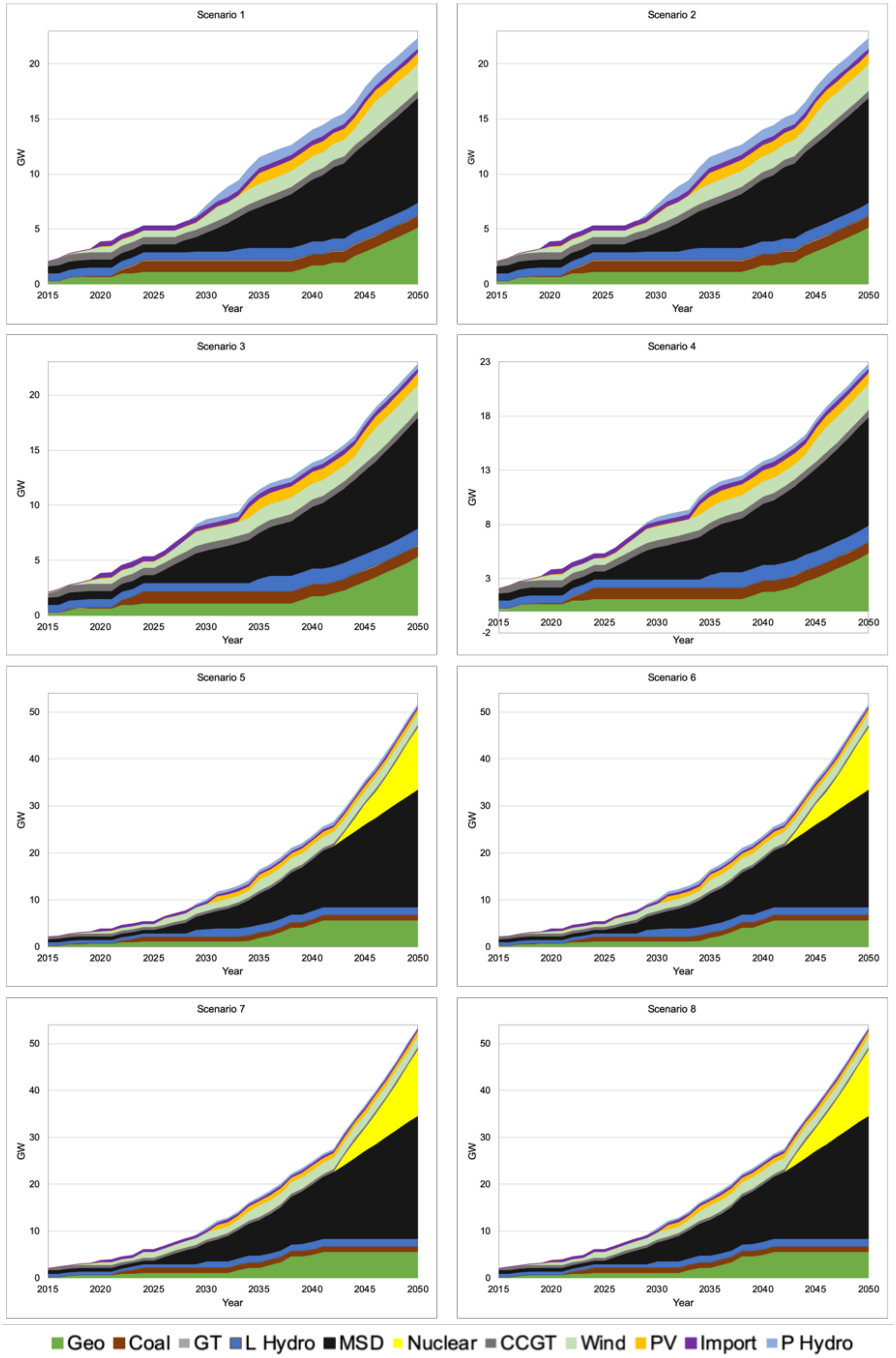

Figure 5: Installed capacity by source for each scenario

In Fig. 6 total production by source for each scenario is presented. It shows that the quantity of installed capacity in each scenario does not directly translate into actual production. This is because of the reduced production capacities when resource dynamics are accounted for. Scenarios with lowest installed capacity are not the ones in which least electricity is produced. In fact, overall installed capacity in low demand scenarios is smallest in S1 and S2. In high demand scenarios overall installed capacity is lowest in S5 and S6. In 2050, highest production levels in both demand categories occur in S1 and S5 (see Table 2). This is because resource dynamics are not included in S1 and S5, which means capacity factors for hydro and geothermal generation stay constant. Hence, installed capacity always translates into the same amount of production and no additional capacity is constructed to compensate production capacity losses. In S2 and S6 slightly higher installations levels are necessary to maintain production to fulfil demand. However, in both scenarios the production levels in 2050 are lower than when no geothermal or hydro resource dynamics are considered (see Table 2). This results from changes in capacity factors due to resource dynamics. For low demand levels least production occurs when both resource dynamics are considered. This is due to altered capacity factors and a delay in well construction and additional capacity construction. This is not the same for high demand levels. Nuclear power is built at such a large scale that it is able to compensate for this effect. Hence, least electricity is produced in S6. This is because geothermal resources are used excessively, which cause reduced geothermal production capacity. In combination with a delay in additional wells, to compensate production capacity losses, this leads to lower production levels. Overall, in 2050, in scenarios 1 to 4 (i.e. low demand scenarios) around 70% of electricity is produced from renewable resources. In scenarios 5 to 8 (i.e. high demand scenarios) only between 27 to 30% of electricity comes from renewable resources in 2050.

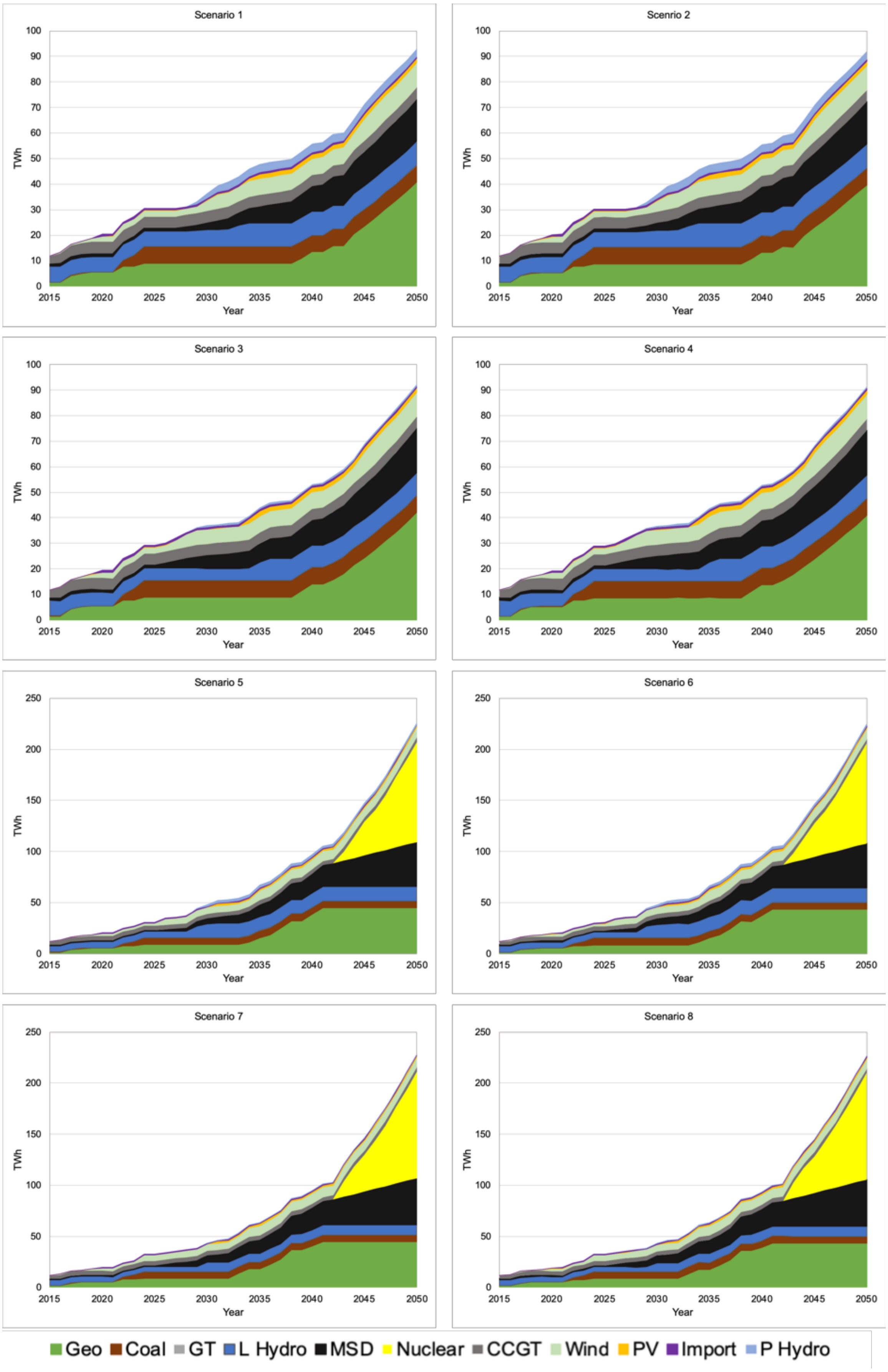

Figure 6: Production by source for each scenario

Capacity factors of hydropower plants gradually decline towards the lower value presented in Annex-Table 2. This means the production from the installed resources also declines over time. In the case of geothermal power, a constant capacity factor of 90% for all power plants is assumed. However, the actual capacity factors of each plant does not stay constant, because of geothermal drawdown make-up well construction, which only occurs with a delay, needs to compensate for potential capacity losses. Thereby, geothermal resource dynamics alter how much of the installed capacity can actually be utilized for electricity production. Fig. 7 presents the average actual capacity factor of all geothermal plants for scenarios that consider geothermal resource dynamics. High resource utilization due to high demand growth rates, decreases the average capacity factor in the long-term and significantly affects capacity factors and production of individual plants.

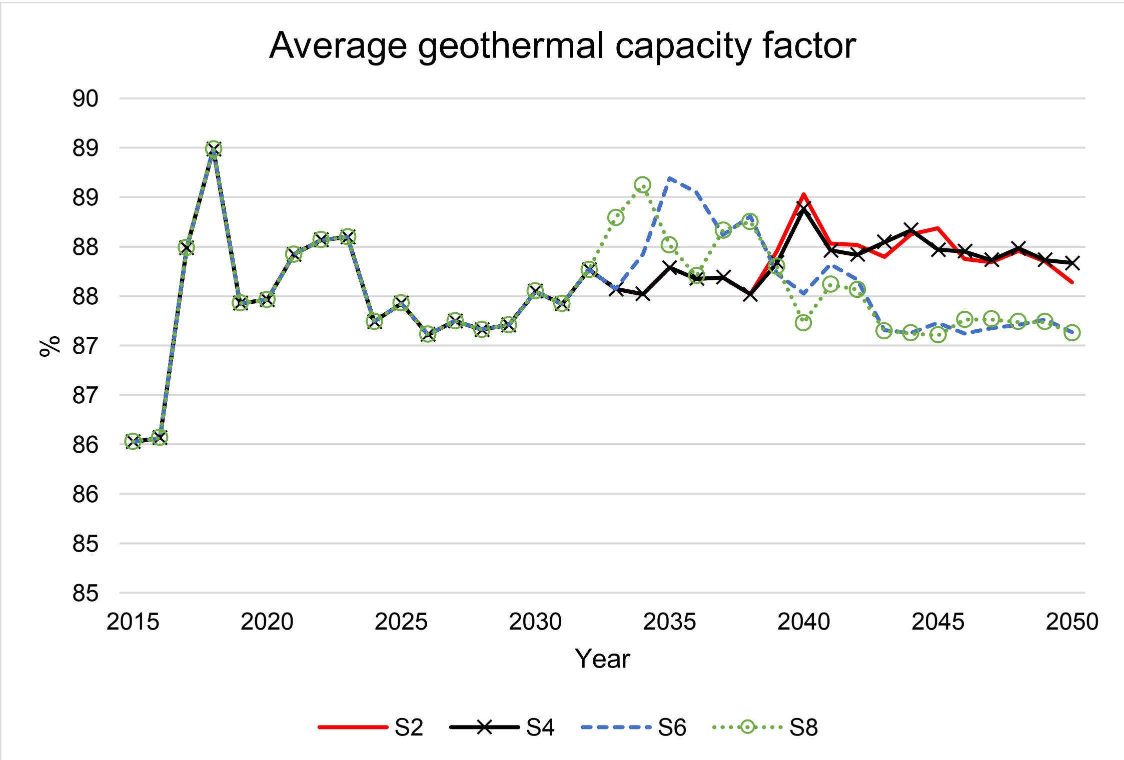

Figure 7: Average actual geothermal capacity factor for scenarios including geothermal resource dynamics (S2, S4, S6, S8) [%/year]

4.2 Cost

Fig. 9 depicts total cost differences between scenarios considering resource dynamics (S2-S4 and S6-S8) compared to those that do not consider them (S1 and S5). It shows total estimated electricity system development cost increases due to geothermal and hydro resource dynamics. When resource dynamics are considered, together or individually, total system cost of electricity supply is always higher than in scenarios in which no dynamics are considered. When only geothermal dynamics are considered (S2 and S6) the cost difference is gradually increasing but it never increases as much as in scenarios that also include hydro dynamics. This is because geothermal production capacity decreases appear gradually over a longer time period. Therefore, larger system impacts are realized slowly over time. Nonetheless, because of overuse of individual reservoirs unit production cost of individual plants can increase up to 76% in the short run, when geothermal resource dynamics are considered. This indicates an overutilization of a geothermal reservoir that is close to depletion. The longer geothermal resources get utilized excessively, the more investment is needed for makeup well construction. However, a significant share of geothermal capacity is only installed after 2035. In other scenarios, which also consider hydro resource dynamics, cost increases significantly. This is due to hydropower contribution to peak load and the constant reduction of hydro capacity factors. The effect on peak load is higher than on base load as capacity factors are already quite low and further reductions increase cost significantly. Hence, additional investment is needed to build additional capacity to maintain the required level of production. After some time, when hydro capacity factors have notably decreased and all economically viable hydro and geothermal resources have been exploited, investment shifts away from hydro and geothermal to other technologies. Therefore, the cost difference decreases again. In this case, peak load is covered by fossil fuel plants and base load by nuclear. The cost difference in low demand scenarios reaches a peak of 6.5 (S3) and 7.6% (S4) in the year 2032. In 2045, the cost difference is highest with 7 (S7) and 8.4% (S8). In general, hydro resource dynamics lead to larger differences, because of their contribution to peak load.

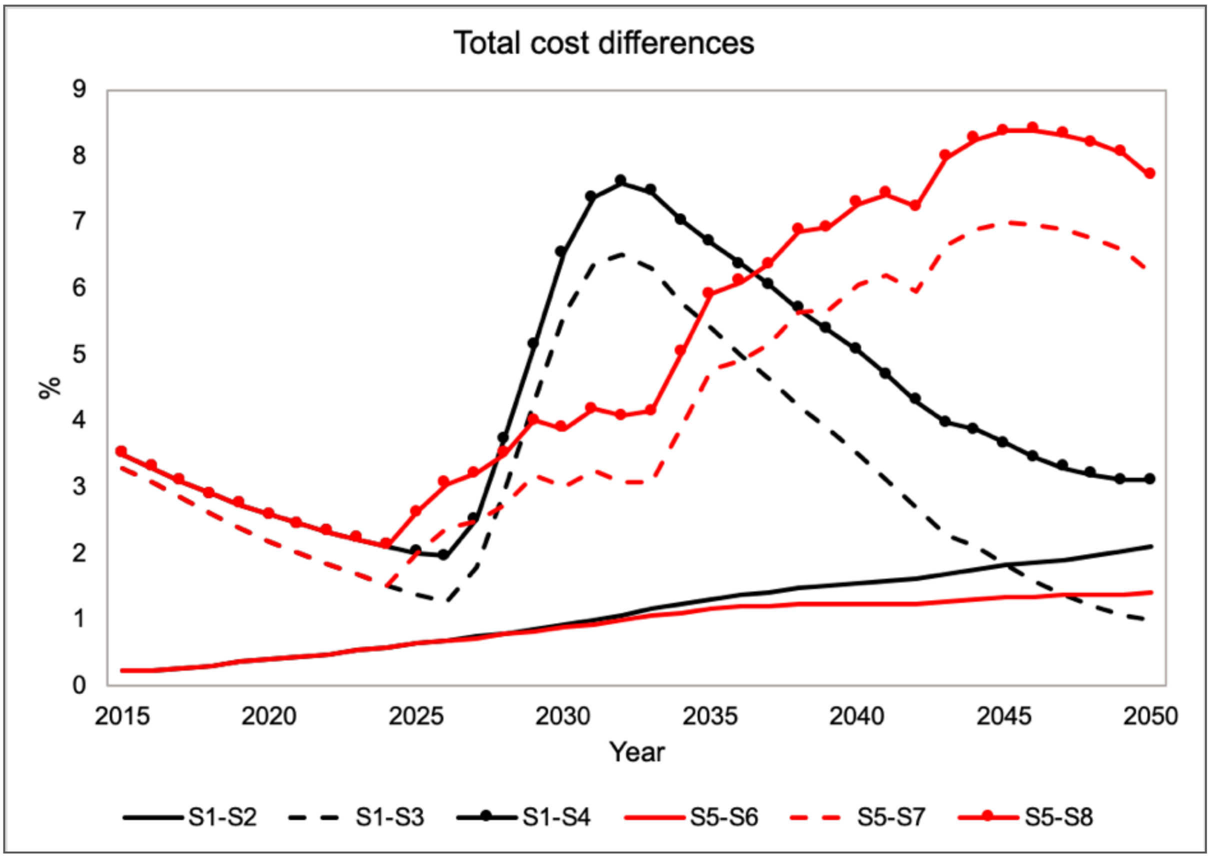

Figure 8: Differences of total cost between scenarios considering and scenarios not considering resource dynamics

Fig. 10 displays the average unit production cost in each of the scenarios. Overall, average unit production cost grows in all eight scenarios. The highest average unit production cost occurs in scenarios in which both resource dynamics are accounted for (S4 and S8). As for total cost differences, hydro dynamics have a larger impact on average unit production cost because they lead to significantly lower capacity factors for peak production of hydropower. Despite geothermal dynamics having a smaller impact on average unit production cost, the average unit production cost for geothermal electricity is around 15% (S2 and S4) and 22% higher (S6 and S8) in scenarios that consider geothermal dynamics. Generally, unit production cost in high demand scenarios (S4-S8) are higher than in low demand scenarios (S1-S4). This is because more capacity needs to be installed, which means once the cheapest technologies have been installed also more expensive ones get built.

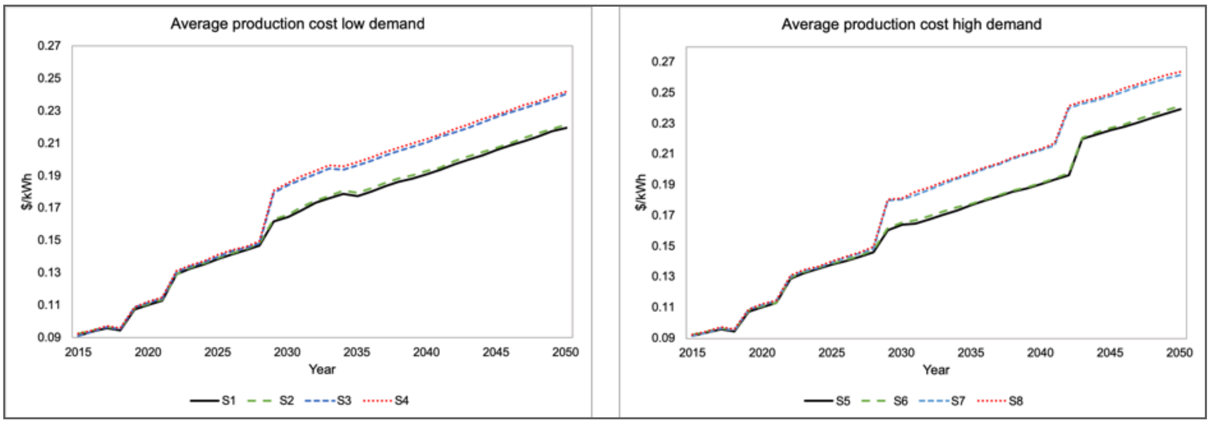

Figure 9: Average unit production cost by scenario

4.3 GHG emissions

Fig. 9 presents CO2 intensity of the electricity system by displaying emissions per GWh in each scenario. Generally, CO2 intensity is higher for scenarios, in which hydro resource dynamics are considered (S3, S4, S7, S8) than when only geothermal or no resource dynamics are considered. This is the case because of additional fossil power plant installations needed to compensate hydro capacity factor declines in peak demand. When geothermal resource dynamics are considered CO2 intensity is only affected minorly because it affects base load. Overall, CO2 emissions per GWh is decreasing because of increased built-up of low or zero CO2 technologies, such as wind, hydro, geothermal and nuclear, instead of coal and gas plants. Energy intensity falls faster in high demand scenarios because of the high share of nuclear in the electricity mix.

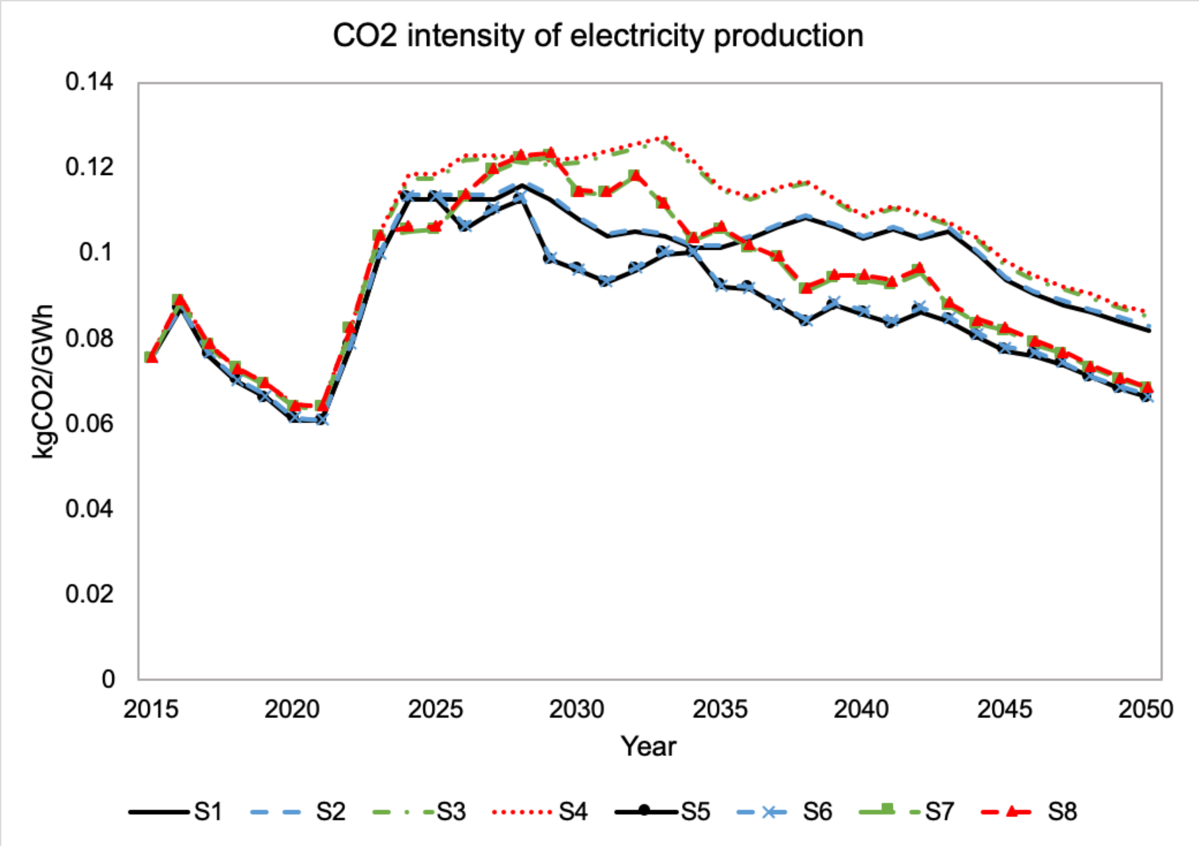

Figure 10: CO2 intensity of electricity mix [tCO2/GWh/year]

5 Discussion

Trade-offs between different (sustainable) electricity system development objectives can be observed between parameters and between their short- and long-term developments are higher when geothermal. As mentioned in the definition of the scenario parameters, a high electricity demand growth rate is needed to fulfil the goals of Kenya Vision 2030 (Lahmeyer International, 2016). At the same time, this high demand growth rate translates into lower production capacity of geothermal resources, higher cost and increased total emissions, although CO2 emissions per GWh are lower due to the large share of nuclear power in the electricity mix. Additionally, a long-term planning approach is needed to avoid negative effects within the energy sector in the future, such as resource exhaustion. According to Dalla Longa and Van der Zwaan, Kenya is able to achieve its climate change goals by 2030 through expansion of renewables (Dalla Longa and van der Zwaan, 2017). This is in line with the government's goal of supplying 80% of electricity from renewables by 2030. However, in the case of high demand scenarios, the share of renewables in the overall electricity supply significantly decreases by 2050 because overall more installations are needed than available economically feasible renewable capacity as outlined in the current plan of Kenya's government. However, Dalla Longa and Van der Zwaan (2017) state that an important prerequisite to achieving a high share of renewables in the energy mix is timely investment in low carbon technologies. This would mean that a re-evaluation and re-consideration of PV as well as concentrated solar (CS) in the on-grid electricity mix would be necessary to avoid high shares of fossil and nuclear production in high demand scenarios. Hence, policies that favour renewables and especially PV and CS technologies need to be put forward and need to be included when assessing least cost power development plans. In fact, Ondraczek (2014) found that the estimates of Kenya's government for LCOE of PV are too high. Also Rose et al. (2016) found that in combination with already existing hydro storage plants in Kenya, PV can be competitive with other technologies. Despite only applying their model to the year 2017 and a limited number of growth scenarios, they found that the government's plans of investment in wind, geothermal and hydropower reduces the value of PV (Rose et al., 2016). However, high electricity demand growth rates and geothermal and hydropower dynamics might alter those results in the long-term, as the effect is cumulative. With regards to nuclear, apart from the fact that a high share of nuclear would negatively affect the government's goals of a high share of renewables in the electricity mix, political and security risks exist. These are acknowledged in the Least Cost Power Development Plan and make actual implementation of such a project questionable, even if support among several stakeholders in Kenya's energy sector is present. While the above-mentioned trade-offs between short- and long-term developments of parameters exist independent of whether geothermal and hydro resource dynamics are considered or not, geothermal and hydro dynamics significantly affect the magnitude of development of parameters such as CO2 emissions and unit production as well as overall system cost. Suberu et al. argue that better planning in the energy sector is a necessary prerequisite to overcome the energy crisis prevailing in Sub-Saharan Africa (Suberu et al., 2013). This supports including geothermal and hydro resources more thoroughly in energy systems modelling and planning. So far, resource dynamics of geothermal resources have not been included into energy system planning and/or modelling in Kenya. An example for the importance of including resource dynamics is that average geothermal unit production cost in 2050 can be expected to be 20% higher than when its dynamics are neglected. In some scenarios individual plants have 76% higher unit production cost because of significantly lower actual capacity factors. Therefore, it is important to consider the resources' behaviour when for example, Power Purchase Agreements (PPAs) of geothermal plants are negotiated, to ensure continuous production by and profitability for the generators (Lahmeyer International, 2016).

Although this study deals with Kenya's electricity system, the presented results link to several objectives of sustainable (energy) system development as defined by SDG 7 and the other 16 SDGs. The results highlight that trade-offs and synergies between some of them exist. On the one hand electricity system expansion is a prerequisite for achieving the goals of Kenya Vision 2030 and affects the SDG´s related to socio-economic development (e.g. SDG 1, SDG 3, SDG 4, SDG 8), on the other hand, sustainable development goals related to environmental and resources concerns (e.g. SDG 13, SDG 15) have to be considered. With regards to Kenya Vision 2030, the high electricity demand growth rate assumed in S5 to S8 is necessary for the implementation of defined flagship projects, which are seen as necessary to grow Kenya's economy and well-being (Government of the Republic of Kenya, 2007; Republic of Kenya, 2018). In the current plan of Kenya's government, the high electricity demand growth rate is also assumed to correspond with the goal of 100% electricity access by 2030 (i.e. SDG 7) (SE4ALL, 2016). Electricity access was found to positively affect educational attainment and life expectancy (i.e. SDG 3 and SDG 4) (Collste et al., 2017). Apart from the beneficial effects of 100% electricity on population and wealth, it was also found to reduce deforestation in rural areas, which corresponds with targets of SDG 15 (Tanner and Johnston, 2017b). However, in the scenarios of high demand (S5-S8) cost are higher than in low demand scenarios (S1-S4) and the resources' dynamics even enhance cost (i.e. unit production cost and total energy system cost). This negatively impacts the target of affordable energy for all within SDG 7, as higher unit production cost translates into higher electricity prices. Higher demand leading to increased electricity production also means higher emissions, which negatively influences climate change and the achievement of SDG 13. Resource dynamics cause even higher emissions as more fossil fuel resources need to be utilized for electricity production. Costs are lower in the low demand scenario, than in the case of high demand. Hence, while energy might be more affordable in that case, this type of demand growth is correlated to lower economic growth (Lahmeyer International, 2016). Thereby, the positive effect on related SDGs (SDG 3, SDG 4, SDG 1) could be diminished.

The presented model follows a demand-driven approach, which does not account for market price (i.e. ignoring effects of price elasticities of production and demand) and the resulting effects on production and consumption (Shafiei et al., 2015b). Including feedback between production cost, supply and demand can allow for further insights into potential future paths of Kenya's energy system and policy recommendations. However, it is beyond the scope of this research as it aims at exploring the significance of the effects of resource dynamics on the supply side for future planning rather than estimating likely energy system developments as a whole. In order to understand the contribution of PV and CS in peak and base-load demand a more detailed modelling approach of hourly load profiles, as for example presented in (Pietzcker et al., 2016), would need to be applied. Using system dynamics for capturing the dynamics of hydro and climate change as well as geothermal drawdown due to overutilization has proven valuable but limitations occur with regards to modelling detailed load profiles. We also acknowledge the general limitation of validating the structure of system dynamics models. However, this limitation has been addressed by using a previously validated model of geothermal resource dynamics (Spittler et al., 2019) as well as results were tested against the outcomes of the models used in Kenya's Least Cost Power Development plan (Lahmeyer International, 2016).

6 Conclusion

Although electricity only accounts for a small part of current energy demand in Kenya, the anticipated expansion of overall electricity generating capacity and especially geothermal and hydroelectricity make it important to consider the dynamics of these resources. The results in this paper confirm that the integration of renewable resource dynamics of hydro and geothermal for electricity generation affects overall electricity supply patterns as well as system costs. Geothermal resource dynamics lead to higher required capacity installations because of losses in production capacity and related significant drawdown of the resource. Hence, additionally installed capacity does not translate into more production. This leads to increased estimated overall system cost, which can be up to 9% higher than when no resource dynamics are considered. Moreover, geothermal and especially hydropower are partly compensated by nuclear and fossil technologies, which affect GHG emissions. Renewable resource dynamics are especially relevant when planning for high demand growth, as is expected to occur in Kenya and when looking at short- and long-term developments of the electricity system as a whole. Certain parameters within it or implications for sustainable development, such as electricity cost and emissions increase. Additionally, the inclusion of resource dynamics can also help to understand the sustainability of the resource utilization itself. By integrating geothermal and hydro resource dynamics into the supply side structure of the electricity system, an important component that needs to be considered when planning Kenya's future energy system has been added. Analysis without such representation can lead to inaccurate information on for example investments needs or CO_2 emission and thereby, result in sub-optimal policies and energy system design.

ANNEX

Annex - Table 1: Data for expected LCOE and unit production cost calculations fossil fuel plants

	Maximum plant size	Minimum plant size	CAPEX	Fixed O&M	Variable O&M	Fuel cost	Fuel cost increase	Construction time	Lifetime	Capacity factor
	MW	*MW*	*$/kW [1,2]*	*$/kW/year [1,2]*	*$/MWh [1,2]*	*$/kWh [3]*	*% [4]*	*years [1]*	*years [1]*	*% [1]*
Coal Lamu	981	240	2479	80	1.3	0.03715	5.3	6	30	75
Coal Kitui	960		2388	69	1.4					
Coal Generic	n.a.									
GT Generic	n.a	27	857	20.9	12.5	0.1331	9.6	1	25	20
GT Nairobi	n.a.		1242							
MSD Generic	n.a.	30	1618	31.5	8.8	0.0586	9.6	2	20	20
Nuclear Generic	n.a.	400	6858	7.5	10.2	0.0116	1	10	40	85
CCGT Generic	926	27	1174	31	13.2	0.03715		3	20	75

Annex - Table 2: Data for expected LCOE and unit production cost calculations hydro power plants

	Maximum plant size	Minimum plant size	CAPEX	Fixed O&M	Variable O&M	Construction time	Lifetime	Capacity factor base load high	Capacity factor reduction base load	Capacity factor peak load high	Capacity factor reduction peak load
	MW	*MW*	*$/kW [1,2]*	*$/kW/year [1,2]*	*$/MWh [1,2]*	*years [1]*	*years [1]*	*% [5]*	*% [5]*	*% [5]*	*% [5]*
SangOro	20	20	3430	27.4	0.5	7	40	95	70	66	17
SondoMiriu	60		3430	27.4				96	75	69	18
Turkwel	105		3430	27.4				95	86	40	13
Tana	20		3430	27.4				80	35	60	26
Gitaru	216		3431	27.4				92	63	49	22
Kiambere	164		3430	27.4				90	51	61	29
Kindaruma	70		3456	27.4				95	84	53	22
Masinga	40		3430	27.4				82	25	49	8
Kamburu	90		3431	27.4				94	83	51	22
HighGrandFalls	693		2739	15.5				92	66	20	8
Karura	89		3691	14.9				93	67	30	12
NandiForest	50		3791	19				91	64	50	18
Magwaga	119		4431	28				91	64	50	18
Arror	59		3087	20				91	64	50	18
LakeVictoriaNorthOther	101		3400	27.4				91	64	50	18
LakeVictoriaSouthOther	0		3400	27.4				91	64	50	18
RiftValleyOther	141		3400	27.4				91	64	50	18
TanaOther	0		3400	27.4				91	64	50	18
AthiOther	60		3400	27.4				91	64	50	18
EwasoNgiroNorthOther	0		3400	27.4				91	64	50	18

Annex - Table 3: Data for expected LCOE and unit production cost calculations wind power plants

	Maximum plant size	**Minimum plant siize**	**CAPEX**	**Fixed O&M**	**Variable O&M**	**Construction time**	**Lifetime**	**Capacity factor**
	MW [6]	*MW*	*$/kW*	*$/kW/year [1,2]*	*$/MWh [1,2]*	*years [1,2]*	*years [1,2]*	*% [6]*
Lake Turkana	1000		2030					55
Aeolus Kinangop	60		2000					34
Kipeto	100		2010					46
Prunus	51		2030					40
Meru	400		2000					32
Ngong	26	10	2030	76.1	0	2	20	35
OlDanyat	10		2030					40
Malindi	50		2030					40
Limuru	50		2030					40
Kajiado	50		2030					40
Marsabit	600		2030					40

Annex - Table 4: Data for expected LCOE and unit production cost calculations geothermal power plants

	Maximum field stock	Maximum well capacity	Maximum recharge	Recharge coefficient	Maximum plant size	Minimum plant size	CAPEX power plant	Fixed O&M total	Variable O&M total	CAPEX well	Construction time	Lifetime	Capacity factor
	TWh [8]	MW [8]	MW [8]	1/TWh [8]	MW [7]	MW	$/kW [9]	$/kW/year [9]	$/kWh [9]	M$/well [9]	years [1]	years [1]	% [1]
Olkaria 1	57.16	4	326	0.01	261		2054	136.9					
Olkaria 2	22.12	5.5	126	0.03	101		1801	137.6					
Olkaria 3	24.09	6	138	0.03	110		3022	87.6					
Olkaria 4&5	61.32	7	350	0.01	280		2054	136.9					
Olkaria 6	30.66	6.3	175	0.02	140		2054	136.9					
Olkaria 7	30.66	5	175	0.02	140		2054	136.9					
Olkaria 8	30.66	6.5	175	0.02	140		2054	136.9					
Olkaria 9	30.66	6.3	175	0.02	140		2054	136.9					
Olkaria Wellheads	19.71	6.7	113	0.04	90		673	111.62					
OrPower	0.00	0	0	0.00	0		0	0					
Eburru 2	5.48	5.9	94	0.13	75		2810	153.2					
Menengai 1	22.56	4.9	129	0.03	103	25	2082	136.4	0	6.55	9	25	90
Menengai 2	78.84	5.8	450	0.01	360		2040	135.4					
Menengai 3	21.90	4.3	125	0.03	100		2130	136.1					
Menengai 4	65.70	5	375	0.01	300		2130	136.1					
Menengai 5	131.40	6	750	0.01	600		2130	136.1					
Suswa 1	32.85	4.7	188	0.02	150		2130	136.1					
Suswa 2	131.40	4.3	750	0.01	600		2130	136.1					
Baringo Silali 1	109.50	5.5	625	0.01	500		2130	136.1					
Baringo Silali 2	241.00	4.9	1380	0.03	1100		2130	136.1					
Baringo Silali 3	30.66	5.1	175	0.02	140		2130	136.1					
Akiira	30.66	5.2	175	0.02	140		2290	137.5					
AGIL	30.66	4.8	175	0.02	140		2290	137.5					

Annex - Table 5: Other assumptions for cost calculations [10]

Discount rate	12%
Cost reduction PV	1.5%
Cost reduction wind	0.5%

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* [7] Lahmeyer International. Development of a Power Generation and Transmission Master Plan, Kenya. Nairobi, Kenya: Ministry of Energy and Petroleum; 2016. p 112-113

* [8] Based on Maximum plant size [7] and Lifetime [1]

* [9] Based on CAPEX and O&M values presented in [1] and [2]

* [10] Lahmeyer International. Development of a Power Generation and Transmission Master Plan, Kenya. Nairobi, Kenya: Ministry of Energy and Petroleum; 2016.

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6 Paper V: The role of geothermal resources in sustainable power system planning in Iceland

The role of geothermal resources in sustainable power system planning in Iceland

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Abstract:

One of the main challenges of sustainable energy system development in Iceland is the decarbonisation of its transport sector. Several studies have investigated alternative fuel options and assessed the socio-economic and climate implications of electrifying Iceland's vehicle fleet. Because Iceland's electricity system is reliant on geothermal and hydropower, the aim of this paper is to understand the relevance of accounting for geothermal resource dynamics in energy system planning in Iceland. Therefore, the energy and transport system model UniSyD_IS is linked to a geothermal resource dynamics model. A total of 16 different scenarios that vary in GDP growth rate, conditions for electric vehicles and consideration of geothermal resource dynamics are analysed in relation to production patterns, cost, resource availability and emissions. Results show that not all aspects of sustainability are influenced significantly. However, incorporating geothermal resource dynamics in the assessment allows to gain more holistic insights into sustainable energy system planning in Iceland, especially regarding the availability of geothermal resources.

Keywords: geothermal resource dynamics; sustainability; energy system modelling; system dynamics; Iceland

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1 Introduction

Sustainable energy system development is currently shaped by two major international agendas: Agenda 2030, in particular Sustainable Development Goal (SDG) 7, which aims at "ensuring access to affordable, reliable and modern energy for all" and the Paris Agreement, which calls for a reduction in greenhouse gas (GHG) emissions to combat climate change. Hence, the objectives of sustainable energy system development can broadly be defined as reducing environmental impact while ensuring socio-economic development. In 2017, about 81% of total primary energy supply and around 98% of electricity in Iceland was produced from indigenous renewable resources, namely hydro and geothermal [1,2]. However, approximately 19% of total primary energy supply came from fossil fuels. As Fig.1 displays, apart from aviation fossil fuels are primarily used in the transport and the fishing sectors.

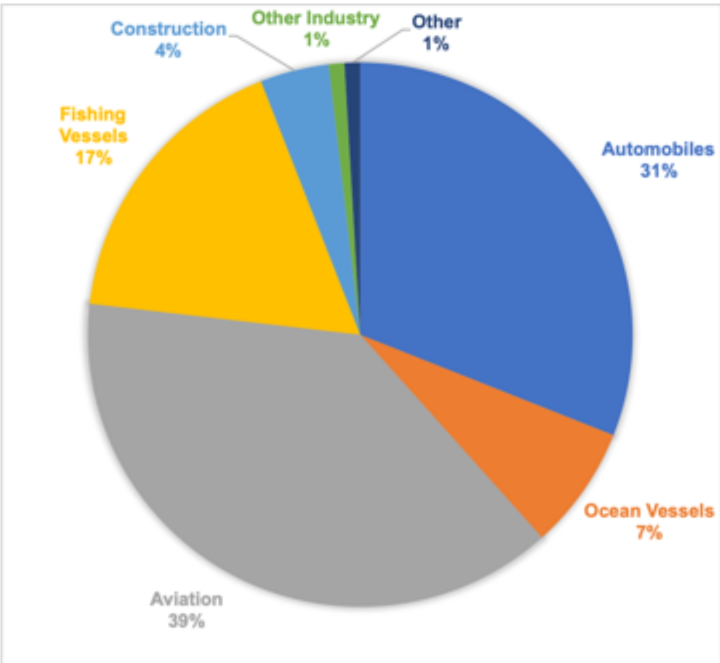

Fig.1: Share of fossil fuel consumption by sector in Iceland in 2017 [3]

With sustainable energy system development in mind, one of the major challenges for Iceland is transitioning away from the use of fossil fuels and the reduction of GHG emissions from transport [2,4,5]. Using the energy and transport system model UniSyD_IS, several studies have assessed economic and environmental implications of various pathways of transitioning from a fossil fuel to an alternative fuel vehicle fleet in Iceland (e.g. [6–8]). These studies have revealed that due to currently low electricity prices and high availability of renewable resources, transitioning the transport sector towards electric mobility is seen as an important step towards a more sustainable energy system development [9]. Demand for Iceland´s renewable electricity is increasing from data centres, heavy industries and possibly from the UK through an undersea cable [10]. As a result, future economic development could challenge the economic feasibility of electrified transport as the desired transitions pathway. Increased demand pressures also could lead to excessive use of Icelandic geothermal resources, limiting the production capabilities of developed geothermal resources [11]. Geothermal resources currently provide around 27% of electricity produced in Iceland. As outlined in [11–13] the excessive use of geothermal resources for electricity production can lead to a reduced utilization of geothermal reservoirs and resource availability, in particular if the rate of extraction exceeds the natural recharge rate. This process can also be referred to as geothermal drawdown, which leads to increased well drilling to compensate for production losses. This causes unit production cost to increase [11]. Hence, an increase in electricity demand caused by economic development and an intensive electrification of Iceland's vehicle fleet may affect the sustainability of Iceland's energy and transport systems, by not only affecting GHG emissions but also the availability of geothermal resources and production cost of electricity and thereby the economic feasibility of electrifying the transport sector.

Therefore, several challenges to achieve sustainable energy system development of the Icelandic energy system with regards to environmental, socio-economic and security aspects exist as also outlined by [5]. The objective of this paper is to understand the importance of the interaction between geothermal resource dynamics and various degrees of electricity demand for sustainable energy system planning on a national level and its effects on different parameters, such as emissions, cost, resource availability and industrialization. The practical motivation is to examine if the electrified transport pathway is robust over diverse demand scenarios, when accounting for geothermal resource dynamics.

To explore the importance of geothermal resource dynamics for sustainable national energy system planning, 16 scenarios are run. To run the scenarios, Iceland's energy and transport system model, UniSyD_IS [4,6,8] is connected to a geothermal resource dynamics model, which captures the dynamics of geothermal resource and its economics on a system's level [11].

The remaining part of this paper is structured into 6 sections. In Section 2, background information on sustainable energy system development in Iceland, its current state, strategies and challenges are presented. In Section 3 the model and its structure are presented. This includes a general description of the UniSyD_IS and the connected structure of the geothermal resource dynamics in the supply module. In Section 4 the scenarios are described. Section 5 contains the results of the modelling process. In Section 6 the findings and their relation to Iceland's sustainability issues are discussed. Finally, Section 7 provides some concluding remarks.

2 Sustainable energy system development in Iceland

When exploring sustainable energy system pathways, multi-dimensional sustainability themes need to be considered. This section reviews the current state and challenges of Iceland's energy system with regards to several sustainability themes, including access and electrification, affordability and equity, security, efficiency, renewables, economic- or cost-efficiency, environmental issues and contribution to well-being [5]. Existing strategies for addressing challenges of sustainable energy system development in Iceland are also introduced. In Iceland, 100% of the population has access to electricity [5]. Currently prices for electricity and heating are low (around 15 cent/kWh for the residential sector) and therefore, affordable to everyone [5,14]. As a result, access and affordability are assured.

Despite energy being affordable for everyone, pricing is not equal between sectors [5]. Large users such as the aluminium industry, which consume close to 70% of all electricity produced in Iceland, enjoys long-term electricity price contracts with power producers at a low price [5]. In some cases, these contracts link the price of electricity to the aluminium price instead of the production cost of electricity. The longest and largest of these contracts lasts until 2048. Additional demand for electricity from a potential undersea cable to UK is likely to affect electricity prices in Iceland, but only those that are not bound in long-term contracts. As a result, electricity prices for the common consumer, such as for charging electric vehicles are likely to increase.

In terms of share of renewable energy, Iceland is performing well as it has a high share of renewables in total primary energy supply as well as total final energy use. A possible undersea cable might positively affect the countries that import the electricity. These for example include increased share of renewable energy in European countries. The Icelandic National Energy Company could also benefit from higher electricity prices and increased sales. However, significant risks lie on the Icelandic side [5,15,16]. These risks can be political risks, higher electricity prices and increased pressures on Icelandic resources.

The term energy security can refer to short- or long-term security. In the short term, grid stability represents a major challenge in one area of the country. The increased production of electricity from intermittent resources such as wind and increased electricity demand calls for renewal of the entire electricity transmission grid [17]. The reliance on fossil energy imports poses a risk for the long-term security of supply. This challenge has been addressed by several studies that investigated strategies to reduce fossil fuel demand, particularly in the road transport sector [4,8,18,19]. Additionally, as explained earlier, the potential of declining resource capacity of geothermal resources due to overutilization for electricity production represents a risk for the long-term security of supply [5]. Overutilization has already led to instances of geothermal drawdown in Iceland. From a research and management perspective, geothermal production capacity dynamics have mostly been investigated for individual reservoirs [12,13,20,21].

More recently, attempts to investigate the effects of geothermal resource dynamics have been made [11], but not in the context of the entire energy system, nor its potential impacts on the future developments of the Icelandic energy system. Geothermal resource dynamics affect the economic viability and cost-efficiency of individual energy development projects [5]. This is because of increasing cost arising from additional well drilling requirements to compensate production capacity losses [22,23]. Therefore, the financial viability and systems implications of such projects needs to be considered in long-term energy system planning [11,21].

Environmental effects of the energy system include those of hydro and geothermal power plant projects, which can influence water and air quality as well as biodiversity in addition to emissions related to the use of fossil fuels [5]. The Icelandic Master Plan, which supports regulation of future power plant construction and resource utilization, is supposed to address this aspect by balancing economic, social and environmental interests of future hydro and geothermal resource developments [24]. Reducing GHG emissions plays an important role in achieving a clean energy system. Therefore, shifting away from fossil fuels is critical. One of the most feasible strategies to reduce GHG emissions, as has been confirmed by several studies, is that of shifting Iceland's vehicle fleet towards EVs [5,6,8,9].

The above shows that Iceland's energy system is performing well in many of the categories of sustainability as defined in Shortall and Davidsdottir (2017), but some challenges still exist including links to energy security and emissions. Moving away from fossil fuels will contribute to resolving both those challenges. Given the longevity of energy infrastructures, such a transition must be robust across different energy demand scenarios, and the corresponding supply dynamics. Transitioning to EVs in the road transport sector together with scenarios of high economic growth indicates a growth in electricity demand and significant expansions of electricity production capacities. Although Iceland has large renewable resource endowments, challenges for harvesting them sustainably exist, especially when it comes to geothermal resources for electricity production [11]. Higher demand pressures, combined with geothermal resource dynamics may affect the feasibility of different energy transition pathways. The potential impact however is not known without assessing the implications at a systems level.

3 Model

This study is carried out using UniSyD_IS, the system dynamics model of Iceland's energy and transport system and connecting it to the geothermal resource dynamics model developed in [11]. UniSyD_IS is a detailed bottom-up partial-equilibrium model that encompasses the following modules: energy demand, infrastructure, energy markets and energy supply. The model has been used for different case studies (see [7] for an overview). In the following, the relevant modules for this study and the connection of UniSyD_IS to the geothermal model are described:

3.1 Energy demand

The most developed component of the energy demand module is the transport sector, because it has been used to assess different strategies of reducing emission of the vehicle fleet by shifting towards alternative vehicles [4,6,8,18,25]. One of the decision criteria in determining the share of different vehicle types is fuel/electricity cost. Based on the share of different vehicle types and mobility requirements, electricity demand of the transport sector is estimated. Electricity demand of other sectors depends on the GDP growth rate and the GDP growth to demand ratio, which is assumed to be 1.3, meaning electricity demand growth is 30% higher than GDP growth [18]. Since no efficiency improvements are assumed this ratio stays constant.

3.2 Energy markets

The energy market module consists of a short-term and a long-term market simulation. For the short-term market simulation, production levels at varying wholesale prices for each source are calculated [19]. Hence, the main outputs of the short-term market are generation scheduling and energy pricing, depending on demand [25]. Long-term market simulation estimates new capacity installation and selects technology type and size to be built. The selection process is based on minimum cost at which power from a specific resource can be supplied and forecasted wholesale prices. For further information on energy market simulation see Shafiei et al. (2016, 2015b).

3.3 Energy supply

The supply module estimates the produced power of each source at different market prices and production costs. It encompasses installed plant capacities, planned or future capacities and production costs [6]. The resource supply curves for geothermal and hydro resources have been introduced in [18], which means that cost of electricity supply increased with increasing level of production. Through the connection of the geothermal resource dynamics model to UniSyD_IS, geothermal production cost calculation is no longer relying on resource supply curves but calculated following the bottom-up approach developed in [11] and explained in the next section.

3.4 Geothermal resource dynamics and its connection to UniSyD_IS

The production cost of electricity from geothermal resources takes into consideration effects of geothermal resource dynamics. Geothermal resource dynamics arise from the stock-like nature of geothermal resources [11,12]. When the geothermal resource is utilized for electricity production, the resource stock decreases. Through natural recharging (i.e. heat inflow and pressure build up), the stock of the reservoir increases. In an already utilized reservoir, changes in the stock lead to changes in average well production capacity and thereby, overall plant production capacity. To compensate for the production capacity losses of an individual well, when extraction rate exceeds recharging, additional wells get drilled to maintain the desired plant production capacity. Additional wells translate into additional investment, which affects production cost. These dynamics are displayed in Fig. 2, in which the green variables depict a simplified structure of the geothermal resource dynamics model (for a more detailed description of the geothermal model also see [11]). Geothermal resource dynamics are calculated for each plant individually. Hence, the unit production cost is calculated individually for each power plant.

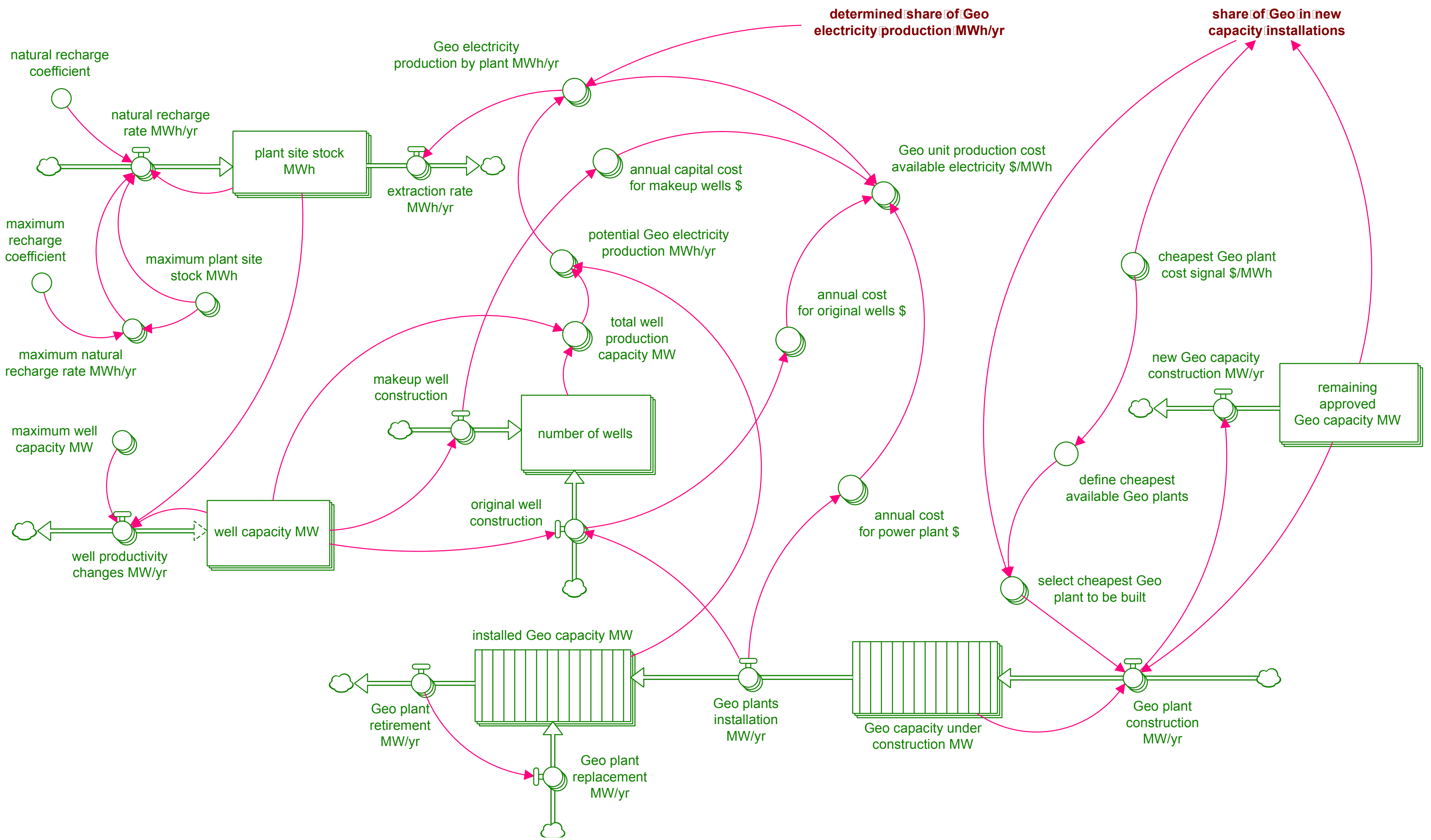

Fig.2: Simplified structure of geothermal resource dynamics model (green) and its connection to UniSyD_IS (red)

Fig. 2 also displays the main connections between the two models. In UniSyD_IS the share of technology in new power capacity is determined, this is influenced by resource availability and cheapest possible cost of production (i.e. levelized cost of electricity). This means geothermal resource availability and cheapest available geothermal power (i.e. minimum levelized cost of electricity at which one kWh can be supplied), which are calculated in the geothermal resource model, influence the share of geothermal in new capacity installations that can be allocated to geothermal power plants. Once the share of geothermal electricity in new installations has been determined in UniSyD_IS, the geothermal model determines the size and the plant site in which this new geothermal capacity gets installed. This decision is based on finding the lowest cost option among all geothermal resource. In total 15 plant sites (A to O) are available for geothermal electricity production. This includes five that were already utilized significantly in 2015. Once the geothermal capacity has been installed at the determined site(s), it can be utilized for electricity production. When the life time of a geothermal power plant is reached, its usage can be prolonged through what is called “Geo plant replacement MW/yr” in Fig. 2. The level of utilization is determined in UniSyD_IS and influenced by unit production cost and power plant production capacity. In the geothermal resource model, those two factors are indirectly affected by geothermal electricity production calculated in UniSyD_IS. This is because geothermal electricity production determines the level of utilization of each plant. This impacts on the availability of the geothermal resource in the reservoir, which affects well capacity and thereby, plant production capacity. This again influences well drilling activity, which causes additional investment into make-up wells, which affects the unit production cost.

4 Assumptions and scenarios

To understand the effect of geothermal resource dynamics on sustainable energy system development, a total of 16 scenarios are run for the period between 2020 and 2050 (see Fig. 3). Those scenarios differ in GDP growth rate, conditions for electric vehicle (EV) uptake and whether or not geothermal resource dynamics are considered. The scenarios parameters are defined as follows:

GDP growth rates are based on the different growth scenarios defined in [10]. The various GDP growth rates translate into energy demand. In the “Electricity demand scenarios 2018-2050” report of Iceland’s National Energy Authority, high efficiency increases are assumed.

However, following previous assumptions we assume a constant ratio between the GDP growth rate and the electricity demand growth rate throughout the simulation period. The following annual GDP growth rates are defined as: (1)1.25%; (2) 2.25%; (3) 2.6% and (4) 2.8%.

The parameters for defining the scenarios for electric vehicles (EVs) are based on the scenarios run in [9]. Two of those scenarios are investigated in this paper: (p) The **P**remium scenario, which considers current governmental policy proposals and additional incentives for the purchase of BEVs within both light and heavy vehicle fleets (in combination with high oil price, high carbon tax, and high fuel excise tax) and (b) the **B**AU scenario, which would mean no additional policies that support EVs are implemented (in combination with low oil price, low carbon tax, and low fuel excise tax).

When geothermal resource dynamics are not considered drawdown does not influence cost and capacity factors. However, in both scenarios, i.e. (Y) when geothermal resource dynamics are considered and (N) when they are not, the influence of development on the geothermal resource is estimated.

Fig.3 displays the relevant combinations of parameters to define 16 scenarios.

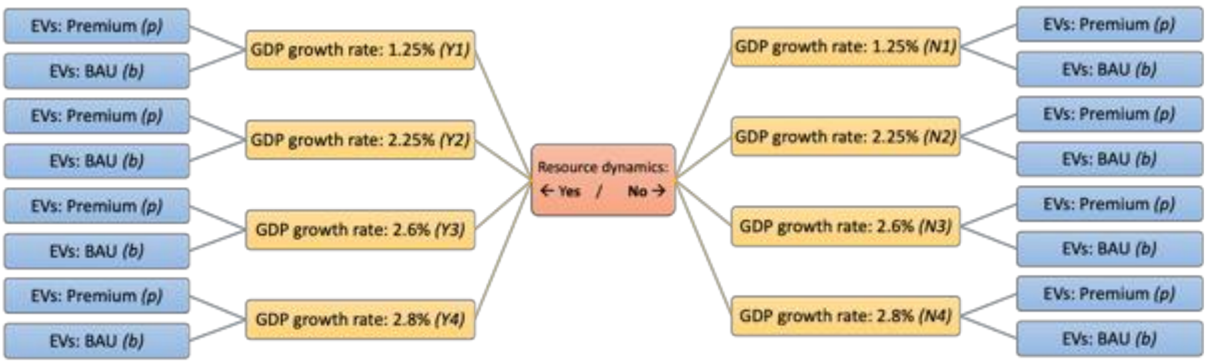

Fig.3: Scenario tree providing an overview of EV and GDP growth rate scenarios grouped by scenarios considering (Y) and not considering (N) resource dynamics

The parameters of the geothermal resource model are based on the assumptions presented in Spittler et al. (2019). The overall geothermal resource limit in all scenarios is set to be twice the size of the approved geothermal resources for development as defined in the Icelandic Master Plan [24]. This implies that close to all geothermal resources that have not been allocated for protection can be developed during the simulation period. Based on results in Spittler et al. (2019), the maximum recharge is assumed to be 0.09 of the total plant site stock. Well capacity is the average of existing wells. Because of geothermal drawdown, for those plant sites that have already been utilized (A to E) the average well capacity and plant site stock is different in 2015. In Tab. 1 the main assumptions for the resource parameters are displayed.

Tab. 1: Assumptions of geothermal resource parameters (based on: [11])

Power plant	Maximum plant site stock [TWh]	Plant site stock 2015 [TWh]	Maximum well capacity [MW]	Well capacity 2015 [MW]	Approved plant size [MW]	Installed plant capacity 2015 [MW]
A	190	189	4.0	3.9	300	60
B	34	29	5.5	4.7	152	76
C	170	162	6.0	5.7	240	120
D	134	122	9.0	8.3	606	303
E	28	23	6.0	5.0	200	100
F	116	116	10.2	10.2	180	0
G	22	22	6.5	6.5	100	0
H	22	22	6.3	6.3	100	0
I	20	20	6.7	6.7	90	0
J	39	39	6.0	6.0	180	0
K	39	39	5.9	5.9	180	0
L	44	44	6.1	6.1	200	0
M	44	44	5.8	5.8	200	0
N	44	44	7.0	7.0	200	0
O	66	66	6.0	6.0	400	0

The parameters for the calculation of geothermal electricity are assumed to be the same as in [11] and are presented in Tab. 2.

Tab. 2: Assumptions for geothermal cost calculations

	Investment cost [a,b]	Operation & Maintenance cost [a,b]	Economic lifetime
Power plant	2870 $/kW (new plants)	0.0114 $/kWh	30 years
Wells	7.08 M$ per well[c]	0.005 $/kWh	30 years

[a] based on the values presented for a 100 MW power plant in [26] and distributed on percentages derived from [27–29].

[b] based on the EUR – USD exchange rate of 1:1.24 .

[c] personal communication with Orkuveita Reykjavikur 5th of December 2017.

5 Results

In this section the results relevant for understanding the connection between geothermal resource dynamics and sustainable energy system development in Iceland are presented. These include, production capacity, average unit production cost, emissions and geothermal resource availability. Implications for sustainable energy development and future planning in Iceland are then derived from those results.

5.1 Electricity production

Fig.4 displays total electricity production by source for each scenario. Each row represents simulations using the same GDP growth rate, and thus each row displays similar production levels in 2050. The results show that while the lowest GDP growth rate of 1.25% gives a production level of 30.1 to 30.3 TWh, the highest GDP growth rate of 2.8% results in 55.1 to 55.8 TWh in 2050. The difference between the simulations represented in each row capture the impact of including resource dynamics or not, and the differing conditions for higher adoption rate of EV´s.

Results show that cconditions for EVs only have a small effect on total electricity production, as demand is expected to be between 0.7% and 1.5% higher in 2050 due to the vehicle electrification. Yet, when geothermal resource dynamics are considered electricity production is slightly lower because of geothermal drawdown and delays in well drilling activities, which are undertaken to compensate for the effects of geothermal drawdown. The more excessive the use of geothermal resources, the higher is geothermal drawdown. With higher GDP growth rates, demand and production of electricity increases, and so does exploitation of geothermal resources.

As shown in Fig. 5, in four scenarios, the share of geothermal resource production decreases, because all geothermal resources have been developed in 2046 (Y4 and N4) and 2048 (Y3 and N3). No further capacity installations are possible in those scenarios. Therefore, higher demand caused by higher GDP growth (Y2p to Y4b and N2p to N4b) leads to more wind capacity installations at an earlier stage. This is because larger capacity expansions increase the minimum cost at which hydropower can be installed (see section 5.2). Fig. 5 also displays the difference between scenarios that do (Y1 to Y4) and those do not (N1 to N4) include the feedback from geothermal resource dynamics. The share in scenarios that do not

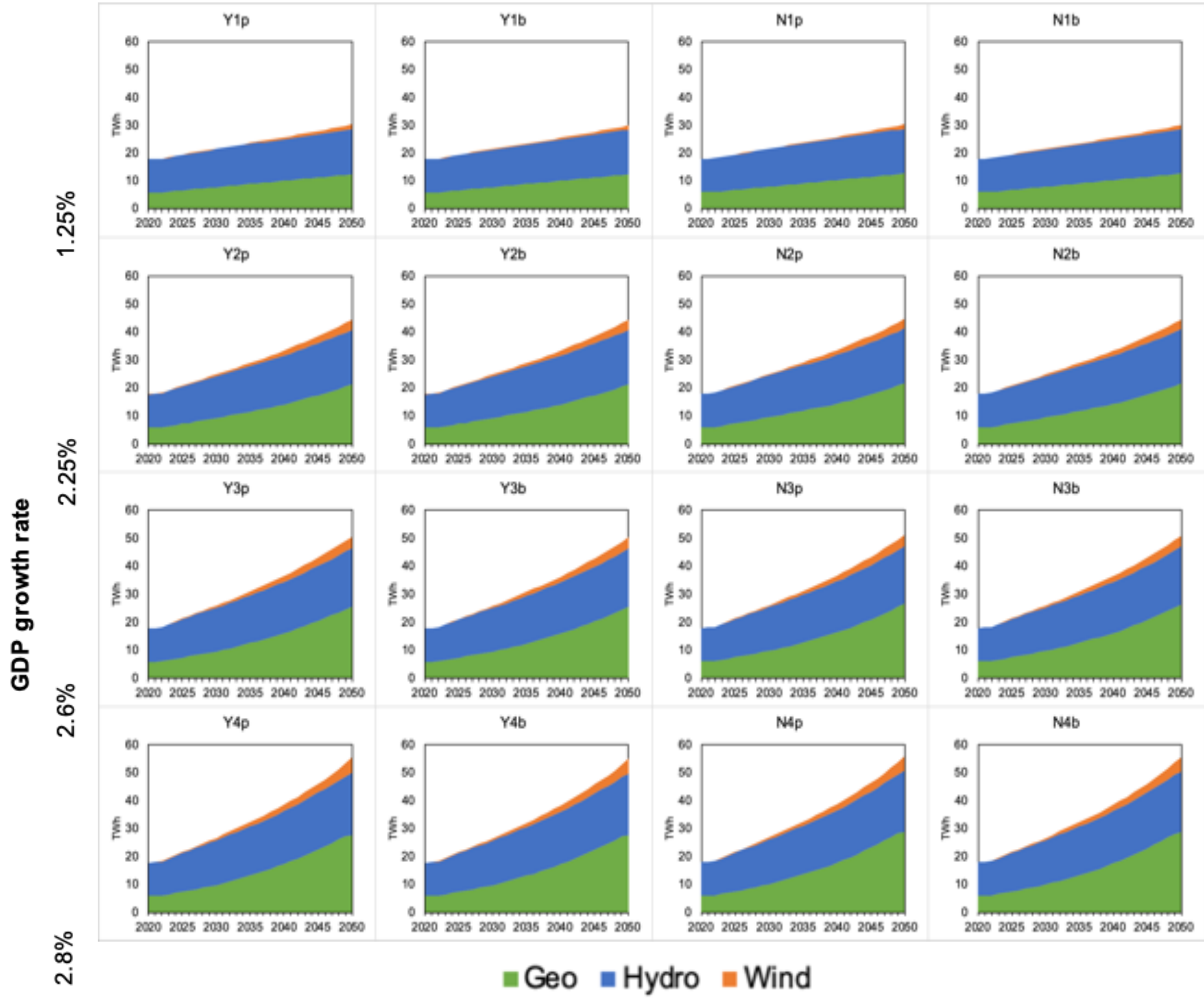

Fig.4: Electricity production by source in Iceland [TWh/year]

consider geothermal resource dynamics is always higher than in those scenarios that do include geothermal resource dynamics. This is because geothermal drawdown reduces geothermal production as well as it becomes less economic to install geothermal plants for electricity production and the share of other technologies, such as wind or hydro increases.

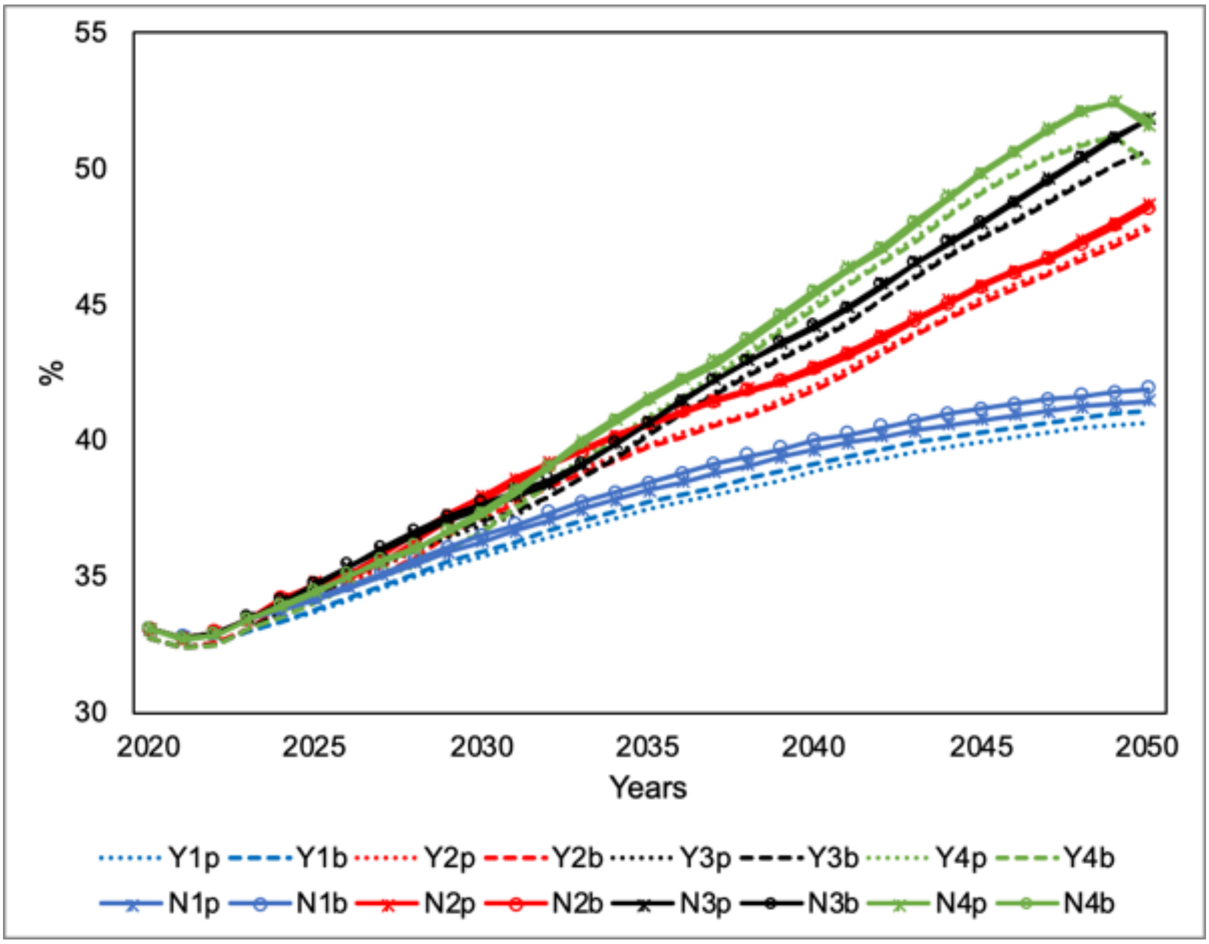

Fig.5: Share of geothermal electricity in total electricity production for different simulation scenarios [%/year] (lines of same colour represent same GDP growth rates)

5.2 Geothermal reservoir stock

Fig. 6 depicts the remaining geothermal resource availability as percentage of maximum plant site stock in different scenarios for each plant site (A to O). In all scenarios with a GDP growth rate higher than 2% (Y2 to Y4 and N2 to N4) a significant reduction in resource availability can already be witnessed for almost all plant sites in 2050 (i.e. D, E, G, H, I, N, O) due to high demand and thus production levels. Plant sites that have only started to be exploited excessively by then follow a clear decreasing trend (i.e. J, K, L, M). However, this is not true for the scenarios of lower GDP growth (Y1 and N1) as production rates are not excessive and only minor drawdown is experienced. The figures for plants J, K, L, M and O show that the consideration of geothermal resource dynamics leads to differences in resource distribution between the different plant sites. The conditions of EVs does not affect resource availability of plant sites significantly, because it only represents a small share of overall electricity demand.

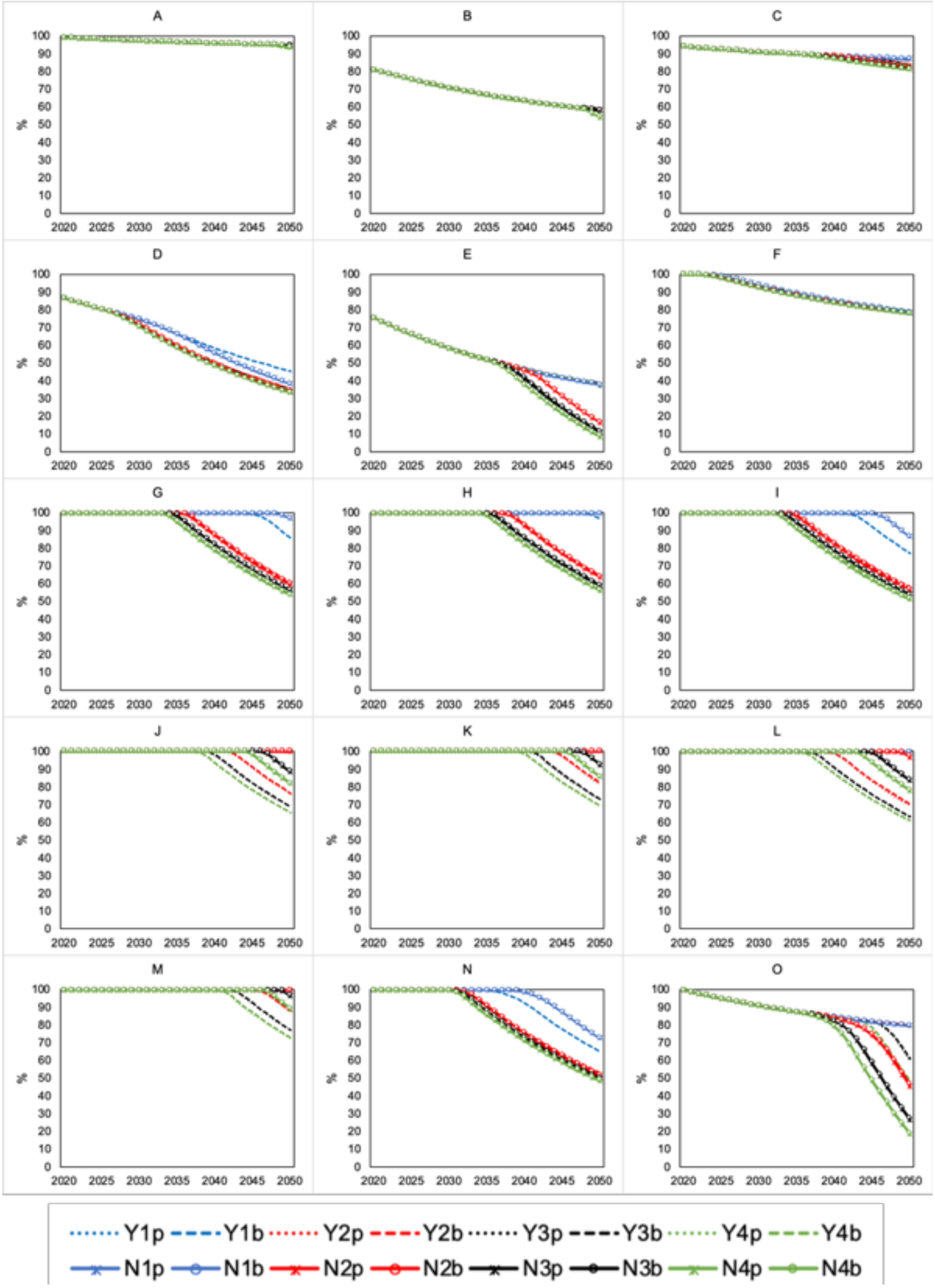

Fig.6: Percent of available geothermal resource of maximum plant site stock per plant site [%/year] (lines of same colour represent same GDP growth rates)

5.3 Average unit production cost

Fig. 7 shows the average unit production cost for electricity for all scenarios, grouped by the rate of GDP growth. In all scenarios, the results depict that when geothermal resource dynamics are considered, estimated average unit production cost will be higher in 2050 than when those dynamics are not considered. This effect occurs because excessive geothermal resource utilization leads to geothermal production capacity losses, which needs to be compensated by additional well drilling investment. In 2050, the average unit production cost can be up to 19% higher (in scenario Y2b) when geothermal resource dynamics are considered than when they are not considered. The reason why the cost difference in 2050 in Y2 scenarios is higher than in scenarios Y3 and Y4 is because after 2046 (Y3) and 2048 (Y4) no additional geothermal capacity can be added in the latter two. This means only hydro and wind capacity can be added, which means the effect of geothermal resources becomes smaller due to its lower share in total capacity. Hence, the difference caused by geothermal resource dynamics decreases after reaching a peak of 22.0% and 21.5% in scenarios Y3p and Y3b and 21.4% and 21.0% in scenarios 4a and 4b, in 2043 and 2041 respectively. The higher electricity demand by EVs influences the average unit production cost to a small extent. As expected, more EV uptake increases electricity demand, which means a higher unit production cost, because geothermal resources get utilized more excessively and more plants need to be installed. In 2050, the difference in average unit production cost caused by EV uptake is similar in all scenarios and follows a growing trend.

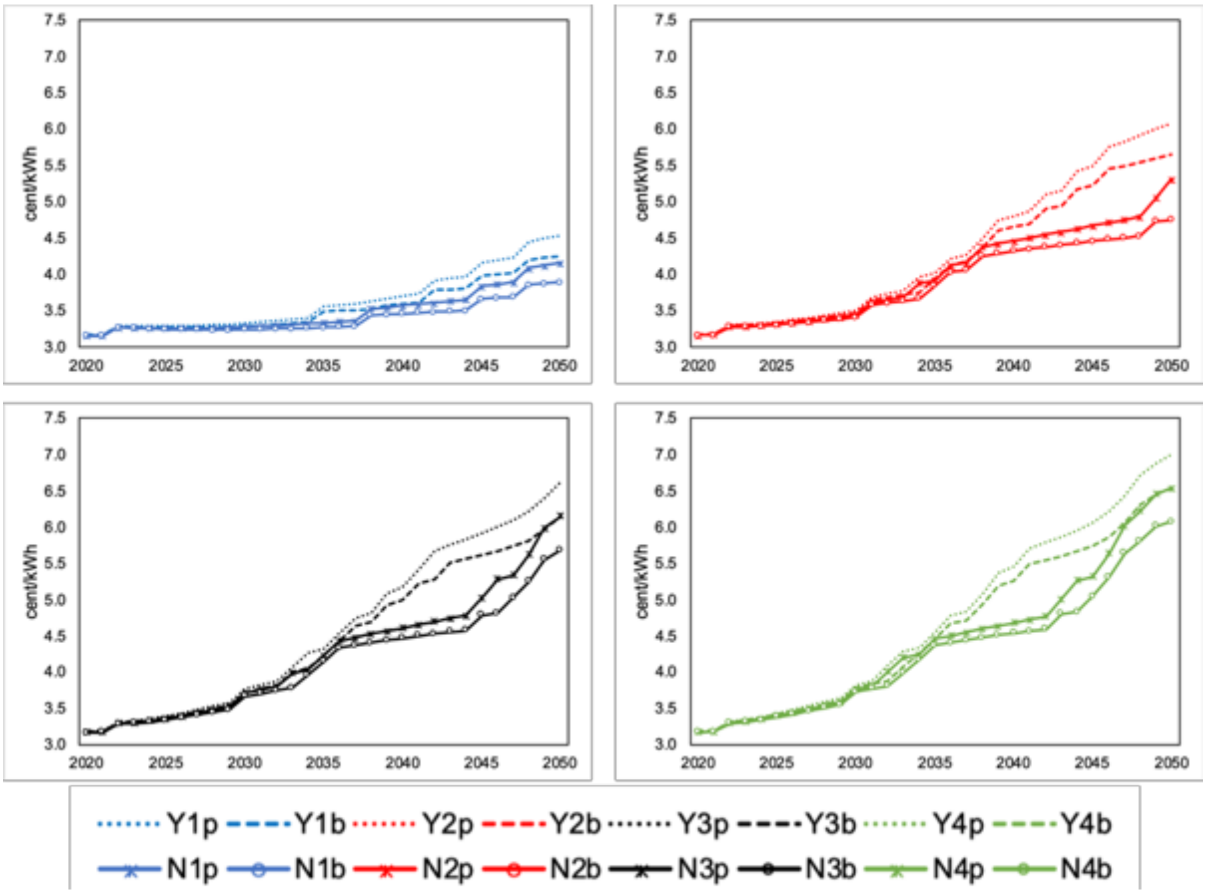

Fig.7: Average unit production cost in Iceland for Iceland's electricity production sector [cent/kWh] (grouped by same GDP growth rates)

Fig. 8 presents the difference in average unit production cost of geothermal electricity between scenarios that do (Y1 to Y4) and those that do not (N1 to N4) account for geothermal resource dynamics. The estimated cost increase is almost 17% higher in high demand scenarios (Y4). The difference in scenarios that are favorable for EVs and those that are not is only visible in scenarios of high demand (Y3 and Y4). This trend is growing towards the end of the simulation period. In scenarios with a GDP growth rate that is higher than 1.25% and geothermal resource dynamics are considered, hydro and wind power become more competitive at an earlier stage. However, despite increasing unit production cost, the minimum cost at which geothermal can be installed remains lower than that of wind for longer (2044 to 2049), because significant cost increases in geothermal electricity production only occur when the geothermal resource has been utilized excessively for some time. In Fig. 5 the effect of higher average unit production cost of geothermal electricity due to resource dynamics, as displayed in Fig. 8, is shown by the lower share of geothermal production in total electricity production in scenarios that account for geothermal resource dynamics (Y1 to Y4) compared to those that do not (N1 to N4).

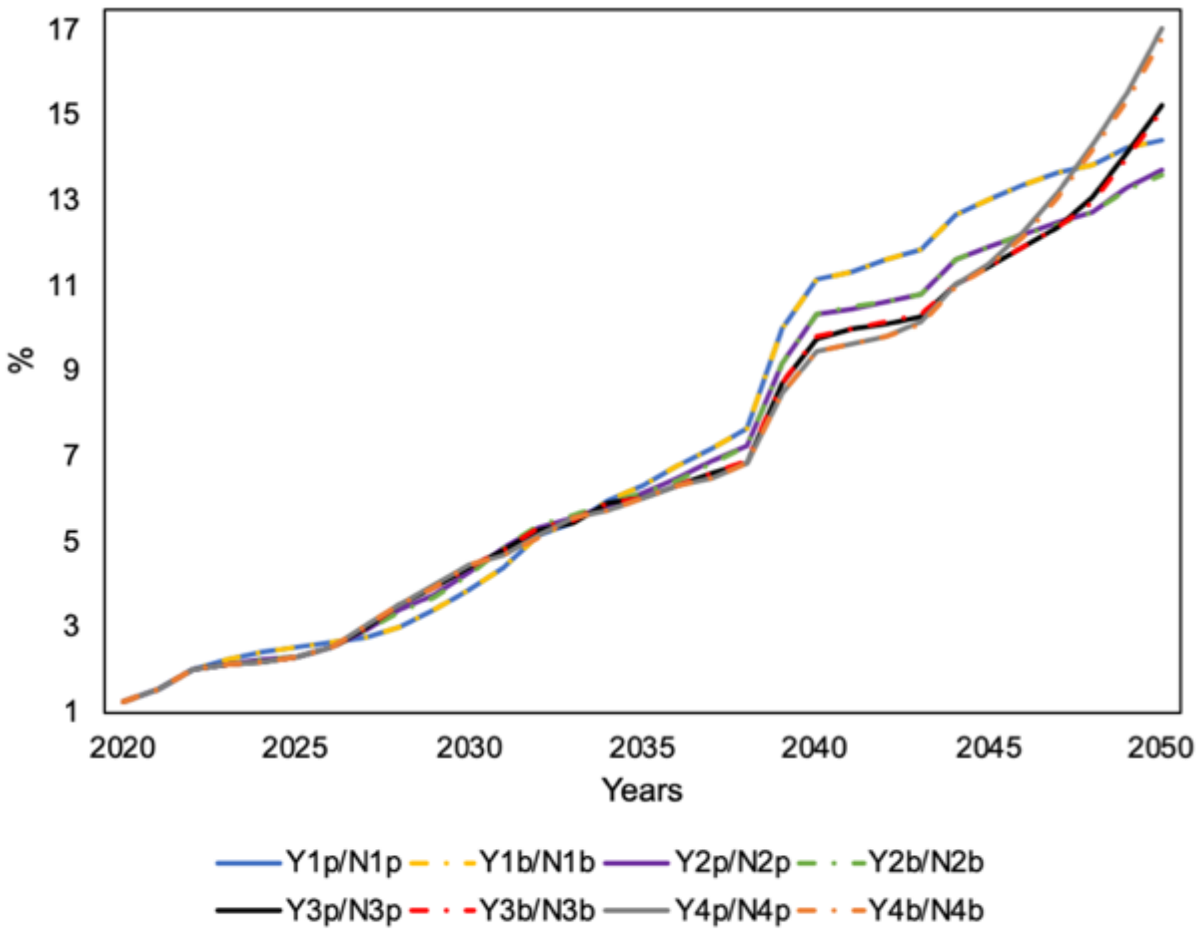

Fig.8: Impact of resource dynamics modelling on estimated average unit production cost of geothermal electricity [%/year]

5.4 GHG Emissions

Fig. 9 presents GHG emissions as MtCO2eq in the various scenarios grouped by the GDP growth rate. Those emissions include emissions from fuel combustion and geothermal electricity production. The effect of favouring conditions for EVs on emissions is similarly significant in all scenarios. However, GDP growth is a major factor. Only in the scenarios in which the GDP growth rate is 1.25%, do emissions per year decrease. In all other scenarios, emissions per year increase. The influence of geothermal resource dynamics on estimating emissions is almost insignificant, because they do not affect EV uptake notably.

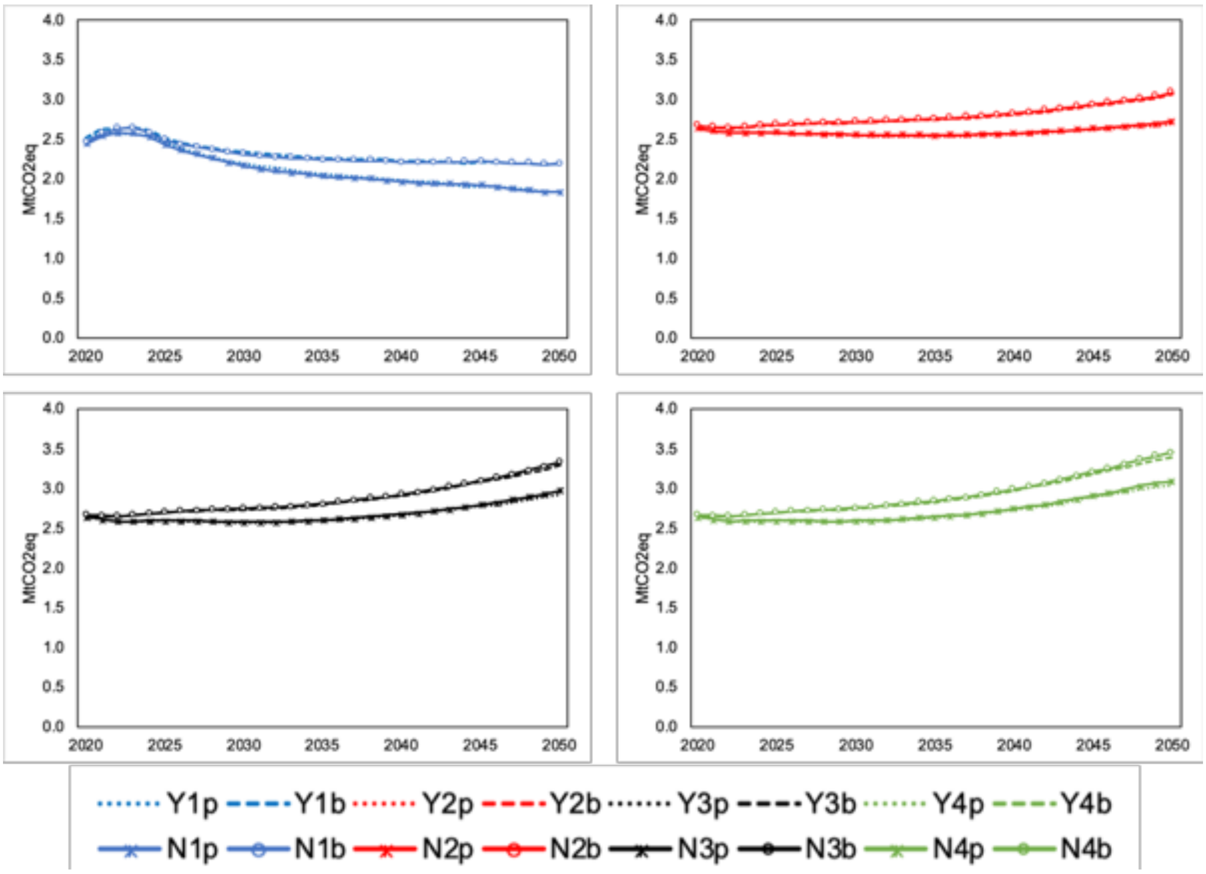

Fig.9: GHG Emissions in Iceland [MtCO2eq per year] (grouped by same GDP growth rates)

6 Discussion

The goal of the simulation analysis was to understand the relevance of geothermal resource dynamics to sustainable energy system development in Iceland and, especially, to investigate if electrified transport pathways presented in previous studies (e.g. [6,9]) are robust considering different demand scenarios as outlined by Iceland's National Energy Authority [10]. Geothermal resources, although assumed to be twice the approved size of that in the Icelandic Master Plan, are completely utilized by 2050 in scenarios of high GDP growth (Y3, Y4, N3, N4), indicating excessive use. In the modelled time period, geothermal resource dynamics only have a small impact on total actual electricity production as it is on average only 0.8% higher in scenarios that do not consider geothermal resource dynamics. Small variations in amount of electricity produced from geothermal resources occur during the simulation period. However, additional well construction and other resources such as hydropower and wind power can compensate for geothermal drawdown. This is because the effects of excessive utilization of geothermal resources and the resulting drawdown, which might eventually lead to a temporary exhaustion of the resource, appear with a delay. Hence, bigger production losses because of geothermal drawdown will become more significant in the long term. This can be seen in decreasing resource availabilities displayed in Fig. 5. This finding is similar to [21], who showed that the optimal plant size of individual plants is bigger if the use of it is restricted to less years. In the short term, the main impact is seen on production cost and resource availability. The share of geothermal electricity produced is lower in scenarios that take into consideration geothermal resource dynamics (see Fig. 5), not only because of the decrease due to drawdown but also because geothermal resources become less cost competitive compared to hydro and wind.

In the scenarios of high GDP growth rates, resulting in high energy demand, geothermal resource availability is notably reduced by 2050. This means that additional well drilling is necessary to keep desired production levels of geothermal plants at each site. This leads to increased unit production cost for geothermal electricity and therefore higher unit production cost on average for the power supply system. Higher overall unit production cost also occur because higher geothermal unit production cost makes them less competitive leading to redistribution of share in new installations and in some scenarios no additional geothermal resources can be harvested. The effect on the share of geothermal resources in the total electricity production is similar other studies, which apply resource cost supply-curves for geothermal resources [18].

Hence, the excessive use of geothermal resources not only affect the sustainability of resources as can be seen in Fig. 6 but also affects the unit production cost, which relates to several aspects linked to sustainable energy system development as pointed out by [5]. Excessive use of geothermal energy reduces the economic feasibility of geothermal power plants, which has been demonstrated for individual plants in Iceland and other countries before and now is shown on a national system's level [30]. As discussed in the paper, energy intensive industries in Iceland have long-term contracts with power suppliers that sustain electricity prices at relatively low levels. Therefore, increases in unit production cost cannot lead to higher electricity prices for those that have such contracts. To maintain profitability, the higher unit production cost will need to translate into higher prices for other consumers, such as households and small businesses. Because of the low electricity prices, this only has a minor effect on demand.

Even if their contribution is small overall, results also show that the effect of EVs uptake on unit production cost is increasing, independent of whether or not resource dynamics are considered. This is because increased electricity demand leads to the utilization of more expensive resources (i.e. hydro and wind) in all scenarios. The unit production cost is highest when resource dynamics are considered as well (see Fig.4). Looking at scenarios S3, S4, S7 and S8 in Fig.7 shows that towards the end of the simulation period emissions are lower when resource dynamics are considered. This results from the increased unit production cost and thereby small but seemingly growing effect on EV uptake.

The results illustrate the limitations of the capacity of the Icelandic geothermal resources and the implications of high demand scenarios for both resource capacity and unit cost of electricity production. The analysis carried out in this paper only explored the effects of considering geothermal resource dynamics. Other supply side dynamics, such as those of potential effects of climate change on hydro resources as studied by [31], in combination with geothermal resource dynamics could provide additional insights on the effects of different pathways on sustainable energy system development in Iceland.

7 Conclusion

Overall, the results show that geothermal resource dynamics are important when assessing future energy pathways to gain a more holistic picture of sustainable energy system development in Iceland, even if not all sustainability relevant factors are influenced to a large extent. Most importantly, the integration of individual geothermal fields and their dynamics, allows to see the effects of growing electricity demands on the geothermal resources themselves. This makes it possible to assess an important component of sustainable energy system development namely that of the sustainability of renewable resource use. The inclusion of geothermal resource dynamics allowed to provide further insights into the implications of industrialization and electrifying Iceland's vehicle fleet. Their rather small effect on resource availability, emissions and cost (compared to general electricity demand growth due to increasing GDP) showed that current efforts of promoting EVs are sustainable and robust in terms of emissions as well as resource aspects. However, high GDP growth rates and increased demand can lead to significant reductions in geothermal resource availability, which in turn affects electricity production cost, which could negatively influence the affordability of electricity.

To even better understand the sustainability implications of potential future pathways, it is recommended to investigate scenarios that include a broader range of resource dynamics on the supply side (i.e. wind and hydro). This will be necessary to understand the long-term effects of electrification in Iceland. While supply curves might be able to capture cost increases due to intensifying resource utilization, they are not able to capture the effects on the resource. By incorporating geothermal resource dynamics not only the cost increases due to higher utilization of the geothermal resource were captured, but also the effects of the excessive utilization on the resource itself was displayed. This means a more holistic picture of the energy system and the resources it is depending on is presented.

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7 Summary and Discussion

7.1 Summary

The main objective of this thesis was to investigate the dynamics of sustainable energy system development in the global north and global south, with a special focus on renewable resource dynamics. This research first focused on understanding the dynamics for achieving sustainable energy system development. This commenced in Paper I, which conceptualized Daly's economic theory of the steady state and applied it to the energy system (Daly, 1974). By employing a system's thinking approach, it became possible to conceptually investigate the inherent system's dynamics and explore the usefulness of different strategies for achieving a sustainable energy system. Furthermore, it supported understanding of the strategies that might facilitate or prevent more sustainable development. For example, efficiency increases, and thus many energy policies and proposed strategies that affect efficiency, leads to less waste along the energy supply chain. However, efficiency increases might actually cause growing resource use even if the direct rebound effect is not considered. Using Donella Meadow's leverage point concept allows understanding of the impact level of various leverages (i.e. intervention strategies/ policies), such as energy efficiency (lower leverage) and energy sufficiency (higher leverage) (B. D. H. Meadows, 1997). Based on the understanding of the dynamics of a sustainable energy system, the way sustainable energy system development and design has been approached by others was examined. The way sustainable energy development is framed in the current discourse led to the definition of the current energy paradigm and eleven questions arising from it in Paper II. As energy system models are a major tool to answer questions about future energy systems and designing them, an analysis of the models focused on how they address the questions arising from the new energy paradigm. This led to identification of the strengths and weaknesses of current energy system models in answering questions related to sustainable energy system development. One of the identified weakness was the representation of renewable resources and their specific constraints. Renewable resource dynamics and their leverage potential were also discussed in Paper I. For the two selected cases, Iceland and Kenya, geothermal energy and related resource dynamics are particularly important (Lahmeyer International, 2016; Orkustofnun - National Energy Authority, 2018d). Hence, in Paper III, a model was developed that is able to capture the physical realities of geothermal resource dynamics and its relevant aspects for energy systems modelling (i.e. power plant construction, utilization for electricity production, resource availability, production cost). This model was tested for geothermal resources in Iceland. Based on this model in Paper IV, the implications of the dynamics of renewable resources, focusing on hydro and geothermal, for electricity system planning in Kenya were assessed. It was found that despite the currently small share of electricity in overall energy consumption in Kenya, future plans for expanding overall capacity, specifically hydro and geothermal power, it is important to consider them in future energy system planning. This is because hydro and geothermal dynamics influence the system's patterns as well as total cost. Additionally, resource dynamics are relevant for (sustainable) future electricity system planning, especially when considering trade-offs between different parameters, such as share of electricity access and share of renewables in the electricity mix. In Paper V, an assessment was conducted of the role of geothermal resource dynamics for national sustainable energy system development, with a focus on CO_2 emissions and cost in Iceland. Findings show that geothermal resource dynamics do not significantly affect current efforts to increase the sustainability of the Icelandic energy system and to reduce GHG emissions by electrifying Iceland's vehicle fleet, assuming low growth in electricity demand from other sectors. However, when incorporating geothermal resource dynamics, it becomes visible that an increase in energy demand, such as from energy intensive industries can, especially in the long-term, lead to reduced availability of geothermal resources and thereby, increase unit production cost of electricity, which in turn results in the reduced economic feasibility of electrified transport.

7.2 Discussion of results

In this section, research approaches and results from the five papers will be discussed in terms of:

- The importance of understanding the dynamics of sustainable energy system development (in different contexts)
- Approaches to addressing sustainable energy system development
- The role of renewable resource dynamics in energy system development

Each section starts with bullet points of the specific findings of this thesis and provides a more general discussion about the insights.

7.2.1 Understanding the dynamics of sustainable energy system development (in different contexts)

- Adapting Daly's Steady State theory to the energy system by using systems thinking supports better understanding of feedbacks, drivers and barriers of sustainable energy system development, globally, in the global north and the global south.
- Despite countries specific contexts and being at different development stages, they can face similar challenges arising from the same underlying dynamics of renewable resources.
- Depending on the context, policies aimed at increasing energy efficiency and renewable energy can put additional pressure on the environment.
- If energy or policy options are analysed independently and do not account for the entire system (i.e. dynamics between different sectors), the side effects of measures and policies are missed.

Sustainable energy system development is a prerequisite for sustainable social, environmental and economic development and thereby, essential for achieving many of the SDGs (Modi et al., 2005; Najam & Cleveland, 2003; Ogola et al., 2011; Steffen et al., 2005; Steinberger & Roberts, 2010). Paper I showed that a global vision of sustainable energy system development is relevant to achieving global environmental and social goals. SDG 7 can be seen as a globally agreed vision of sustainable energy system development. Its targets are wide enough to be relevant to the global north and the global south (United Nations, 2018). Despite targets (7.1 to 7.3) of SDG 7 demanding more reliable and affordable energy access, a higher share of renewables and efficiency improvements, globally no clearly defined goal exists in terms of numbers for each of these (United Nations, 2018). Paper I showed that a clearly defined vision of sustainable energy system development and a holistic understanding of the dynamics of such a system is important for designing sustainable future (energy) systems. This is because it helps to understand on how strategies to improve certain components of the system (e.g. energy efficiency, switching from fossil to renewable resources) relate to other components (e.g. additional energy service demand). Thereby, a systems perspective allows investigation of how changes in one variable affect other variables of the system and makes it possible to identify synergetic and adverse feedbacks arising from changes in that variable due to interventions, such as policies. Although focused on the SDGs in a broader context, Collste et al. also found that systems thinking is important for coherent policy-making when dealing with systems that aim to attain several goals (Collste, Pedercini, & Cornell, 2017). More explicitly focused on energy systems, Bale et al. argue that energy systems are complex systems, which are closely linked to social, environmental and economic aspects. Thus, they argue for the consideration of elements of the energy system in a holistic manner rather than isolated from each other (Bale, Varga, & Foxon, 2015). Although Paper I focused on developing a general and global vision of sustainable energy system development, it became apparent that this overall vision can translate into various distinct visions and related actions in different contexts, such as different stages of development in the global north and global south. This is in line with SDG 7, which provides a general vision but detailed objectives of sustainable energy system development and ways of achieving them are determined on a smaller scale, such as the national scale (e.g. (Orkustofnun - National Energy Authority, 2018c; SE4ALL, 2016). This idea is supported by Langlois and Vera, who argue that the objective value for a sustainable energy system indicator and its desired direction of change (i.e. increase/decrease) as well as the prioritization of goals vary depending on the context (I Vera & Langlois, 2007). In relation to Daly's steady state economics, Kerschner argues for a global steady state in which the global north de-grows and the global south grows (Daly, 1974; Kerschner, 2010). As outlined in Paper I, for the energy system this means the global north needs to transition from one modern fuel to the other to de-grow their negative environmental impacts and the global south needs to grow by building up a modern energy system to increase positive socio-economic effects. Therefore, the global vision of sustainable energy system development is also shaped by climate concerns (e.g. SDG 13, Paris Agreement) and not only SDG 7, and needs to be translated into several visions that fit the specific context on the national or local level. This argument of differing goals and challenges for achieving more sustainable energy system development is also supported by Paper IV and V. While environmental issues are a major concern in Iceland, the main concern in Kenya is providing access to affordable electricity to everyone (Republic of Kenya, 2018; SE4ALL, 2016; Shafiei, Davidsdottir, et al., 2017; Shortall & Davidsdottir, 2017; Shortall et al., 2015). In both cases, the goal is to achieve sustainable energy system development. While this means something different in Kenya and Iceland, in both cases they are guided by the overarching vision of sustainable global (energy) system development of sustaining and enhancing socio-economic well-being and keeping environmental effects to a minimum. This also means different targets of SDG 7 and other SDGs (e.g. SDG 13) are prioritized. Even if the priorities for achieving different goals of sustainable energy system development are distinct in both countries, the underlying dynamics of the geothermal resources influencing sustainable energy system development are the same.

7.2.2 Approaches to addressing sustainable energy system development

- Current energy policies mostly tackle low leverages (e.g. energy efficiency) but tackling high leverages (e.g. sufficiency, energy justice) is necessary for achieving sustainable energy system development globally.

- Many energy system models do not at all or just address important aspects of the current energy paradigm in an oversimplified manner, such as the limits of renewable resources and social aspects (e.g. equity, accessibility, affordability).
- Developing energy system models further and making them adaptable to specific contexts can help to address and answer a wider range of questions arising from the current energy paradigm.

In line with what Abson et al. found for general sustainability-related policy, the leverage point analysis in Paper I showed that many of the current energy policies or proposed strategies (e.g. energy efficiency increases) to make the energy systems more sustainable are of lower leverage (e.g. (European Commission, 2017; United Nations, 2018) (Abson et al., 2017)). Lower leverage points are those that do not lead to system change on a larger scale and thereby, are not as effective as leverages of higher order. However, the identified higher leverages, such as redefining the goals of the system to energy sufficiency or justice, are not addressed as much in current energy-related policies. Especially energy justice is an often abstract emerging field, the results of which need to be made comprehensible for future policy-making (Jenkins, McCauley, & Forman, 2017).

Paper II investigates how sustainable energy system development has been addressed in more detail. It explores how the world view in the field of energy has changed and the current energy paradigm emerged. The definition and analysis of the current energy paradigm in Paper II found that the focus of the debate in the field of energy research and policy has shifted from a more techno-economic understanding of the energy system to a more holistic understanding. This is due to the fact that energy increasingly gained attention in the field of sustainable development and the political debates around it. Because of the connection between energy and sustainable development, the following question is central to the current energy paradigm: "How do different energy system pathways impact the (sustainable) development of the energy system and overall (sustainable) development globally and nationally?". From this a number of sub-questions, which address environmental, economic, technological and social aspects related to the energy system, were formulated in Paper II. Those should be answered or at least addressed when dealing with future energy systems. A common tool for understanding and facilitating decisions about (sustainable) energy system development are energy system models. Hence, they should address and answer the questions related to the current energy paradigm. Since Paper II is the most recent and holistic approach to defining the current energy paradigm, other energy model reviews have not assessed available models in such a holistic manner. However, the importance of better understanding of models and relating them to current research and policy interests is reflected by a number of energy model reviews (e.g. (DeCarolis, Hunter, & Sreepathi, 2012; Després et al., 2015; Jebaraj & Iniyan, 2006; Lopion, Markewitz, Robinius, & Stolten, 2018; Nakata, 2004; Nakata, Silva, & Rodionov, 2011; Pfenninger et al., 2014; Ringkjøb, Haugan, & Solbrekke, 2018)). Those reviews investigated models through different lenses. Some reviews mainly dealt with general questions on the challenges models face when used for policy-making, such as transparency, accuracy, uncertainty and argue that potential for improvement exists (e.g. (DeCarolis et al., 2012; Jebaraj & Iniyan, 2006; Pfenninger et al., 2014). Others focused on the applicability of models in a specific context. For example, Bhattacharyya and Timilsina assessed whether existing energy system models were suitable to be used in the context of developing countries and found that this was often not the case (Bhattacharyya & Timilsina, 2010a). Some model reviews address questions regarding explicit sectors or aspects of energy system modelling. For example, energy demand, which is often modelled in a simplified manner by for example using price elasticities (Bhattacharyya & Timilsina, 2010a; Pfenninger et al., 2014). However, it can be argued that more realistic ways for capturing demand including aspects such as the role of actors' behaviours and especially technological learning needs to be considered in more detail in order to be able to understand sustainable energy system pathways (Bhattacharyya & Timilsina, 2010b; Li, 2017; Martinsen, 2011). This has not been addressed explicitly in the model review presented in Paper II but could be investigated when assessing the models' capabilities to capture path dependencies and links between the energy, economic and social systems (questions 8 and 9 arising from the new energy paradigm). The question of emissions reductions and the representation of renewable resources has been explored in detail by several reviews (e.g.(Després et al., 2015; Lopion et al., 2018; Nakata, 2004; Nakata et al., 2011; Pfenninger et al., 2014; Ringkjøb et al., 2018)).

The research carried out in this thesis also shows the relevance of the context for how sustainable energy system development is addressed from a research and policy perspective. As already pointed out previously and discussed in more detail in Paper I, IV and V, goals and priorities of those might vary in different countries. Therefore, it was found that research objectives, models and policies addressing sustainable energy system development (should) adhere to the specific national contexts. This is in line with what others have found and argued before. However, more recent and context-specific modelling efforts for the energy system in Kenya have included low carbon energy or electricity system models that estimate macro-economic effects (e.g. (Willenbockel, Osiolo, & Bawakyillenuo, 2017)) or models that calculate the most favourable combination of on- and off-grid electrification (Moksnes, Korkovelos, Mentis, & Howells, 2017; Zeyringer et al., 2015). A central aspect of those and the following models is cost-minimization. This is also in line with the government's plans of least cost power development planning (Lahmeyer International, 2016; Republic of Kenya, 2018). In general, energy system development and access to modern energy has been addressed as a prerequisite for socio-economic development and important for achieving the goals of Kenya Vision 2030 (Gainer, 2015; Government of Kenya, 2018; SE4ALL, 2016). Despite the high reliance of renewable resources for electricity production in Kenya, especially hydro and geothermal, none of the above-mentioned studies considered the dynamics of geothermal resources. Hydro dynamics were only considered by Lahmeyer International (2016). Paper IV depicts the importance of those dynamics when addressing sustainable electricity system development, especially in the long-term because those dynamics influence resource availabilities and possible generation, production cost and thereby prices, which are key parameters for providing affordable and accessible electricity for all.

In Iceland, the main modelling efforts concerning sustainable energy system development have been based on UniSyD_IS, Iceland's energy and transport system model (Shafiei et al., 2018, 2016; Shafiei, Davidsdottir, Leaver, Stefansson, et al., 2015b). This model is used for assessing different pathways, of particularly the transport sector, to transition away from fossil fuels. It focuses on understanding alternative fuel options and the effects of such a transition on parameters including cost for consumers, emissions and macro-economic cost of policies supporting the transition. This is also in line with the government's policies to achieve a carbon-neutral energy system by 2040 (Shafiei et al., 2019). Paper V showed that another important aspect of sustainable energy system development is geothermal resource availability. Energy intensive industrial developments draw heavily on geothermal resources, leading to unsustainable utilization of them. The sustainability of geothermal resources in Iceland has only ever been analyzed through individual reservoir management studies but not on a system's level before (e.g. (Gudni Axelsson, 2012; Juliusson et al., 2011; Stefansson & Axelsson, 2005).

The above shows that sustainable energy system development has been addressed through various modelling efforts for Iceland and Kenya. In both cases, context specific models were used to investigate sustainable energy system development. However, none of them considered the dynamics of geothermal resources. The only resource dynamics considered were those of hydro, as the effects of climate change on hydro resources were explored (i.e. question 3 in Paper II) (Lahmeyer International, 2016; Shafiei, Davidsdottir, Leaver, Stefansson, et al., 2015a).

7.2.3 The role of renewable resource dynamics in energy system development

- Physical realities of geothermal resources are important when trying to understand long-term sustainable energy system development holistically (i.e. including resource availabilities).
- Increasing cost due to overutilization of geothermal resources is a challenge faced in the global north and global south, which is only visible when renewable resource dynamics are incorporated in national energy/electricity system models.
- In future energy system analyses, the dynamics of renewable resources and fossils need to be considered because they alter the economic feasibility of different resources, leading to shifts in the electricity/energy mix.
- In Iceland, renewable resource dynamics are particularly important in high demand scenarios because they affect the feasibility of different decarbonisation pathways.
- In Kenya, renewable resource dynamics are especially important when trying to understand the connection between electricity access, affordability and shares of renewables in the energy system.

As outlined in this thesis, Kenya and Iceland both have high renewable resource potential, which play a major role in their plans for sustainable energy system development. In addition, they both have distinctive visions and priorities with regards to sustainable (energy) system development. Still, both countries are faced with the same challenges on the supply side, which are the dynamics of renewable resources, especially hydro and geothermal. Paper IV and V show how geothermal resource dynamics are relevant for sustainable energy system development in both cases and should be considered in energy system models. Renewable energy resources and their physical realities have also been defined as an important component of the current energy paradigm in Paper II. The results of Paper II showed that specific models and model types can provide answers to some of the relevant questions of the current energy paradigm. However, not all questions, such as the ones relating to the physical realities of renewable resources (questions 3 and 5), can be fully answered by existing models. This connects to the analysis in Paper I that showed that renewable resource dynamics are of a complex nature, which need to be considered when dealing with sustainable energy on a systems level. In models, the physical realities of renewables (e.g. intermittencies) are often only represented in a simplified manner by including exogenously defined limits (e.g. (Lan et al., 2016; Mondal et al., 2017; Ou et al., 2018; Shmelev & Van Den Bergh, 2016)) or through cost-supply curves (e.g. (de Boer & van Vuuren, 2017; Shafiei et al., 2014; Shafiei, Davidsdottir, et al., 2017; Shafiei, Davidsdottir, Leaver, Stefansson, et al., 2015b; Shafiei, Leaver, et al., 2017)). Efforts have been made to more accurately integrate the physical reality of the intermittencies of many renewable resources into energy systems models (e.g. (Després et al., 2015, 2017)). The impacts of climate change on renewable resources has increasingly been addressed, particularly the effects on hydro resources (de Queiroz et al., 2016; Fant et al., 2016; Hisdal et al., 2007; Pryor & Barthelmie, 2010; Schaeffer et al., 2012; Shafiei, Davidsdottir, Leaver, Stefansson, et al., 2015a; Turner, Hejazi, Kim, Clarke, & Edmonds, 2017). Despite growing awareness about the need to represent the physical realities of renewable resources and the importance of sustainable management of them in reservoir management research (e.g. (Gudni Axelsson et al., 2005; Juliusson et al., 2011), geothermal resources for electricity production are usually represented in a simplified manner by including exogenous resource constraints or cost-supply curves (e.g. (Hori, Matsui, Hasuike, Fukui, & Machimura, 2016; Lenzen et al., 2016)). This can lead to misleading estimations of electricity production cost and resource availability and thereby, suboptimal strategies for sustainable energy system development, as shown through the cases of Iceland and Kenya. As outlined in Paper I, renewable resource dynamics are important in all contexts (i.e. global, global north, global south) and their dynamics need to be considered independent of the context. However, the detail of representation needs to vary for different spatial scales (global, regional, national). While the effects of renewable resource dynamics are the same in all contexts (e.g. cost increases), the strategies to deal with them and their implications might vary depending on the specific goals of energy system development in different national contexts. For the Kenyan case (i.e. Paper IV), it was decided to focus on the role of renewable resources with regards to electricity system expansion, because this is central to achieving Kenya's defined economic and energy system goals (Government of Kenya, 2018; Lahmeyer International, 2016; SE4ALL, 2016). Another reason to focus on the supply side of the electricity system was availability of data. Also, Bhattacharyya and Timilsina identified a lack of data as a major challenge for using popular existing energy system models (e.g. MARKAL) in developing countries (Bhattacharyya & Timilsina, 2010a). In the case of Iceland, connecting geothermal resource dynamics to a broader energy and transport system model (i.e. UniSyD_IS) was necessary to understand the role of resource dynamics in the overall objective of sustainable energy system development. The integration of the geothermal resource module into UniSyD_IS (Shafiei, Davidsdottir, et al., 2017; Shafiei, Leaver, et al., 2017) made it possible to understand how economic growth and the transition away from fossil fuels, especially of the transport sector, affects environmental sustainability in terms of defined decarbonisation goals and resource availability. When geothermal resource dynamics are considered, current efforts to reduce emissions through electrifying Iceland's vehicle fleet remain sustainable from an environmental perspective and robust for the modelled time horizon (i.e. 2050) even in scenarios of high industrial energy demand. However, resource availability is threatened and other parameters, such as unit production cost, influencing the sustainability of the energy system follow negative trends in the long-term.

Additional to the dynamics of renewable resources, Paper I discussed the role of renewable resources for sustainable energy system development. It showed that although renewable resources are often seen as a core solution to achieving sustainable energy system development, several issues exist regarding their sustainability and their contribution to sustainable energy system development. As discussed in Paper I, generally renewables are of lower quality than fossil fuels when considering the EROI. Hence, with an increasing share of renewables, the EROI of the energy system decreases. Atlason and Unnthorsson (2014) found that in Iceland geothermal and wind power plants have the lowest EROIs. When geothermal resources are used for cogeneration, their EROI can be improved but still remains small (R. Atlason & Unnthorsson, 2014). This challenges the assumption about the contribution of large geothermal power to a sustainable energy system transition, even when geothermal resource dynamics are not considered. When geothermal resources are used at different temperatures (i.e. cascading use), such as in cogeneration, the EROI can be improved. Geothermal fluids can also be utilized at different temperatures for non-power related purposes. Depending on the context, the hot fluids can be used differently. In Iceland, this includes the heating of houses and greenhouses (R. S. Atlason & Unnthorsson, 2013). In Kenya, the hot water is used to boil food (especially eggs and meat) and heat greenhouses (Achieng, Davidsdottir, & Birgir, 2012).

Extensive exploitation and excessive utilization of renewables can be unsustainable. This is especially the case for geothermal resources, because they have a low EROI, which makes them unsustainable from a resource perspective, and their dynamics lead to additional effects that make them unsustainable from a resource as well as economic perspective. Therefore, plans of utilizing geothermal resources to the extent Iceland has done, and Kenya plans to do, cannot be considered sustainable energy system development, unless geothermal power plants are developed in a step-wise manner, preventing excessive utilization and ensuring cascading use of the geothermal resource. Therefore, an electricity system that largely relies and is planned to rely on renewables is not enough to consider it a sustainable energy system but more aspects need to be considered. If the energy system heavily relies on resources that can be exhausted and this is not considered, a renewable based electricity system can also be unsustainable. As shown in the validation in Paper III, Iceland has experienced this. This is also in line with the findings in (Shortall et al., 2015), which identified that renewability, efficiency, economic management and profitability, energy equity, energy security and reliability are essential components of sustainable geothermal energy. This means renewables and geothermal resources in particular need to be considered more holistically when modelling and planning sustainable energy systems.

7.3 Contribution to knowledge

This research has both practical and academic implications. The development of the resource dynamics model is the most tangible contribution, however, other important contributions can be identified.

7.3.1 Practical

The practical contribution of this research mainly relates to energy system modelling. However, the more conceptual part of this research can also be used in a more applied way. Paper I provides insights into how effective different energy policy interventions are by assessing their leverage according to Meadow's leverage point concept. The developed sustainable energy system vision together with Meadow's leverage point concept can be used to also assess future policies, by either looking into how a change in an already included variable influences the overall system or by investigating how a new structure that is added to the existing one could affect the system. The developed CLD is an additional visual tool that practitioners can use to comprehend and communicate the complexity of sustainable energy system transitions.

The questions presented in Paper II represent the worldview of ongoing energy research and policy debate as they are resulting from the current energy paradigm. Defining the energy paradigm and resulting questions in such a holistic manner has not been done recently. The definition of the current energy paradigm and arising questions helps to understand the main challenges of current energy system development and modelling. Additionally, the questions determined by the current energy paradigm can support energy system modellers or analysists as well as policy makers to guide their model choice to best address and answer the proposed questions.

The geothermal model is a practical tool that captures geothermal resources in a simplified manner. It makes it possible to run scenarios and assess the resource and its economics on a system's level (e.g. national scale). This has two practical implications: (i) better decision-making on the utilization of the resource, because desired demand scenarios (i.e. allocated share to geothermal) can be tested and their possible effects on resource availability, production overall and of individual plants and cost can be assessed in a simplified manner; (ii) improved decision-making in overall electricity and energy system planning because of more accurate calculations of aforementioned variables and their effects on overall energy systems (e.g. new adjusted share of geothermal electricity, production levels).

The model presented for electricity system planning in Kenya can be used to test different demand scenarios and their effects on geothermal resources. This makes it possible to quantitatively assess the risks of excessive geothermal utilization in terms of resource availability and cost as well as sustainability implications. The connection of geothermal resource dynamics to a national energy system model, such as UniSyD_IS, enables understanding of the implications of geothermal resource dynamics for sustainable energy system design on a national energy system's level. Thereby, this research contributes to a more holistic understanding of sustainable energy system development in Iceland, including resource effects. This can support improved policy-making, due to more accurate representation of cost dynamics and estimations of resource potentials.

7.3.2 Academic

Paper I contributed to developing a systemic and dynamic understanding of sustainable energy system development. Placing energy at the centre of Daly's steady state theory supported building a holistic vision of a sustainable energy system. This contributed to the debate on steady state economics, which has only been addressed to a very small extent in recent literature. By using CLDs, the steady state theory was investigated from a more dynamic perspective. This made it possible to uncover underlying dynamics of a steady state of energy system and explore how different strategies for achieving such an energy system interact with other variables than the one that is explicitly targeted. For example, increasing energy efficiency leads to additional service need, which again means more energy is required overall. Adding the dynamic perspective led to a clearer understanding of feedbacks and leverages and their potential for promoting or preventing sustainable energy system development. Thereby, it added to a more holistic understanding of sustainable energy system development. This research departed from looking at different aspects from an atomistic and mechanistic manner and investigated them from a complex system perspective. Additionally, using Daly's concept in the context of energy system development, brought a new perspective to the importance of sustainable energy system development to stay within planetary boundaries, on the source and sink side.

Through the analysis carried out in Paper II, the current energy paradigm was defined. The need for a new energy paradigm has been addressed before, but no comprehensive definition existed of the current energy paradigm, including its social, environmental, technological and economic aspects. By explicitly defining the current energy paradigm, it became possible to define the relevant questions of the field and assess how energy system models are able to answer those questions. Defining the paradigm and carrying out a model review also pointed to the research gaps concerning sustainable energy system development and its modelling.

The geothermal resource dynamics model contributes in two ways. First, it contributes to an academic debate on simplifying complicated geothermal reservoir dynamics. It builds on already existing research on capturing geothermal resource dynamics on an individual reservoir level but expands it as it investigates geothermal resource dynamics on a system's level. This meant connecting the geothermal resource dynamics of a number of different reservoirs to geothermal plant construction and development cost on a national level. This was done by connecting the dynamics of individual reservoirs to economic calculations, which influence plant and reservoir choice, affecting the level of resource utilization in the different reservoirs. These varying levels of utilization of individual reservoirs influence resource availability in the reservoir, which again impacts on cost and thereby determines plant choice. Second, it contributes to efforts of representing the realities of renewable resources more accurately in energy system models. So far, attempts at improving the representation of renewable resources have mainly concerned intermittent, hydro and biomass resources in energy system models. This is also the case for Kenya and Iceland, in which large geothermal resources exist. Hydro resources and their possible altered behaviour because of climate change have been considered in those two countries.

Through the connection of the geothermal resource model to an electricity / energy system model, the importance of considering geothermal resource dynamics of the specific country in a more realistic way is demonstrated for Kenya and Iceland. Even if cost-supply curves are able to capture increasing cost due to increased utilization of the resource, they cannot provide more detailed insights, such as the relation between the level of resource utilization and resource availability. The geothermal resource module facilitated the observation that in both countries geothermal resource dynamics lead to decreased resource availability and increased unit production cost. This contributes to a more holistic understanding of sustainable energy system development on the supply side, moving beyond a focus merely on emissions .

Finally, the thesis portrayed how different tools of systems thinking can help to understand energy system dynamics. It became clear that different tools (e.g. CLDs, Stock-Flow models, leverage point concept) are useful for different purposes. CLDs proved useful to understand the dynamics and leverages of a potential steady state of energy. It shows that in the case of energy system modelling, system dynamics is a suitable tool, because it allows capture of the feedback between variables and explore various possible future scenarios of national energy systems. The investigated scenarios are based on models which represent the structures of the specific system. Thereby, they explore possible future pathways and possible implications, rather than finding the optimal pathway based on a general theoretical one over simplified assumptions about the system, especially about the physical realities of renewable resources. Due to the physical realities of geothermal and hydro resources, system dynamics represented the best option to capture the stock-like behaviour of geothermal resources and the feedbacks between climate change and hydro resource utilization.

7.4 Limitations and further research

In this section, first the limitations and weaknesses of the study are discussed with respect to the research methods and data used. This is followed by suggestions for further research.

7.4.1 Limitations

In Paper I, the dynamics of a steady state of energy are conceptualized in a purely theoretical manner. Hence, it is only possible to explore the potential influence of variables on each other and the effects caused by strategies (i.e. policies, initiatives, etc.) to achieve a sustainable energy system, but determining the magnitude of such effects is not possible. However, the dynamic conceptual analysis still allowed ranking of different strategies and related policies with regards to their potential leverage. Moreover, several authors point out that understanding dynamics, leverages and their impacts is important for sustainable development (Abson et al., 2017; Bale et al., 2015). Hence, this work is still seen to contribute to sustainable energy system development. Parts of the identified dynamics, especially those of renewable resource dynamics, were investigated further during a later stage in the research (Paper III to V).

In order to prevent biases in defining the current energy paradigm (Paper II), Jabareen's procedure for developing a conceptual framework was applied (Jabareen, 2009). Subjectivism of researchers is often seen as a major limitation in many qualitative research methods. To reduce the effects of this limitation, an extensive and broad literature review was carried out and several iterations of defining the concepts and validating them took place. This is in line with Jabareen's recommendations for preventing subjective results (Jabareen, 2009). Despite those measures, in retrospect the relevance of a more detailed understanding of the demand side, including technological progress and individual behaviour (Li, 2017; Martinsen, 2011), could have received more attention in the review.

The main limitations of the applied part of this research are a result of the general nature of modelling. On the one hand they concern the model and modelling method, on the other hand, they relate to data issues. Models are simplified representations of reality, which is why they can only be used as a support tool for decision-making but their limitations need to be considered too (e.g. (Nakata et al., 2011; Pfenninger et al., 2014)). Like all other modelling approaches, system dynamics has its strengths and weaknesses. The main criticisms of system dynamics addressed by (Featherston & Doolan, 2012) and relevant for this research are now briefly discussed. The first criticism does not concern the paradigm of system dynamics itself but rather the type of systems/problems, which are analysed using system dynamics. This criticism comes from within the system dynamics community (e.g. (Forrester, 2007; Sterman, 2010)), which claims that system dynamics should be applied to non-linear problems, ones involving feedbacks and are not exogenously driven. Due to the characteristics of geothermal resources (i.e. stock-flow systems including feedbacks) and energy systems (i.e. complex systems encompassing a large number of stock-flow structures and feedbacks), this criticism does not apply to the modelling work carried out in this thesis. The second criticism concerns the limitation of system dynamics to represent reality. While this is a limitation of models in general, it is often brought forward in connection to system dynamics, which is more focused on representing general system patterns and scenarios than producing predictions of the future (Featherston & Doolan, 2012). In the case of the geothermal model (Paper III) this limitation was addressed by successfully validating the results for makeup well construction and production levels against historic data for Iceland, which means that the model is able to capture geothermal resources dynamics reasonably accurately for those fields and reproduce it also for others. In the case of the Iceland and Kenya paper (Paper IV and V), the results were compared with results of other models and previous studies. The third criticism concerns oversimplification of real world issues and lack of accuracy of results (Featherston & Doolan, 2012). This limitation was also considered and addressed in the geothermal resource dynamics model developed in Paper III. Usually geothermal resource dynamics are captured in complex physical models (e.g. (G Axelsson & Stefansson, 2003). Based on Juliusson's simplified stock-model, the geothermal resource dynamics model was developed (Júlíusson & Axelsson, 2018). To be able to connect the resource dynamics to an energy system model, they need to be represented in a simplified manner. Through the simplification some accuracy was lost. However, sensitivity analysis showed that the effects of geothermal resource dynamics is of a similar magnitude for higher recharging rates but much stronger when lower recharging rates are assumed. Both results, from the validation and sensitivity analysis, show that despite simplifications the mode was able to capture geothermal resource dynamics legitimately using the model.

Another limitation regarding the geothermal resource model was data availability and accuracy. This issue concerned especially the data for the geothermal resources in Iceland and Kenya (i.e. Paper III and IV) as well as other data for the Kenya model (i.e. Paper IV). The former is related to uncertainties regarding geothermal resource availabilities. In general, estimates about potential for the resources in Iceland and Kenya exist but these can only be proven once drilling and extraction in a field has taken place (Júlíusson & Axelsson, 2018; Lahmeyer International, 2016). Hence, estimations of resource availabilities of undeveloped fields could only be based on estimates. For the Icelandic case this limitation was addressed by using data from previous assessments of resource potential (see Table 1, Paper III). By using the method explained in Juliusson, other resource dynamic parameters (e.g. recharge coefficient) were calibrated for those plants for which data was available (Júlíusson & Axelsson, 2018). These results were used to estimate parameters for other fields as well. Due to this limitation the exact values of remaining resources and well capacities might differ but the dynamics and resulting effects on parameters such as cost remain the same. Due to a lack of data the already developed fields could not be used to validate estimates of resource availability. This limitation was addressed by basing calculations of resource potential and parameters on numbers presented in the Least Cost Power Development Plan and other studies dealing with geothermal resource availabilities in Kenya (Gudni Axelsson, Arnaldsson, Ármannsson, Árnason, & Einarsson, 2013; Lahmeyer International, 2016; Ngugi, 2012; Omenda, Simiyu, & Muchemi, 2014). Like for the Icelandic case, the exact values of results might slightly differ but the dynamics and resulting implications remain the same. The lack of real cost data for all plants in Iceland and Kenya was compensated by using values from other publications (see Table 3, Paper III and Annex Paper IV). The last point does not really represent a major limitation. For the case of geothermal plants international data on overall cost and shares of different aspects (e.g. wells, operation and maintenance) was used (see Table 3 Paper III). For other power plants in Kenya, the cost assumptions that are also used by the Kenyan government were applied (Lahmeyer International, 2016; Republic of Kenya, 2018).

7.4.2 Further research

Based on the presented research, a number of possibilities for future research arise regarding sustainable energy system development. The vision and concept based on Daly's steady state economics presented in Paper I already provides the basis for understanding the dynamics and leverages for promoting and preventing sustainable energy system development. Further research that focuses on quantifying the conceptual framework and developing a system dynamics model can help to assess the importance of different feedbacks in the system and explore what would be the implications of a sustainable energy system. Additionally, it would also allow an exploration of further leverages and the magnitude of their effects, desired and undesired. Depending on the particular research interest, global / national level or more detailed understanding of certain dynamics / leverages, various focuses for modelling could be chosen.

For example, when looking into energy justice on a global level, a detailed structure of the relevant components for understanding this leverage would need to be built, while other components of the system could be simplified (e.g. EROI). Comprehending the interaction between regional or national and global developments under the framework of a steady state based sustainable energy system can provide further insights into the relevance of global and national visions and choosing the right leverages to achieve optimal results on all levels. Another aspect that could be explored in more detail are the demand dynamics and their effects on the social system and individual well-being. This could be done by conceptualizing demand patterns in the global north and global south using a systems thinking approach. A first step could involve CLDs of the demand patterns, which are translated into a quantitative model at a later stage. Through participatory approaches like group model building, the dynamics of specific regions could be captured and represented in a more realistic manner.

Based on the questions defined in Paper II, a more detailed analysis of individual energy system models can be carried out by using the questions to investigate a larger number of already existing energy system models in more detail. A scale (e.g. from "not addressed at all" to "answered in great detail") can complement this analysis. The results of Paper II can also serve as a basis for identifying gaps in current modelling practice that should be addressed in future modelling efforts to align the models with the current energy paradigm. Additionally, the issue of scales (global to local) is only addressed to a limited extent in the current review. As well as the relevance of integrating more complex demand side dynamics, especially technological progress and individual behaviour is not discussed. This should be integrated in future research.

As Bhattacharyya and Timilsina pointed out, many computable energy system models designed for developed countries are often not applicable in the context of developing countries (Bhattacharyya & Timilsina, 2010b). While Paper III added a more realistic structure of geothermal resources on the supply side, this is only a first step towards more context-specific modelling efforts in Kenya (and other countries in the global south). Since Kenya is endowed with a large number of renewable resources, better representation of other renewable resources such as wind and solar would be necessary. One option could be to follow the approach presented in Despres et al. (Després et al., 2015). To better understand the effects of energy system development on human development and well-being when analysing future scenarios, further advancements on the demand side would be necessary. A first step towards modelling this is to implement the feedback structures between supply and demand of different sectors by adding electricity prices. This would enable an exploration of who benefits from increased electricity production. In a more long-term perspective, other components that can be added to the detailed bottom-up structure on the supply side include off-grid systems, household fuel choice and the demand of distinct industrial sectors, among others. To understand the impacts of household energy demand on fuel choice and health, a similar study could be done to the one in India and China that was carried out with MESSAGE-Access (Pachauri & Jiang, 2008). Riva et al. present a conceptual analysis of the complex socio-economic dynamics arising from modern energy access in rural areas (Riva, Ahlborg, Hartvigsson, Pachauri, & Colombo, 2018). All those components, ranging from more accurate representation of renewable resources to the impacts of modern energy access in rural areas, are specifically important when exploring sustainable energy system pathways in countries of the global south. It is suggested to develop a simple model structure that is able to captures components especially relevant to the global south and can be used to assess how sustainable energy system development is possible and the effects of energy system development on other SDGs, such as those relating to poverty and health.

For the geothermal resource module itself, additional data on the available resources should be collected and historic data should be used to refine the representation of geothermal resource dynamics in Iceland and Kenya (Paper III to V). Additional research that analyses the data of geothermal resources, also from other countries, for example Italy and New Zealand, that are utilized for electricity production can be used for improving the current geothermal resource model. On the other hand, considering the growing use of geothermal resources, the dynamics presented in the model should be used when energy systems, in countries with large geothermal potential and plans for utilizing them (e.g. New Zealand), are modelled.

7.5 Recommendations

The results of this thesis lead to recommendations for the use of the developed theory and model and specific recommendations for policy- and decision-makers in Kenya and Iceland.

7.5.1 Recommendations for use of developed concepts

The developed sustainable energy system vision together with Meadow's leverage point concept can be used to assess future policies. Being able to rely on the already developed dynamic vision of a sustainable energy system makes it possible to place the intervention within the system. For example, a policy (e.g. an emissions trading scheme) targeting a change in GHG emissions and its systemic effects could be explored. To do this it is advised that the variable that would change is placed or changed within the system by using the presented CLD capturing sustainable energy system dynamics (Paper I, Fig. 3) to investigate the effects on other variables within the energy system and thereby test its effects on the energy system as a whole. If pursuing more complex strategies, such as for achieving sufficiency, new variables and structures need to be added (see, for example, Paper I, Fig. 8). By adding new variables and related structures to the already existing one, the effects on sustainable energy system development can be investigated. It enables an assessment of the system's level and also see the influence of the new variable or structure on variables not directly linked to the change, but indirectly through other variables and system structures.

The questions presented in Paper II are a result of the current energy paradigm, meaning answers and ways to address them should be found by the energy research community. While other researchers have also assessed the suitability of models for addressing particular questions (e.g. (Lopion et al., 2018; Ringkjøb et al., 2018)), they only concern part of the current energy paradigm. While not all models have to provide answers, they should be addressed and discussed by energy modellers as they represent the current worldview emerging from the broader energy research and policy debate. The questions proposed in Paper II capture the aspects of the current energy paradigm in a holistic manner and can help to comprehend how models relate to the current energy paradigm. On the one hand, they can be used by policy makers to understand to what extent models, which they base their policy on, address different questions. Through this it is also possible to see which aspects are not addressed in the modelling process and the effects of a certain policy that might not be captured (e.g. increasing the share of renewable resources in the energy mix but not accounting for climate impacts on those resources). On the other hand, decision makers and researchers can reflect on the realm their intended policies belongs to and use the questions for the assessment of various models, thereby guiding the model choice of researchers or decision makers.

7.5.2 Recommendations for use of developed model

As the common aphorism based on George Box says, “essentially, all models are wrong, but some are useful”. While the developed geothermal resource dynamics model has some limitations, it is a useful tool and addition for assessing future energy system pathways. It is recommended to use the geothermal resource model for two types of assessments: (i) of the geothermal resource itself on a system’s level like it was done for Iceland in Paper III; and (ii) modelling national electricity or energy system pathways as was done in Paper IV and V respectively. For the first kind of assessment it can be used as a stand-alone model to either estimate how much geothermal resources can be utilized sustainably for electricity production on a national level and what the dynamics of this are or how different electricity demand levels influence geothermal resource availability, production levels and cost. This can be done for any country using geothermal resources for electricity generation. To be able to do this, assessment data on the estimated resource potential in the individual reservoirs and data of already utilized fields should be collected and used to calculate the relevant resource and recharging parameters. This data can then be put in the geothermal resource model. If cost data for the individual components of the geothermal power plant is available, this can be used in the model too. This would facilitate more accurate cost estimations, thereby also altering resource utilization patterns. Once the relevant resource and cost data has been collected, the model can be calibrated to the specific case. Once the model is calibrated and validated against historic data, different demand scenarios can be defined. Then the model can be run for the defined scenarios and the effects of different levels of resource utilization can be explored. The second type of assessment is useful when trying to understand potential future (sustainable) energy system pathways and their socio-economic and environmental implications, in countries where geothermal resources are utilized or intended to be utilized for electricity production. In order to do this, the first step is to follow the procedure of the first type of assessment explained above. The second step involves linking the geothermal resource model to the energy or electricity system model. This is done through the linkage of cost and plant choice variables as it was done in Paper V when the geothermal resource model was linked to the UniSyD_IS model. Due to the more accurate estimations of geothermal parameters, integrating geothermal resource dynamics can facilitate improved planning for national energy systems. Hence, using the model is advised to assess possible future developments in terms of the overall energy mix, resource availabilities and cost.

7.5.3 Recommendations to policy- and decision-makers

Based on the research, the following recommendations to policy- and decision makers are made:

- A clear vision of the desired sustainable energy system should be developed on a national level, including its social, environmental and economic aspects. Making use of systems thinking approaches (i.e. CLDs) can facilitate a better understanding of the interactions between the components. Once the vision has been developed on a national level it should be placed within the global system to investigate its viability. This includes assessing whether the vision can contribute to staying within planetary boundaries and can contribute to a just energy system.
- National policies should be assessed from a system’s perspective, using the developed concept of the steady state of energy to understand the influence of policies (e.g. increase in share of renewable, efficiency increases) on all relevant components of the system (e.g. overall demand).

- Analysing geothermal resources on a system's level is recommended.
    - In Iceland it should inform resource utilization plans, such as the Icelandic Master Plan (Orkustofnun - National Energy Authority 2018a), because it facilitates an assessment of how geothermal resource availabilities are influenced on a national level considering different demand scenarios. This can be used to improve decision-making on how much and how many geothermal sites should be utilized for electricity production. In order to do this further technical data on the geothermal resource and the cost of exploiting those resources should be collected (see previous section) and used as inputs for the model.
    - In Kenya, geothermal resource dynamics should be considered in electricity expansion planning. Their dynamics should be accounted for when negotiating PPAs to avoid bankruptcy of power plants and shortfalls of supply. This means the geothermal resource dynamics model should be connected to the cost minimization model that is used for electricity expansion planning.
- Analysing the impacts of policies on a system's level is recommended. This is prerequisite to understand how they influence relevant components of the system and avoid undesired side-effects. Additionally, it is recommended to apply Meadow's leverage point concept to policies to assess the effectiveness of them. Policies of higher leverage such as the rules of the system, for example incentives and constraints, should be tackled rather than those of low leverages, which only change parameters such as efficiency.
- Policy makers should be aware about the strengths and weaknesses of the models they base their decisions on. It is advised to use the questions arising from the current energy paradigm as guiding questions to improve understanding of the models.

7.6 Conclusion

This thesis set out to explore the dynamics of sustainable energy system development in the global north and global south. The first step to do this was to adopt Daly's Steady State theory in a dynamic manner by applying a system's thinking approach. This revealed the feedbacks, drivers and barriers of sustainable energy system development on the national as well as global level. This pointed to the importance of assessing different policy options by considering the entire system and not just one part of it, since this can lead to undesired side effects, as evidenced through the example of energy efficiency. In general, it was found that current policies mostly tackle lower leverages (e.g. energy efficiency) rather than higher leverages (e.g. energy sufficiency), which are necessary to achieve sustainable energy system development on the national as well as global level.

In the second step, various approaches were explored concerning how sustainable energy system development has been addressed in research, modelling and the public debate. This led to the definition of the current energy system paradigm. An analysis of the questions arising from this paradigm and whether these are addressed or answered by different types of energy model helped to identify several gaps between the current energy paradigm and the answers models are able to provide. One of the identified gaps concerns the limits of renewable resources. While intermittent resources have increasingly gained attention, geothermal resources and their stock-like behaviour have received less attention. This led to the development of a geothermal resource model. This model captures geothermal resource dynamics in a simplified manner, which enables its integration into broader national energy system models. It is shown that geothermal resource dynamics in combination with high electricity demands (i.e. excessive utilization of the resource) lead to decreasing availability of geothermal resources and thereby cause increasing cost and other long-term challenges, such as production capacity losses. To gain insights on the energy system level, the geothermal resource model was connected to an electricity system model in the global south (i.e. Kenya) and an energy system model in the global north (i.e. Iceland). The two example cases, Iceland and Kenya, both rely on geothermal resources, among other resources, for electricity production. Modelling the two national example cases showed that despite the specific context countries might have (e.g. level of development, geographical location, size of population), they can still face similar challenges because of the underlying dynamics of renewable resources, as was evident in Iceland and Kenya. Both countries face significant geothermal resource reductions and rising cost if high electricity demands are realized. In Iceland, understanding the connection between geothermal resource dynamics and electricity demand is important because it can provide important insights on the feasibility of different decarbonization pathways, especially in the long-term. In Kenya, the integration of renewable resource dynamics (i.e. geothermal and hydro) into electricity planning scenarios is particularly relevant to understand trade-offs between electricity access goals, affordability and the share of renewables in the overall electricity mix.

Although some limitations with regards to the model development were faced, in particular relating to data availability, the generated insights provided can still support better decision-making in energy system planning in Iceland and Kenya. Further research on the dynamics of already explored geothermal fields and data collection from these can help to refine the exact numbers in the future, but the general patterns reported in this thesis will not change.

Based on the presented research it is recommended to enhance energy system models in the global north and global south in a way that is able to capture the context-specific challenges and answer the relevant questions arising from the current energy paradigm.

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