Renewable energies in 2050: Modelling the link between renewable energies and climate change

Nathalie Spittler, PhD Candidate, University of Iceland
Nas14@hi.is
Sæmundargötu 2
101 Reykjavík
Iceland
Ganna Gladkykh, PhD Candidate, University of Clermont Auvergne

Introduction

The conventional fossil-fuel-based energy system has proven to be one of the main drivers of earth system change, especially climate change[1]. The transition from the fossil fuel based energy system to a renewable based energy system is one of the widely advocated and modelled solution pathways for achieving long-term sustainable development and climate change mitigation. However, results regarding their contribution to climate change mitigation and sustainable development are dependent on the assumptions made with regards to renewable energies. While renewables, generally, play an important role in terms of climate change mitigation as they are less carbon intensive than fossil fuels, their characteristics need to be considered when it comes to climate change adaptation as some of them can be impacted by climate change. Therefore, the paper deals with the following research question: *How to model renewable energies in energy-climate models for 2050?*

First, renewable energies and their technological, environmental and economic characteristics that are relevant for the national and global scale are analysed in a disaggregated manner. Second, this is contrasted with assumption on renewables in selected climate-energy models. Based on this the gap between the current knowledge on renewable energy potentials and modelling practices is explored. To further strengthen this argument and to present a possible alternative of modelling renewable energies two case studies at the national and global level are provided. A model that draws from the pre-existing energy and transport system model of the Icelandic energy system but captures the physical realities of renewable resources for electricity production such as the impact of climate change on hydro resources as well as geothermal resource drawdown, is built. For the global scale the example of Neodymium (Nd), a critical and potentially scarce material especially relevant for wind turbines and electric vehicles, is modelled in order to show how material scarcities can influence the contribution of wind power in the future energy system. The simulation of both example cases run up to 2100. The simulation efforts provide insights into how different assumptions on renewables can affect model results.

Theoretical background on renewable energy characteristics

Renewable energy as defined in the IPCC report 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, win*d, *tide and waves and ocean*

[1] Will Steffen et al., *Global Change and the Earth System* (Berlin Heidelberg New York: Springer, 2005).

thermal energy, as well as renewable fuels such as biomass"[2]. The German Advisory Council on Global Change (2003) adds geothermal energy to the list of renewables and states that renewables' "overall potential is in principle unlimited or renewable, and is CO2-free or -neutral"[3].

Combined, those two definitions comprise a broad spectrum of renewables and explain assumptions about them. One important aspect about the definition is the notion of the rate of use, because any energy resource harvested beyond its recovery rate can be unsustainable even if the resource is renewable. This relates to the second aspect addressed by the IPCC's definition and the theoretical limits of renewable resources. In their paper "An assessment of global energy resource economic potentials" Mercure and Salas (2012) define renewable and stock energy resources. They describe "stocks, where "energy may be extracted from fixed amounts of geologically occurring materials with specific calorific contents" and "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"[4]. This definition clearly distinguishes between stock and flow resources. According to this definition all renewable resources would count as flows and fossil as stocks. However, some renewables can be depleted for a period of time, if they are harvested excessively, and their regeneration rate is slower than their harvesting rate. For example, in some cases geothermal regeneration can take up to 100 years[5] . Thus, it is argued that not all renewable energy sources can be seen as flows (flow-based), should be seen as stocks (stock-based).

While those renewable resources that are flow-based are more or less temporarily available in unlimited quantities, the renewable resources that are stock-based can be exhausted if the rate of use exceeds the regeneration rate. Flow-based means that resources can be harvested while the flow occurs (e.g. sun shining, wind blowing), but do not build up and accumulate and therefore cannot be stored or harvested at a later point in time. At the same time making use of those flow-based renewable resources does not reduce their availability. Stock-based renewable resources, on the other hand, build up and accumulate in a stock (e.g. biomass). Once the stock is available the resource can in principle be used at any time, however any use of this resource draws from the available stock and decreases availability. Additional capacity, up to a certain limit (e.g. due to space available) can be added to the stock.

Whereas stock-based renewables are limited by some capacity factor and rate of recovery, flow-based renewables do in theory not have any limitations as pointed out by the German Research Council of Global Change. 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. There is an ongoing discussion about the dependence of

---

[2] O. Edenhofer, R. Pichs Madruga, and Y. Sokona, eds., *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2011), doi:10.5860/CHOICE.49-6309.

[3] German Advisory Council on Global Change, *World in Transition – Towards Sustainable Energy Systems*, *Flagship Report*, 2003.

[4] Jean-François Mercure and Pablo Salas, "An Assessement of Global Energy Resource Economic Potentials," *Energy* 46, no. 1 (October 2012): 322–36, doi:10.1016/j.energy.2012.08.018.

[5] Egill Juliusson et al., "Optimal Extraction of Geothermal Resources," *Geothermal Resources Council Transactions* 35 (2011): 1457–66, doi:10.1002/yd.430.

sustainable development on mineral supply[6]. Research on materials criticality in general and materials criticality for renewable energy technologies in particular is an emergent field[7] [8] [9] [10].
With regards to their CO2 characteristics renewables are often described as CO2 neutral or free, as in the definition above. Bio resources (e.g. biomass, biofuels) also produce CO2 emissions during their use. In this case, the rate of use is an important indicator, since they can be considered CO2 neutral if the CO2 emissions during the harvesting process are offset during by the growth of the bio resource used[11]. This factor is also considered in the European Union's (EU) Renewable Energy Directive. Hence, the "Commission's November 2016 proposal for a revised Renewable Energy Directive includes updated sustainability criteria for biofuels used in transport and bioliquids, and solid and gaseous biomass fuels used for heat and power. Annexes V and VI include updated greenhouse gas emission accounting rules and default values"[12].
An important aspect, which is not explicitly addressed in the definition but stems from the nature of all renewable resources, except geothermal energy resources, is their weather and climate dependency. A number of studies have investigated climate impacts on the overall energy system[13] [14]. Since most renewable energy resources depend on the climate the impacts of climate changes on renewable resources has increasingly gained attention. The effects of climate change can be positive if a change in the climate might increase the availability of a certain renewable resource (e.g. more sun radiation) or its production capacity (e.g. better growth conditions for biomass). Another positive effect could be the more equal distribution of a certain resource throughout the year, decreasing seasonal variations (e.g. more equal hydro flows). Climate change can also negatively affect the availability of resources as the conditions might decrease available resources (e.g. less available hydro resources through decreasing glaciers and rainfalls) or make conditions of production harder (e.g. lack of water or more parasites threatening biomass production due to hotter climates) and extreme events can alter the supply

---

[6] Saleem H. Ali et al., "Mineral Supply for Sustainable Development Requires Resource Governance," *Nature* 543, no. 7645 (2017): 367–72, doi:10.1038/nature21359.
[7] Lorenz Erdmann and Thomas E. Graedel, "Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses," *Environmental Science & Technology* 45, no. 18 (September 2011): 7620–30, doi:10.1021/es200563g.
[8] Bram Buijs, Henrike Sievers, and Luis A. Tercero Espinoza, "Limits to the Critical Raw Materials Approach," *Proceedings of the Institution of Civil Engineers - Waste and Resource Management* 165, no. 4 (November 2012): 201–8, doi:10.1680/warm.12.00010.
[9] Guido Sonnemann et al., "From a Critical Review to a Conceptual Framework for Integrating the Criticality of Resources into Life Cycle Sustainability Assessment," *Journal of Cleaner Production* 94 (May 2015): 20–34, doi:10.1016/j.jclepro.2015.01.082.
[10] T. E. Graedel and Barbara K. Reck, "Six Years of Criticality Assessments: What Have We Learned So Far?," *Journal of Industrial Ecology* 20, no. 4 (August 2016): 692–99, doi:10.1111/jiec.12305.
[11] IIASA, *Global Energy Assessment (GEA)*, ed. Thomas B. Johansson et al. (Cambridge: Cambridge University Press, 2012), doi:10.1017/CBO9780511793677.
[12] European Commission, "Energy," 2017.
[13] Roberto Schaeffer et al., "Energy Sector Vulnerability to Climate Change: A Review," *Energy* 38, no. 1 (2012): 1–12, doi:10.1016/j.energy.2011.11.056.
[14] Jane Ebinger and Walter Vergara, *Climate Impacts on Energy Systems* (The World Bank, 2011), doi:10.1596/978-0-8213-8697.

capacity of renewable resources[15 16]. Since climate change, at least to some extent, seems unavoidable, its impacts on the renewable energy resources and therefore energy supply should be considered when building future energy scenarios, especially because renewable energy resources are often seen as the solution to combating climate change. This was shown by a study carried out for the Nordic countries[17].

Each of the renewable energy resources has very specific characteristics. Those characteristics of renewable energies are functions of physical realities and some are related to technological factors (e.g. climate impact on renewable resources, existing harvesting technologies). Consequently, analysing renewable energy is a complex task and to identify and assess their possible contribution to climate change mitigation and or adaptation is complicated.

So far, many of the energy system models do not consider the characteristics of renewables in a detailed manner, but given the importance of the aforementioned characteristics a more careful treatment of renewables in climate-energy models is necessary.

Renewable energy resources in models

There are a number of reasons why the advancement of materials criticality study field has not influenced the modelling practice of renewable energy so far. One of the main reasons that materials criticality studies are not included by renewable energy modellers is the absence of a commonly agreed methodology for materials criticality assessment[18 19]. As a result of this, different studies on critical materials assessment come up with divergent results and lists of critical materials, which makes it hard to integrate the assumptions on material scarcity to the energy model. Another challenging aspect of assessing material criticality is the scale. Criticality can be assessed on a national scale or international scale[20], comprising all major sectors of the economy[21 22 23 24 25] or particular sectors[26 27].

---

[15] Schaeffer et al., “Energy Sector Vulnerability to Climate Change: A Review.”

[16] Ebinger and Vergara, *Climate Impacts on Energy Systems*.

[17] Hege Hisdal et al., *Impacts of Climate Change on Renewable Energy Sources*, ed. Jes Fenger, *Impacts of Climate Change on Renewable Energy Sources - Their Role in the Nordic Energy System*, 2007.

[18] Jo Dewulf et al., “Criticality on the International Scene: Quo Vadis?,” *Resources Policy* 50 (December 2016): 169–76, doi:10.1016/j.resourpol.2016.09.008.

[19] Benjamin Achzet and Christoph Helbig, “How to Evaluate Raw Material Supply Risks—an Overview,” *Resources Policy* 38, no. 4 (December 2013): 435–47, doi:10.1016/j.resourpol.2013.06.003.

[20] T E Graedel et al., “Criticality of Metals and Metalloids.,” *Proceedings of the National Academy of Sciences of the United States of America* 112, no. 14 (April 2015): 4257–62, doi:10.1073/pnas.1500415112.

[21] National Research Council, “Minerals, Critical Minerals, and the US Economy,” *National Academy of Sciences* (Washington, D.C.: National Academies Press, February 2007), doi:10.17226/12034.

[22] Renaud Coulomb et al., “Critical Minerals Today and in 2030: An Analysis of OECD Countries,” 2015.

[23] Roger G Skirrow et al., “Critical Commodities for a High‐tech World: Australia’s Potential to Supply Global Demand,” n.d.

[24] European Commission. “Critical Raw Materials for the EU.” Eucom 39, no. July (2010): 1–84. doi:10.1002/eji.200839120.IL-17-Producing.

Most of available long-term energy scenarios based on energy system models do not take to account availability of minerals and metals necessary for providing enough renewable energy harvesting materials[28]. This statement is based on analysing the renewable energy assumptions of the following models: MESSAGE[29], TIMES[30], PRIMES[31], NEMS[32], OSeMOSYS[33], Prometheus[34], LEAP[35], En-Roads[36]. With regards to the climate change impact on energy resources themselves, this has been modelled for some cases. However, as this is connected to uncertainties about the actual impact of climate change, often this is not modelled on a national energy system scale or beyond[37]. Concerning geothermal resources, their drawdown is usually estimated for individual wells and it is difficult to provide exact numbers due to the nature of its complexity[38]. Therefore, it is hard to integrate them into national energy system models and has not been done in any of the reviewed models.

Simulation of renewable resources example cases

In order to understand how the assumptions underlying energy models influence their results related to climate change two simple system dynamics simulation models are built. The simulation period is 2100 as it is assumed that a sustainable energy system for 2050 needs to be able to be sustained beyond this.

---

[25] Zepf, V., Simmons, J., & Universität Augsburg. (2014). Materials critical to the energy industry: An introduction. BP plc.

[26] R L Moss et al., "Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector," n.d.

[27] Bauer, Diana, David Diamond, Jennifer Li, David Sandalow, Paul Telleen, and Brent Wanner. "US Department of Energy: Critical Materials Strategy, December 2010." *Agenda*, no. December (2010): 1–166. doi:10.2172/1000846.

[28] International Energy Agency IEA, "World Energy Outlook," 2015, doi:http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf.

[29] S Messner and Strubegger, "User's Guide for MESSAGE III," 1995.

[30] Loulou, Richard, Gary Goldstein, and Ken Noble. "Energy Technology Systems Analysis Programme Documentation for the MARKAL Family of Models General Map of the Documentation (2004): http://www.etsap.org/tools.htm (accessed 30.07.2017).

[31] E3MLab. "PRIMES Model, Version 6. Detailed Model Description.," 2016. http://www.e3mlab.ntua.gr/e3mlab/PRIMES Manual/The PRIMES MODEL 2016-7.pdf.

[32] Energy Information Administration. Office of Integrated Analysis and Forecasting U.S. Department of Energy, "The National Energy Modeling System: An Overview 2009," 2009.

[33] Moksnes, N., Welsch, M., Gardumi, F., Shivakumar, A., Broad, O., Howells, M., ... & Sridharan, V. (2015). 2015 OSeMOSYS User Manual.

[34] World Energy Modelling: The PROMETHEUS Model." *Environmental Modeling and Assessment* 20, no. 5 (2015): 549–69. doi:10.1007/s10666-015-9442-x.

[35] Stockholm Environment Institute, "Long-Range Energy Alternatives Planning System User Guide for LEAP 2005," 2005.

[36] Climate Interactive website : https://www.climateinteractive.org/tools/en-roads/ (accessed 30.07.2017).

[37] Hisdal et al., *Impacts of Climate Change on Renewable Energy Sources*.

[38] G Axelsson and Valgarður Stefansson, "Sustainable Management of Geothermal Resources," *International Geothermal Conference, Reykjavík*, 2003, 40–48.

The two example case models are developed to illustrate how variations in the inclusion of different characteristics of renewables can affect their role in the overall energy system by using system dynamics modelling. The first case provides an example of the possible impact of resource scarcities on wind energy a global scale. The second case takes Iceland as a national case example to show how the integration of potential climate change and different assumptions about geothermal drawdown influence resource availabilities for the electricity supply system.

Since it can be argued that the energy system holds characteristics of a complex system and system dynamics is a methodology for analysing complex systems[39], system dynamics modelling is seen as an appropriate method for the simulation of the two example cases.

There are three main advantages of system dynamics as a methodology that make its use especially relevant for this study:

(i) System dynamics is suitable for modelling feedbacks between different variables[40].

This aspect is particularly relevant in this study for addressing the feedback between resource scarcities and/or climate change and the energy system is a central element of analysis.

(ii) System dynamics makes structural difference between stock and flow structures[41].

This aspect is particularly relevant considering that modelling renewable energy resource limits we depart from the assumption that flow-based renewable energy sources are not unlimited and depend on the stocks of natural materials needed for harvesting.

(iii) System dynamics is suitable for addressing material as well as information delays in systems[42].

There are number of delays associated with energy system capacities and with connections between energy system and climate system. None of the climate or energy capacity building delays are explicitly addressed in this study, but addressing them would be very beneficial for further research.

The modelling software used for building the example models on the global as well as the national scale is STELLA.

Global example case

On a global scale an example model structure to address the aspect of materials criticality for renewable energy was built. The goal of this simulation exercise is to show an example of how the connection between scarce materials and renewable energy harvesting technologies can be modelled. The ultimate objective of doing this is checking a feasibility of long-term scenarios for renewable energy supply for mitigating climate change. For this purpose, a simplified example of wind energy dependence on Nd on a global scale was provided. According to long term global energy scenarios up to 60% of electricity on a global scale will come from solar photovoltaics (PV) and wind[43].

---

[39] Catherine S.E. Bale, Liz Varga, and Timothy J. Foxon, "Energy and Complexity: New Ways Forward," *Applied Energy* 138 (2015): 150–59, doi:10.1016/j.apenergy.2014.10.057.

[40] John D Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, *Management*, 2000, doi:10.1057/palgrave.jors.2601336.

[41] Ibid.

[42] Ibid.

[43] EIA, "Annual Energy Outlook 2016," *Office of Integrated and International Energy Analysis*, 2015.

To reach the desired level of wind energy generation enough wind energy capacity needs to be built, which would require a certain amount of scarce or critical materials. Among those materials is neodymium (Nd) which is considered to be a critical one according to materials' criticality studies[44].

The model structure is based on the Generic Exploratory System Dynamics Model by Erik Pruyt[45]. Considering the simplified structure of the model, the simulation is not aimed at providing realistic numerical results, but rather seeks for stocks and flows behaviour patterns that may help illustrating the importance of accounting for material scarcities in the long run to better understand sustainable energy transition patterns.

There are several main assumptions on which the model structure is based:

(i) Nd is the only critical material needed to produce the magnets for windmills;

(ii) availability of Nd is the only factor influencing supply of wind-generated energy;

(iii) all Nd mined globally used only for the windmills magnets;

(iv) the Nd mining capacities are static and cannot be increased during the simulation period;

(v) the availability of Nd is dependent only on the physical material stock of metal, no economic or political factors are included;

(vi) there is no obsolescence of wind energy capacities.

By changing the assumptions in this modelling exercise and broadening the boundaries of the explored system (for example, by including a potential increase of mining capacities and associated with this long-time delays), it is expected to get additional insights and increased results accuracy for better understanding of energy system transitions can be obtained.

National example case - Iceland

The Icelandic example case model simulates possible future electricity scenarios for Iceland. According to the Icelandic National Energy Authority currently 97% of the electricity produced in Iceland either comes from geothermal (25%) or hydro (72%) electricity production[46]. In order to show how differing characteristics of renewables considered for modelling the electricity system affect the results with regards to the resource utilization and its impact on the energy system (i.e. installed electricity generation capacity, electricity prices, electricity generation, construction of additional generation capacity) following four different scenarios are investigated:

(i) Simulation 1 baseline scenario - geothermal resources without drawdown and the hydro resource without climate change impacts on them;

(ii) Simulation 2 geo drawdown scenario - geothermal resource drawdown is considered but the impact of climate change on the hydro resource is not considered;

(iii) Simulation 3 CC impact on hydro scenario - geothermal resource drawdown is not considered but the impact of climate change on the hydro resource is considered;

---

[44] Matthew Riddle et al., "Global Critical Materials Markets: An Agent-Based Modeling Approach," *Resources Policy* 45 (September 2015): 307–21, doi:10.1016/j.resourpol.2015.01.002.

[45] Erik Pruyt, "Scarcity of Minerals and Metals: A Generic Exploratory System Dynamics Model,"2010, http://www.systemdynamics.org/conferences/2010/proceed/papers/P1268.pdf.

[46] Orkustofnun - National Energy Authority, "Hydro," 2017, http://www.nea.is/hydro/; Orkustofnun - National Energy Authority, "Geothermal," 2017, http://www.nea.is/geothermal/.

(iv) Simulation 4 combined scenario - geothermal resource drawdown as well as the impact of climate change on the hydro resource is considered.

The model used for modelling the Icelandic example case draws on the UniSyD_IS model, which has been developed jointly by the University of Iceland and Unitec. UniSyD_IS is the Icelandic energy and transport systems model used to conduct research on energy and transport transition pathways within Iceland[47].

The model used to simulate the Icelandic example case builds on the electricity supply and market module of the UniSyD_IS model. While the latest version of the UniSyD_IS model includes an option for assessing the impact of climate change on hydro resources[48], it does not include the effect of geothermal drawdown. The effect of climate change on hydro resources, like for other renewable resources, is locally specific[49] . The climate change impact for Iceland is integrated as the option for the hydro resource to adapt to climate change. The geothermal resource can be seen as a stock-based resource because a certain capacity of the resource is available and using it reduces its available production capacity, which is referred to as geothermal drawdown. Several studies have shown that geothermal drawdown is an important aspect when planning and assessing (future) geothermal supply systems[50]. Geothermal drawdown is a process that occurs when harvesting geothermal resources. As the geothermal resource gets used pressure of the resource decreases within the reservoir. To some extent the drawdown is compensated through a natural recharging process, but if the resource is used excessively the drawdown exceeds natural recharge and the geothermal production capacity decreases. An option to prevent a too rapid drawdown is artificial reinjection[51] (Axelsson 2012). As it is very complex to evaluate geothermal drawdown on a national scale, an assumed scenario is used to simulate the dynamics resulting from geothermal drawdown, without considering detail on reinjection[52]. The demand is assumed to be inelastic to prices and based on the forecast of the Icelandic energy authority, which goes until 2050 and after this it is assumed that demand growth levels off and stays almost constant.

---

[47] Ehsan Shafiei et al., “Simulation of Alternative Fuel Markets Using Integrated System Dynamics Model of Energy System,” *Procedia Computer Science* 51 (2015): 513–21, doi:10.1016/j.procs.2015.05.277;
Ehsan Shafiei et al., “Analysis of Supply-Push Strategies Governing the Transition to Biofuel Vehicles in a Market-Oriented Renewable Energy System” 94 (2016): 409–21, doi:10.1016/j.energy.2015.11.013.

[48] Ehsan Shafiei et al., “Economic Impact of Adaptation to Climate Change in Iceland ’ S Energy Supply Sector,” 2015, 0–4.

[49] Schaeffer et al., “Energy Sector Vulnerability to Climate Change: A Review.”

[50] George M. Dayan and Maureen Ambunya, “Geothermal Energy-Making It Renewable and Sustainable,” *Fourtieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 26-28, 2015*, 2015, 1–8; Gudni Axelsson et al., “Sustainable Management of Geothermal Resources and Utilization for 100 – 300 Years,” *World Geothermal Congres 2005*, no. April (2005): 24–29; Axelsson and Stefansson, “Sustainable Management of Geothermal Resources.”

[51] G Axelsson, “Role and Management of Geothermal Reinjection,” *Presented at “Short Course on Geothermal Development and Geothermal Wells”, Organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 11-17, 2012.*, 2012, 1–21.

[52] Reinjection is practiced in Iceland, however the ultimate impact of reinjection on the geothermal resource is uncertain and is outside the scope of this analysis.

Results and Discussion

Global example case – Nd

The simulation of Nd on a global level shows that in the latter half of this century scarcities will affect the availability, hence also prices of Nd. Additionally, delays due to the construction of mining capacities may occur.

Simulation results show that a deficit of Nd can be expected after 2080, when available Nd mining capacities cannot cover Nd demand needs. This time period goes beyond 2050 which is the final simulation year for most of energy scenarios. To address this potential bottleneck of Nd, additional mental mining capacities may be required. An increase of mining capacities may be associated with long time delays, political and economic risks. An increase of Nd recycling capacities helps partly compensate for Nd supply scarcity. However, if in the long run if Nd supply demand continues to rise, an increase of mining capacities will still be needed. As it was mentioned before, the structure of the current simulation does not include an obsolescence of wind power capacities. Considering the simulation time beyond 2050, a replacement of installed wind power capacities with new capacities should be expected. This would lead to additional increase of demand for materials needed for power capacity building.

Economic consequences of Nd supply shortage in a simulated model are modeled as a Nd supply shortage effect on Nd price based on Erik Pruyt's system dynamics model structure[53]. Simulation results show increasing speed of Nd price growth, especially after Nd supply shortage becomes evident.

The main question the Nd simulation exercise aimed to answer is: whether modelling stocks of scarce materials for harvesting renewable energy sources can affect availability of renewable energy in a long run and, consequently, its contribution to climate change mitigation? The simulation results illustrated that availability of scarce materials needed for harvesting certain types of renewable energy indeed can influence the renewable energy production capacity. In fact, the simulation results described in this section are the product of the underlying modelling assumptions. Thus, such results should not be interpreted as a confirmation that availability of renewable energy in a long run will be threatened by the availability of scarce materials needed for harvesting, but rather should be seen as an illustrative exercise for supporting further discussion on challenging conventional assumptions about renewable energy in energy models.

Despite the fact that physical supply chain structure, as well as market structure for Nd in the current simulation are modelled in a simplified way and further development of more detailed and realistic model's structure is needed, simulation results help supporting the discussion of whether it is possible to meet long-term goals on renewable energy supply, considering potential material limits of harvesting technologies for flow-based renewable energy.

National example case – Iceland

In the baseline scenario, the electricity price increases moderately in the beginning of the first half of the century and levels off once no additional capacity construction is required, because demand is almost constant after 2050. As the hydropower capacity as well as the geothermal capacity stays constant, due to the lack of drawdown, no further construction after 2050 takes place.

---

[53] Erik Pruyt, "Scarcity of Minerals and Metals: A Generic Exploratory System Dynamics Model," 2010, http://www.systemdynamics.org/conferences/2010/proceed/papers/P1268.pdf. *Proceedings of the 28th International Conference of the System Dynamics Society* (2010).

The highest electricity price occurs in the geo drawdown scenario. Due to the drawdown of installed geothermal capacity a constant construction of additional capacity is required. Although geothermal as well as hydro capacity are added, the main share of electricity installed and produced comes from hydro power plants. For approximately 50 years in the mid of the century total generation capacity is slightly lower due to geothermal drawdown and delays in construction of new generating capacity.
The lowest price occurs in the CC impact on hydro scenario. The price only grows for a short period of time and then stabilizes. Similar to the first scenario additional generation capacity is added up to 2050 when demand stabilizes. The overall generation capacity of hydro and geothermal generation capacity is almost the same as in the baseline scenario. However, geothermal generation is lower and hydro generation is higher, due to the more constant and higher water flows more electricity can be generated from the same amount of installed hydro capacity.
The price in the combined scenario is between the price of the highest price and the one of the baseline scenario. This results from the installed capacity and the built up of geothermal and hydro capacity that is slightly higher for hydro capacity and slightly lower for geothermal capacity than in the scenario of geo drawdown. The electricity generated by hydro power plants is the highest, as there is a positive impact of climate change as well as a drawdown geothermal resource capacities.
The simulation results show that depending on the assumptions underlying the resource potential different possible future energy scenarios emerge. While some investigated aspects, such as installed capacity, electricity generation and additional capacity construction show similar trends in some scenarios, the electricity price significantly differs in all four scenarios.
One aspect not addressed in detail in this analysis is the aspect of wind power plants for electricity generation. Especially in the scenarios of the second and fourth simulation, wind significantly increases as geothermal drawdown becomes apparent. This means a continuous renewable resource is replaced by an intermittent one. A detailed analysis of the implications of wind generation into the electricity system goes beyond this study and should be subject of further research.
Another factor not addressed in this example case simulation is the feedback between electricity prices and demand. Generally, increasing prices lead to a decreasing demand. Hence, including this mechanism into the model will be important for future analysis.

Conclusion

Modelling renewables and their distinct physical characteristics affects assessments of their ability to contribute to climate change mitigation and a to the long-term sustainability of the energy system. This study aimed to look at how changing assumptions for renewable energy modelling can impact long-term scenarios of renewable energy availability. By simulating the case of climate change impact on geothermal energy availability in Iceland and the case of Nd availability for wind power on a global scale, we show that supply and prices of renewable energy in a long are affected by climate change and critical materials availability.
There are many assumptions in our models to be reconsidered by the further research to make the simulations' behaviour more realistic and to test the feasibility of sustainable energy future in a more rigorous way. Reconsidering assumptions of renewable energy may require an increase of simulation time beyond 2050, since there are insights related to materials availability, climate change effects or need for additional power and mining capacity that become evident after 2050.