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Sustainability guardrails for energy scenarios of the global energy transition

Michael Child*, Otto Koskinen, Lassi Linnanen, Christian Breyer

Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland

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ABSTRACT

Sustainability guardrails in global energy scenarios were reviewed and further developed based on a literature review of global energy system transition scenarios. Environmental planetary boundaries mark out the safe operation space for human activities. The planetary boundary framework has yet to be fully incorporated into global energy scenario modeling, where the emphasis has been almost solely on CO_2 emission mitigation. Stress on biochemical flows, land use change, biodiversity, ocean and climate systems are often neglected. Concurrently, social and economic aspects, such as limiting air pollution, providing universal access to modern energy services and improving energy efficiency by electrification of energy services are emerging as new paradigms in energy scenario modeling frameworks. However, ethical choices, such as current and future generations' access to preserved ecosystems, aversion of energy resource risks, preventing resource use conflicts, and negative impacts on human lives from energy extraction and use are not usually discussed or justified in energy scenario modeling. All investigated global energy transition scenarios failed to adequately describing the critical roles of flexibility in future energy systems based on high shares of renewable energy, such as storage, grids, demand response, supply side management and sector coupling. Nor did they adequately incorporate the concept of resilience in socio-ecological systems.

1. Introduction

It has been recognized that human civilization is over-exploiting planetary resources faster than they are being renewed [1]. Nine planetary boundaries have been defined to assess the safe limits into which human activities should be confined in order to take into account assimilative capacities of the planet, related uncertainties, the complexity of the biosphere, and possible tipping points [2,3]. Currently, the biosphere's capacity to assimilate the impacts of human action is being exceeded, resulting in dangerous interference in the global climate system [4], an increased rate of biodiversity loss, and overstressed nitrogen and phosphorus cycles [2,3]. In addition, the planetary boundaries framework includes stratospheric ozone depletion, ocean acidification, chemical pollution, land-system change, freshwater use and aerosol loading [2]. Human activities are the largest drivers at the planetary scale, thus the current geological era has been proposed to be named the "Anthropocene" [5]. The growing awareness of the environmental state of the planet and concerns about the threats of climate change have led world leaders to agree on a shared, long-term goal of limiting global emissions of greenhouse gases to ensure a 2 °C compatible pathway within this century, and pursue efforts to limit global warming to 1.5 °C above pre-industrial levels [6]. A common, long-term, legally binding climate target is a start; however, a truly sustainable development of resource extraction and use for human needs would address the other planetary boundaries as well.

Motivations of influential global energy scenarios differ. Governments can assess implications of different energy and environmental policies, non-governmental organizations (NGOs) can draw attention to alternative polices, and companies can assess market risks and their investments [7]. Thus, an energy scenario can be handcrafted to drive certain interests. For this reason, transparency in the creation of energy scenarios is essential, since model assumptions greatly affect

Abbreviations: 2DS, Two degree scenario; AFOLU, Agriculture, forestry and land use; BECCS, Bioenergy and carbon capture and storage; BEV, Battery electric vehicle; CAES, Compressed air energy storage; CCS, Carbon capture and storage; CCU, Carbon capture and utilisation; COP21, Twenty first annual Conference of Parties; CSP, Concentrating solar thermal power; DACCS, Direct air carbon capture and storage; EMF, Energy Modeling Forum; ETP, Energy Technology Perspectives; hi-Ren, High renewable energy; hi-Nuc, High nuclear energy; GEA, Global Energy Assessment; GHG, Greenhouse gas; IAM, Integrated assessment modeling; IEA, International Energy Agency; IIASA, International Institute for Applied Systems Analysis; IMF, International Monetary Fund; IPCC, Intergovernmental Panel on Climate Change; IRENA, International Renewable Energy Agency; LCOE, Levelised cost of electricity; NELD, Non-economic loss and damage; NGOs, Non-governmental organizations; OECD, Organization for Economic Co-operation and Development; PHS, Pumped hydro storage; ppm, Parts per million; PtX, Power-to-X; PV, Photovoltaic; R&D, Research and development; RE, Renewable energy; TES, Thermal energy storage; WBGU, German Advisory Council on Global Change; WEC, World Energy Council; WEO, World Energy Outlook; WRI, World Resource Institute; WWF, World Wildlife Fund; WWS, Wind, wave and solar; Subscripts, eq, Equivalent

* Corresponding author.
E-mail address: Michael.Child@lut.fi (M. Child).

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the modeling outcomes. For example, incorrect assumptions have often been made concerning the future costs of solar photovoltaics (PV), no doubt a key technology on global level. In one case, Luderer et al. claim capital costs for solar PV projects will be in the range of 800–1400 $/kWp (620–1080 €/kWp[1]) in 2050. In reality, utility-scale project costs in Europe, India and China have already reached those same price levels today [8,9], and PV experts expect costs in the range of 360–520 €/kWp [10] and 320–430 €/kWp [11] in 2050, depending on the deployment scenario. Transparency of assumptions thus becomes an important precursor to assessing the quality of a scenario.

It appears safe to assume that a global energy transition is underway, and that world leaders will need to provide plans and solid policy options for the future. To do this, realistic and valid information concerning key technologies that drive the transition must be presented. It appears clear that global installed capacity of solar PV will increase significantly and that the cost of this technology will fall accordingly. The same could be argued for wind power. Therefore, policymakers must be able to carefully consider the important nature of solar PV and wind power technology costs relative to future global, cumulative installed capacities. In addition, such weather dependent energy generation technologies must be seen in the context of greater temporal and spatial accuracy, something which is neglected in past IAM exercises. Such consideration can only arise from accurate and relevant energy system model frameworks that conform to a meaningful set of sustainability criteria. Several studies which do have high temporal and spatial resolution on a continental scale and realistic technological representation of weather dependent power generation imply that fully renewable energy mixes, mostly based on wind and solar PV, are technically and economically viable options [12–14]. First insights from global scale modeling with an hourly resolution for a full year imply that not only are fully renewable power systems technically possible, they are economically attractive as well, from the system point of view and all over the world [14–17].

The ongoing energy transition is not only technological, but also a combination of economic, political, institutional and socio-cultural changes; thus, it should be guided by ethics and sustainability [18], as well as with a resilience perspective [19]. Importantly, the mitigation of climate change must not only be seen as a challenge to be overcome, but as a real-life, real-time struggle to prevent damage to humans, many of whom are paying or will pay disproportionate costs related to climate change. These groups include people who may be most vulnerable to the impacts of climate change, such as future generations, minority groups, and people in economically disadvantaged countries. Determining energy mixes for energy scenarios requires ethical choices due to long reaching impacts of energy decision-making and profound impacts on economics, the environment and people's lives. Consequently, future energy scenarios take on the role of long-term social contracts, which must be based on principles of justice [20].

For these reasons, the first aim of this study is to highlight the need for consideration of planetary boundaries and other sustainability principles in global energy scenario frameworks. This consideration includes not only climate change constraints, but other limitations as well. Second, we propose a literature derived hierarchy and sustainability guardrails according to which future global energy scenarios (and the transition) could be scrutinized. Third, we investigate whether sustainability guardrails have been deployed before in global energy scenarios and discuss how the determined sustainability principles could be operationalized into the creation of energy scenarios. This includes what kind of indices can be used for tracking the sustainable development of the global energy system.

2. Sustainability guardrails for the global energy system

Generally, sustainable futures must acknowledge that certain levels of cost and damage are intolerable, no matter what short term gains can be achieved. To this one can add that certain rights are inalienable. In essence, higher normative requirements will always outweigh any gains that can be achieved through intolerable acts. Such is the motivation for opposing such things as slavery, inequality, child labour, hazardous work conditions, etc. And this same motivation can be extended into all three spheres of sustainability (social, environmental, economic). Specifically, the world can seek to exclude anything which is unacceptable by establishing clear boundaries of tolerance. Such boundaries have also been introduced as guardrails for sustainable energy policy [21]. The German Advisory Council on Global Change (WBGU) has applied the principle of setting normative guardrails in order to create a sustainable global energy scenario. WBGU's ecological guardrails consist of compliance with a climate protection window, protection of marine ecosystems (by limiting carbon sequestration), sustainable land use (by limiting bioenergy), protection of rivers and catchment areas (by limiting large hydro power) and prevention of air pollution. The socio-economic guardrails include keeping risks within a normal range (by limiting nuclear power), preventing disease caused by energy use, limiting the proportion of income expended on energy, providing access to modern energy services, meeting an individual minimum requirement for modern energy services, and establishing a minimum level of macroeconomic development. Similarly, according to a definition by the Brundtland Commission [22], we should ensure that future generations are able to meet their needs, and that the resource limitations for sustainable development are contemporary and bounded by the present state of technology, social organization around environmental resources, and the ability of the biosphere to absorb human activities.

Häyhä et al. [23] point out that although the planetary boundaries framework proposes quantitative global limits, decisions regarding resource use and emissions are made nationally and sub-nationally. Thus, the operationalization of planetary boundaries as biophysical, socio-economic, and ethical dimensions in national policymaking is of high priority. Keeping this in mind, the realization of multiple sustainability targets requires that they can be simplified to pass in real world politics, as is argued to be the case for the two degree target. Determining sustainability targets in an objective manner is no easy task given that some guardrails must never be breached. For this reason, Serdeczny et al. [24] propose a framework for categorising different aspects of non-economic loss and damage (NELD): human life, meaningful places, cultural artefacts, biodiversity, communal sites, intrinsic values, agency (the ability to engage with or change one's world), identity, production sites and ecosystem services. The identified methods for valuing NELD are economic evaluation, multi-criteria decision analysis, composite risk indices, and qualitative and semi-quantitative approaches.

Given that social and economic sustainability targets are context dependent and subjective choices, their valuation could be based on the United Nation's development goals [25], global question polls, and participatory workshops. For example, 10 000 citizens from 76 countries participated in a global survey [26], and the majority of respondents (56%) preferred subsidization for wind, solar, marine and geothermal energy resources in order to make large scale cuts in greenhouse gas emissions. A very high proportion (97%) of the participants thought that a global dialogue, such as the survey they answered, should be conducted in the future when dealing with similar issues.

It can be argued that sustainability principles are hierarchical (Fig. 1). In the concept of strong sustainability, it is emphasized that certain elements of natural capital[2] are irreplaceable [27], and thus the

[1] A long-term exchange rate of 1.3 USD/EUR is applied in this study. Brackets signal conversion preceded by original number.

[2] Consists of resources for production, waste absorption from production, life-support