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Review

Defining and Operationalizing Sustainability in the Context of Energy

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Abstract: The terms sustainable and sustainability are currently often used in scientific journals, including *Energies*. There are cases where these terms are defined or operationalized, but more often they are not. This is problematic, as there are reportedly hundreds of (different) definitions and operationalizations (in terms of standards or goals) of sustainability. This large number has its roots in history. Many current definitions and operationalizations of sustainability are social constructs. As these constructs vary, there can be variation in the characterization of specific ways to provide energy as sustainable or not sustainable. There are also definitions of sustainability that have emerged from the sciences. These definitions can also lead to differences in the characterization of specific ways to provide energy as sustainable or not sustainable. In view thereof, there is a case to define and/or operationalize sustainable and sustainability when these terms are used in the context of energy.

Keywords: sustainable; sustainability; definitions; operationalizations; goals; standards

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1. Introduction

Salas-Zapata et al. [1] studied the usage of the terms sustainable and sustainability in scientific publications (found in the Science Direct and EBSCO databases for the year 2013). They noted that these terms were often (in more than 90% of the publications) not defined. In *Energies*, there are examples of sustainable and sustainability being defined or operationalized, but apparently more often they apparently are not (cf. Section 2). The absence of definitions or operationalizations is remarkable, as there are reportedly hundreds of (different) definitions and operationalizations (in terms of standards or goals) of sustainable and sustainability [2–10]. The large number of definitions and operationalizations has its roots in history. For this reason, Section 1 will present a very brief history of the terms sustainable and sustainability. Differences in the characterization of specific ways of providing energy as sustainable or not sustainable will be discussed in Section 2. Section 3 presents the conclusions of this paper.

2. A Very Brief History of the Terms Sustainable and Sustainability

Old definitions of sustainability refer to an equilibrium relation of humans with the environment [11]. In 1713, H.C. von Carlowitz, active in German forestry, suggested sustainable use (nachhaltende Nutzung) of forestry resources: not to harvest more wood than is added to the forest stock of wood by the growth of trees [11,12]. Since then, the application of this type of sustainable use to forestry has been geographically widened [12]. In the 19th century, economists discussed the stationary state: an equilibrium between, on the one hand, the environment and, on the other hand, the economy [13]. The economist D. Ricardo felt that the stationary state was ultimately inevitable [13], and the economist J.S. Mill stated: 'I sincerely hope for the sake of posterity that they (the people) will be content to be stationary, long before necessity compels them to it´ [14]. In 1973, H.E. Daly [15] revived this discussion with his publication of *Toward a steady state economy*, using ´steady state´ as a modern equivalent of ´stationary´. The focus of the terms sustainable and sustainability on an equilibrium relation between humans and the environment remained until 1980, when the International Union for the Conservation of Nature (IUCN) published the *World Conservation Strategy. Living resource conservation for sustainable development*, advocating the conservation of ecosystems and biodiversity [16].

Definitions of sustainability exclusively regarding the relation between humans and their environment have persisted in the scientific literature since 1980. In the 1980s, operationalizations of sustainability in terms of environmental utilization space within boundaries were introduced [17]. By now, a considerable number of operationalizations using sustainability-related boundaries have been published [18]. An influential example thereof is the safe operation space for humankind [19]. This space is defined within planetary boundaries as global environmental limits to avoid risking collapses of ecosystems [19]. The environmental issues for which planetary boundaries have been proposed are in Box 1. The safe operating space for humankind [19] has been applied in 'absolute sustainability assessments' [20].

Box 1. Environmental issues for which planetary boundaries, leading to a safe operating space for humankind, have been proposed [19,21].

- Climate change: atmospheric CO_2 concentration; energy imbalance at top of atmosphere.
- Ozone layer depletion.
- Atmospheric aerosol loading.
- Ocean acidification.
- Fresh surface water and groundwater consumption.
- Land system change: amount of forested land remaining.
- Biogeochemical flows impacting phosphorus (P) and nitrogen (N) cycles.
- Change of biosphere integrity.
- Novel entities: hazardous human-made chemicals, plastics (tentative)

As can be seen in Box 1, no boundary has been proposed for the usage of agricultural soils or for mineral resources generated in slow geological processes, whereas both are important for the functioning of current societies [22]. This is in line with the focus of the safe operating space for humanity on preventing the collapse of ecosystems [23].

Agricultural soils and resources generated in slow geological processes are included when sustainability is defined as conserving natural capital for transferal to generations living in the future [22,24]. So defined, sustainability is a characteristic of a steady-state economy [25]. Currently, natural capital is defined as the stock of environmental assets from which products and services can be derived that are useful to humankind, now and in the future. It comprises natural resources (e.g., fossil carbon compounds), ecosystems, generating ecosystem services, and the physical environment providing, e.g., wind for wind power [22]. Daly [26] and Ekins et al. [27] have stated that when the creation of substituting renewables at least equals the depletion rate of natural resources generated in slow geological processes, this can be considered to be conserving natural capital. However, it has also been argued that to conserve natural capital for transferal to generations living in the future, depletion of resources generated by slow geological processes should be near-zero [22].

In the 1980s, besides environmental matters, other elements were also included in definitions and operationalizations of sustainability. For instance, Solow [28] defined sustainability as conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita. However, the most important change concerning the inclusion of matters other than the environmental came in 1987 with the publication of *Our Common Future* [29]. This publication addressed environmental, economic, and social concerns. In *Our Common Future*, it was stated that 'sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs´. This definition is a social construct: a result of deliberations in the committee authoring *Our Common Future.*

Our Common Future has started a proliferation of definitions and operationalizations (in terms of standards and goals) of sustainable and sustainability that are social constructs (outcomes of social interactions such as deliberations and negotiations). Such constructs often include environmental, social, and economic elements. Whereas the definition in *Our Common Future* is general, operationalizations are often specific; they refer to or instance specific ways to provide energy (e.g., hydropower), specific activities (e.g., coal mining) or specific products (e.g., biofuels) [30–32]. It may occur that environmental issues are not included. The paper of Dauenhauer et al. [33], who evaluated the sustainability of community-based photovoltaic projects in Malawi, is an illustration thereof.

An important operationalization, including environmental, social, and economic elements, is found in the Sustainable Development Goals of the United Nations. The most recent set of these goals is set for the year 2030 and numbers seventeen, covering a variety of environmental, social, and economic issues. For energy the goal (number 7) is specified as: ensure access to affordable, reliable, sustainable, and modern energy for all. Specified goals under this heading are in Box 2. The history of Sustainable Development Goal 7 (which may be framed as sustainable energy development) has been outlined by Gunnarsdottir et al. [34].

Box 2. Energy goals of the 2030 Agenda for Sustainable Development [35].

7.1. By 2030, ensure universal access to affordable, reliable and modern energy services.
7.2. By 2030, increase substantially the share of renewable energy in the global energy mix.
7.3. By 2030, double the global rate of improvement of energy efficiency.

Many operationalizations of sustainability and sustainable development as social constructs (sustainability standards, sustainability goals, sustainable development goals) have emerged from companies and groups of companies [30,36–40]. They tend to diverge due to the variety of social contexts from which they emerge. Oil and gas companies have formulated divergent sustainability goals [36,41–43]. The Mining Association of Canada developed the Towards Sustainable Mining (TSM) standard, applying it e.g., to tar, sand and coal mining. The TSM standard has been adapted by several mining organizations in countries outside Canada [44–46]. The Minerals Council of Australia developed its own Enduring Value sustainability standard for mining, including coal mining [45].

Non-governmental organizations have also developed (diverging) sustainability standards, for instance for biofuels [10,38,46] and energy in buildings, the latter linked to different definitions of sustainability [7,9]. Governments of countries have been active in the establishment of mandatory and voluntary sustainability standards, the implementation and adaptation of sustainable development goals and the characterization of activities and products as (un)sustainable [32,38,47,48]. They also have developed sustainable development plans for specific parts of the energy sector such as coal mining [49,50]. The outcomes of these government activities diverge [32,38,47–50]. There are variable definitions of sustainable cities [51]. City governments have developed or adapted sustainable development goals in divergent ways [32,47] and have been active in the fields of sustainable building standards and of sustainable energy action plans, with variable operationalizations of sustainability goals [52,53].

Furthermore, operationalizations of sustainability as a social construct have emerged from international organizations of stakeholders and experts [54]. Examples of such organizations are the Roundtable on Sustainable Biofuels [55], The Forest Stewardship Council (relevant to forest-derived biofuels) [56] and the Hydropower Sustainability Council [57]. Another example in this category is the Sustainable Nuclear Energy Technology Platform [58], which operationalizes sustainability in terms of safe, reliable, and efficient. Sustainability goals for geothermal energy have emerged from a project involving experts and stakeholder groups in Iceland, New Zealand and Kenya [59].

All in all, the variations as to social contexts in which definitions and operationalizations of sustainability and sustainable have been constructed have led to variations in definitions, standards, and goals.

3. Differences as to the Sustainability of Ways to Provide Energy

Because, as pointed out in Section 1, the social constructs that operationalize sustainable and sustainability (in terms of standards and goals) vary, there can be differences in the characterization of ways to provide energy, or aspects thereof, as sustainable or not sustainable. In principle, such differences may regard all aspects of providing energy, including, e.g., mining, generation of biomass, siting, distribution, and storage.

Examples of differences in the characterization of a practice as sustainable or not sustainable following from different sustainability standards or goals are the following. In 2021 the United States Department of Energy characterized nuclear energy as sustainable, whereas the German government considered nuclear power to be not sustainable [60,61]. There are strongly opposing views in the European Union about the sustainability of using forest biomass for providing energy [62]. Baudry et al. [63] found a low level of agreement among French stakeholders about sustainability standards for biofuels. Sustainability standards for biofuels diverge as to the protection of biodiversity and ecosystems [6,48]. Whereas there are sustainability standards for palm oil in the major palm oil-producing countries Indonesia and Malaysia, the European Union has decided to phase out the use of palm oil for biofuel production by 2030 as being not sustainable due to its link with deforestation [10,48]. This is now the subject of litigation at the World Trade Organization [48]. Corvellec et al. [64] documented disagreement as to the question of whether or not a waste incinerator plant serving electricity production and district heating in Göteborg (Sweden) contributed to sustainable urban development. Höfer and Madlener [65] found that stakeholder opinions regarding sustainable energy transition scenarios in Germany varied widely. Lehmann et al. [66], studying spatial sustainability of wind power in Germany, found no agreement among stakeholders about the ranking of sustainability criteria regarding costs, impacts on humans and impacts on ecosystems. Tost et al. [45] found that the sustainability standard for mining formulated by the Initiative for Responsible Mining Assurance was stricter than the sustainability standards of Towards Sustainable Mining and Enduring Value, that were referred to above.

To illustrate the impact of different definitions of sustainability on the characterization of ways to provide energy, I have selected three definitions of sustainability proposed in scientific literature.

They are:

- Sustainability is conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita [28].
- Sustainability is conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24].
- Sustainability is remaining within planetary boundaries allowing for a safe operating space for humankind [19,21].

These definitions will be used to characterize nuclear power, transport biofuels (based on freshwater autotrophic microalgae), coal-based energy (involving aged coal mines and ultra-low-emission power plants) and current photovoltaics. The choice of these ways to provide energy is linked to papers in *Energies* that used the terms sustainable and sustainability regarding nuclear power, transport biofuels, coal-based energy, and photovoltaics.

As to nuclear power, Xu et al. [67] described the replacement of Chinese coal-fired power stations by nuclear power plants in terms of sustainable development, whereas Heo [68] used the term sustainability in the context of safety assessment of nuclear energy. Zhang et al. [69] focused on sustainable development for China´s coal power industry using ultra-low-emission plants. Gao et al. [70] discussed the sustainable development of an aged Chinese coal mine, to be achieved by recovering pillar-blocked coal resources. In none of these papers was sustainable or sustainability defined or operationalized. Zhironkin and Cehlar [71] considered the sustainable development of coal mining and operationalized this as: reducing environmental damage, digital modernization and finding a new place in the context of the rapid development of renewable energy sources. The term sustainable biofuels for use in aviation was used by Cabrera and de Sousa [72]. They state that there is no universally agreed definition of such biofuels, but do not select a definition for use in their paper. Cabrera and Sousa [72] considered biofuels which raise sustainability issues and biofuels which do not. In the latter category they include (liquid) transport biofuels from freshwater autotrophic microalgae. The term sustainable for applications of biofuels in internal combustion engines was used by Awogbemi et al. [73]. They state that biofuels are accepted as sustainable, but the term was not defined. Against this background, the sustainability of (liquid) transport biofuels based on freshwater autotrophic microalgae will be considered here. According to the paper of Wittman et al. [74], photovoltaics has a major role to play in global sustainable development. In this case, the United Nations Sustainable Development Goals were used to operationalize sustainable development.

The three definitions of sustainability selected here are used to characterize the sustainability of nuclear power in Table 1, and of (liquid) transport biofuels based on freshwater autotrophic microalgae in Table 2. The characterization of coal-based provision of energy (involving aged coal mines and ultra-low-emission power plants) is in Table 3, and of current photovoltaics in Table 4. From these tables it may be concluded that all these ways to provide energy are sustainable according to the definition of Solow [28]. However, none of them are sustainable when sustainability is defined as conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24]. When the safe operating space for humankind based on planetary boundaries [19,21] is used as the definition of sustainability, nuclear power is sustainable when there is a timely phase-out of life cycle greenhouse gas emissions, but (liquid) transport biofuels based on freshwater autotrophic microalgae are not sustainable.

Table 1. The sustainability of nuclear power using three definitions of sustainability.

Definition of Sustainability	Characterization of Nuclear Power	Comments
Sustainability is conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita [28].	Sustainable.	Increase in manufactured capital exceeds reduction in natural capital.
Sustainability is conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24].	Not sustainable.	Natural capital to be transferred to future generations is negatively impacted by substantial (well above near-zero) reduction in stock of natural resources generated by slow geological processes (such as uranium ores), greenhouse gas emissions emitted during the life cycle, and legacy to future generations of hazardous nuclear wastes and pollution by radionuclides having a long half-life.
Sustainability is remaining within planetary boundaries allowing for a safe operating space for humankind [19,21]	Sustainable when life cycle greenhouse gas emissions are phased-out in a timely way.	For timely phase-out of greenhouse gases; see Sandin et al. [75]. Other boundaries presented in Box 1 are currently not at risk of exceedance due to nuclear power.

Table 2. The sustainability of (liquid) transport biofuels based on freshwater autotrophic microalgae using three definitions of sustainability.

Definition of Sustainability	Characterization of (Liquid) Transport Biofuels Based on Freshwater Autotrophic Microalgae	Comments
Sustainability is conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita [28].	Sustainable.	Increase in manufactured capital exceeds reduction in natural capital.
Sustainability is conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24].	Not sustainable.	Substantial negative impacts on stocks of natural resources generated in slow geological processes (such as phosphate ores, fossil fuels) and on climate, and often also on water-resources [76].
Sustainability is remaining within planetary boundaries, allowing for a safe operating space for humankind [19,21].	Not sustainable.	Impacts on P&N flows violate planetary boundaries [76].

Table 3. The sustainability of coal-based energy involving aged coal mines and ultra-low-emission power plants using three definitions of sustainability.

Definition of Sustainability	Characterization of Coal-Based Provision of Energy Involving Aged Coal Mines and Ultra-Low-Emission Power Plants	Comments
Sustainability is conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita [28].	Sustainable.	Manufactured capital monetarily outweighs reduced stock of coal in view of expected future coal consumption.
Sustainability is conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24].	Not sustainable.	Contributes to long-lasting climate change, leads to a substantially reduced stock of resources generated by slow geological processes and to hazardous wastes to be transferred to future generations.
Sustainability is remaining within planetary boundaries allowing for a safe operating space for humankind [19,21].	Sustainable when the emission of coal-related greenhouse gases is phased out in a timely way.	For timely phase-out of greenhouse gases; see Sandin et al. [75]. Other boundaries (see Box 1) are currently not at risk of exceedance by the type of coal-based energy considered here.

Table 4. The sustainability of current photovoltaics using three definitions of sustainability.

Definitions of Sustainability	Characterization of Current Photovoltaics	Comments
Sustainability is conserving the sum of natural capital (monetarized natural resources) and manufactured capital per capita [28].	Sustainable.	Increase in manufactured capital exceeds reduction in natural capital.
Sustainability is conserving natural capital for transferal to generations living in the future, with a near-zero depletion of resources generated by slow geological processes [22,24].	Not sustainable.	Negative impact on natural capital linked to substantial life cycle losses of geochemically scarce elements such as Cu and In, and to inputs of fossil fuels and associated emissions of gases contributing to climate change during the life cycle [22].
Sustainability is remaining within planetary boundaries allowing for a safe operating space for humankind [19,21].	Sustainable when life cycle greenhouse gas emissions are phased-out in a timely way.	For timely phase-out of greenhouse gases; see Sandin et al. [75]. When locations are well chosen (e.g., on roofs) no other boundary presented in Box 1 will be exceeded.

4. Conclusions

In the previous sections, it has been shown that definitions and operationalizations of sustainable and sustainability vary. As a consequence thereof, characterizations of the concepts of sustainability and sustainable can vary regarding ways to provide energy and aspects thereof. Examples were presented of differences in the characterization of sources of energy (such as photovoltaics and nuclear power), and of aspects of ways to provide energy such as mining and siting, as sustainable or not sustainable.

It can be concluded that there is a case to operationalize (in terms of standards or goals) and/or define sustainable and sustainability when these terms are used in the context of energy.

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