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Indicator system for the sustainability assessment of the German energy system and its transition

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Abstract

In response to climate change, the limited availability of fossil fuels and the risks associated with nuclear energy, Germany's energy transition aims to achieve a sustainable, environmentally sound supply of energy services. A monitoring process was established by the Federal Government to ensure that the targets defined for the transformation will be reached. The indicator system developed for that purpose mainly focuses on "classical" environmental, economic and technological indicators for which statistical time series data and political targets are available. Important socio-technical aspects of the energy system and its transition, such as affordability, participation and acceptance, remain largely neglected. This paper aims to contribute to the discussion on indicators needed for political decision-making to appropriately address sustainability aspects of the energy system and its transition, as well as to contribute to improving existing indicator systems. Therefore, the sustainability rules of the Integrative Concept of Sustainable Development were translated into indicators based on an in-depth literature review. The resulting abundance of possible indicators was then reduced using selection criteria such as comprehensiveness, possibility to determine targets and availability of data. Finally, the indicator system was adjusted based on feedback of experts from different disciplines and stakeholder interviews in the particular investigation area of southwest Thuringia. Besides classical indicators related to techno-economic and environmental aspects, the finally developed indicator system includes new sustainability indicators related to the socio-technical interface of the energy system. Thus, it is considered suitable for assessing the sustainability of the Germany energy system and its transition in an integrative and comprehensive way. The indicator system is helpful to systematically identify strengths and weaknesses of the energy system and interdependencies and conflicts of goals between different sustainability aspects. All in all, we believe that applying the indicator system appropriately can support the development of resilient political strategies for a successful energy transition.

Keywords: Sustainability, Assessment, Indicators, Energy system, Energy transition

Background

The energy system plays a key role in realizing a more sustainable development at the global and national level. The Federal Government is aware of this and has determined political targets and adopted measures to transform the energy system into a more sustainable one [1]. The overall objective is to establish a secure, affordable and ecologically compatible energy supply without nuclear power and based on a growing share of renewables and increasing energy efficiency. The monitoring process 'Energy of the future' was established to ensure that the energy transition develops in the desired direction. In this process, indicators are used to take annual stock of progress made in achieving the quantitative targets of the German Energy Concept [2]. The core indicators relate to well-known characteristics of the energy system, like the share of renewable energies and greenhouse gas emissions. Social aspects such as the fair allocation of benefits and burdens of the energy transition among social groups or the participation of citizens in the transformation process are to a large extent missing. The scientific expert commission accompanying the monitoring process has drawn attention to this deficiency.

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The experts recommended not to focus only on classical indicators for which statistical time series data and targets are available but also to take into consideration aspects such as affordability, participation and acceptance [3, 4]. In light of the above, it is concluded that a holistic indicator system is needed as an analytical tool to assess the sustainability of the German energy system and to support the development of resilient political strategies for a successful energy transition.

Methods

Since the idea of sustainable development is common ground in scientific and political contexts, a number of guidelines, frameworks and tools have been developed to assess the sustainability of technologies, processes and systems [5–11]. The latest and most relevant work in this respect are the 17 Sustainable Development Goals (SDGs) defined by the UN [12], including 230 indicators substantiating these goals. The SDGs partly build upon the Millennium Development Goals (MDGs) adopted by the UN in 2000. They are aimed at an array of issues, such as slashing poverty, hunger, diseases and gender inequality and improving access to fresh water and sanitation. The SDGs go much further than the MDGs by addressing the reasons for poverty and the universal need for an equitable and sustainable development for all people. Each SDG has specific targets to be achieved over the next 15 years. Target 17 refers to energy and includes five sub-goals to be achieved by 2030:

- ❖ Ensure universal access to affordable, reliable and modern energy services
- ❖ Increase substantially the share of renewable energy in the global energy mix
- ❖ Double the global rate of improvement in energy efficiency
- ❖ Enhance international co-operation to facilitate access to clean energy research and technology and promote investment in energy infrastructure and clean energy technology
- ❖ Expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in accordance with their respective programmes of support

The SDGs were developed and agreed upon by developed and developing countries, with transformative action being dedicated primarily to the national level. Here, further and more differentiated indicators are needed to strike a careful balance between different sustainable development issues. For defining additional indicators relevant to scientific debates and societal and political decision-making, a theoretically well-founded and operable conceptual approach to analysis and assessment is required. The Integrative Concept of Sustainable Development developed within the German Helmholtz Association [13] is such a concept and is used in this work as a methodological framework to derive a coherent system of sustainability indicators.

The Integrative Concept of Sustainable Development

For almost 30 years, several approaches to conceptualizing sustainable development have been developed and applied, such as the three- or four-pillar model or the cross-pillar integrative approaches [14, 15]. The three-pillar model prevails in political and scientific practice, despite being criticized for its lack of theoretical depth in justifying sustainable development as overall guiding principle, its systematic neglect of interdependencies between the pillars and insufficient consideration of the postulate of justice and fairness [14, 15]. The Integrative Concept of Sustainable Development [13] was developed to overcome these deficits. In contrast to other concepts structured along the economic, ecological and social dimension, it is based upon three constitutive elements of sustainable development underlying the key documents of sustainable development, such as the Brundtland report [16], the Rio Declaration and the Agenda 21 [17]:

(1) Inter- and intragenerational justice, both equally weighted, as theoretical and ethical fundament. Justice is understood as distributional justice with respect to rights and obligations, benefits and burdens.
(2) A global perspective, by addressing key challenges of the global community and developing goals and strategies to achieve them. It includes a strategic justification for translating globally defined goals into the national and regional context.
(3) An enlightened anthropocentric approach including the obligation of mankind to interact cautiously with nature based on a well-understood self-interest.

These constitutive elements are translated into three general goals and preconditions of sustainable development:

(1) Securing human existence, including basic needs and the capability of human beings to shape their lives on their own
(2) Maintaining society's productive potential, which consists of natural, man-made, human and knowledge capital
(3) Preserving society's options for development and action, addressing immaterial needs such as integration in cultural and social contexts in addition to material needs

These goals are specified by substantial sustainability rules (Table 1) forming the core element of the concept. They describe minimum requirements for sustainable development in the sense of a welfare base that need to be assured for all people of present and future generations.

A set of instrumental rules was defined addressing the economic, political and institutional framework conditions to fulfil the substantial rules. Internalization of external costs, for example, addresses the approach to implementing the 'polluter pays' principle. The discount rate and handling and dealing with public indebtedness strongly influence intergenerational justice. The issues of intragenerational and international fairness and solidarity are related to the global economic framework conditions and international co-operation.

In the concept, sustainable development is considered as a 'regulatory idea' that inspires political action, based on an understanding of policy as a polycentric process involving different actors and institutions. This requires institutional settings to be shaped accordingly and innovations to be developed within a societal dialogue. To this end, specific rules to overcome the problems identified were developed [18]. The rule 'society's ability to respond' addresses the ability of actors and institutions to distinguish between relevant and less relevant issues and to respond to them adequately. The rule 'society's ability of reflexivity' aims to consider the impact on others of acting in a societal sub-system in order to reduce or prevent conflicts in advance. The need to design and implement appropriate measures is addressed by the rule 'society's ability to govern'. The rule 'society's ability of self-organization' is related to the degree to which societal actors themselves take responsibility and support sustainable development strategies. This requires avoiding unjustified imbalances of power and of possibilities to articulate and influence processes between actors, an issue that is addressed by the rule 'balance of power between societal actors'.

The set of substantial and instrumental rules provides basic orientation for development as well as criteria to assess different states or development paths. They are, a priori, universally valid and equally weighted. Thus, conflicts between rules cannot be solved by a hierarchical decision prioritizing specific rules. Nevertheless, priorities and weightings, i.e. relevant considerations, are possible and even necessary at the level of specific thematic, regional or other contexts. With this sophisticated architecture and the elements outlined above, the Integrative Concept of Sustainable Development is a multi-level concept, theoretically well-founded, clearly defined and non-arbitrary, that provides a good fundament for setting up something that could be called a theory of sustainable development [14].

Selection and definition of sustainability indicators

The application of the Integrative Concept of Sustainable Development for defining sustainability indicators to assess the German energy system consists of two phases. First, relevant decisions have to be made regarding the rules. Then, the relevant rules are contextualized by indicators [19]. Indicators are the most common and popular tools to measure progress towards sustainable development and for any sustainability analysis [20–22]. They are useful to communicate ideas, thoughts and values and can lead to better decisions and more

Table 1 Rules of the Integrative Concept of Sustainable Development [13]

Substantial rules		
Securing human existence	Maintaining society's productive potential	Preserving society's options for development and action
1. Protection of human health	6. Sustainable use of renewable resources	11. Equal access for all to information, education and occupation
2. Satisfaction of basic needs	7. Sustainable use of non-renewable resources	12. Participation in societal decision-making processes
3. Autonomous subsistence based on income from own work	8. Sustainable use of the environment as a sink for waste and emissions	13. Conservation of cultural heritage and cultural diversity
4. Just distribution of opportunities to use natural resources	9. Avoidance of technical risks with potentially catastrophic impacts	14. Conservation of the cultural function of nature
5. Reduction of extreme income and wealth inequality	10. Sustainable development of man-made, human and knowledge capital	15. Conservation of social resources
Instrumental rules		
1. Internalization of external social and ecological costs	5. Promotion of international co-operation	8. Society's ability to govern
2. Adequate discounting	6. Society's ability to respond	9. Society's ability of self-organization
3. Limitation of public debt	7. Society's ability of reflexivity	10. Balance of power between societal actors
4. Fair international economic framework conditions		

effective actions by simplifying, clarifying and making information available to policymakers. Besides, they provide an early warning to prevent economic, social and environmental setbacks [21]. Taking this into account, the development of indicator faces several challenges and requirements [23, 24]. One issue refers to the suitable number of indicators, allowing for both an appropriate substantiation of goals and manageability of analyses and communicability of results. An appropriate combination of different indicator types should be chosen, including context-adapted single or socio-economically differentiated objective and subjective indicators. Besides, a sound combination of a science-based 'top-down' and a stakeholder-based 'bottom-up' approach is needed.

With regard to sustainability assessment of the German energy system, it can be stated that not all rules have a clearly defined relation to the subject of investigation. This is true for the rule 'conservation of cultural heritage and cultural diversity' because it focuses on cultural treasures such as heritage-listed buildings or precious historical items saved for present and future generations. Similar considerations apply to the rule 'fair international economic framework conditions'. This rule is only weakly connected to the German energy system as it focuses on global economic and political conditions created by supranational institutions. The rule 'limitation of public debt', too, is not considered relevant because the transition of the energy system is designed in a way that it will not directly increase public debt over time. Beyond that, there are rules which are not concretized by an indicator due to principle problems of obtaining significant and reliable information to define feasible indicators. This applies to the rule 'adequate discounting'. Although this rule is relevant, it was not included due to the difficulty of raising valid and representative data for the discounting practice in public and private investment decisions.

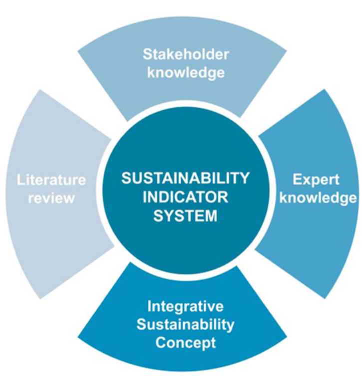
In order to assess the German energy system, a number of indicators have been developed to address the relevant rules. The indicators were selected in a multi-stage process (Fig. 1) including the following three steps:

Table 2 lists the literature used in the comprehensive and in-depth review process. The focus was on German literature in order to conduct the queries as efficient as possible. Besides, the intention of the work was to emphasize deficits of existing indicator sets used in Germany. For that reason, the selected indicators are a priori applicable only to the assessment of the German energy system. However, they can easily be adapted to evaluate other European energy systems.

An indicator system consisting of a very large number of indicators is difficult to handle in terms of reporting requirements, trade-offs between indicators and consideration processes in politics. The number of indicators in this work was limited to below 50. Other indicator sets were used as reference to determine this number. The UN Commission on Sustainable Development (CSD), for example, uses 59 core indicators and, based on them, Eurostat and the European Environment Agency (EEA) apply 63 indicators [9, 25]. Policymakers often require a smaller number of indicators, which, however, is not feasible from the scientific point of view because of the complex and comprehensive nature of sustainable development. The indicator system chosen appropriately represents this rather sophisticated reality—the state of society, its social, economic and ecological connections, and its development and targets.

Results

Before presenting the results in detail, a few characteristics of the indicator system shall be highlighted. First of all, the indicator system does not represent the entire rules due to relevant considerations. Another important



- Translation of sustainability rules into indicators based on a literature review and the assignment of indicators to the relevant rules.
- Reduction of indicators by applying the criteria of comprehensiveness, possibility to determine targets and availability of data [24].
- Adjustment of the indicator system in response to the feedback of experts (written comments, workshop evaluation) and the results of stakeholder interviews.

Fig. 1 Development of the sustainability indicator system

Table 2 Literature used for the selection of indicators

Author/editor	Report
Agentur für Erneuerbare Energien (AEE) 2015 [53]	Bundesländer mit neuer Energie—Jahresreport Föderal Erneuerbar 2014/2015
Deutsches Institut für Wirtschaftsforschung, Zentrum für Sonnenenergie- und Wasserstoffforschung Baden-Württemberg (AEE) 2014 [54]	Vergleich der Bundesländer: Analyse der Erfolgsfaktoren für den Ausbau der Erneuerbaren Energien 2014—Indikatoren und Ranking. Endbericht
Bundesverband der Deutschen Industrie e.V. 2014 [55]	Energiewende-Navigator 2014
Bundesministerium für Wirtschaft und Energie 2015 [56]	Vierter Monitoring-Bericht „Energie der Zukunft"
Ecoplan, Factor 2001 [57]	Nachhaltigkeit: Kriterien und Indikatoren für den Energiebereich. Endbericht für das Bundesamt für Energie (CH)
Compiling and Refining Environmental and Economic Accounts (CREEA) 2014 [58]	Compiling and refining environmental and economic accounts. Ergebnisberichte des EU-Projekts
Statistisches Bundesamt – Destatis 2014 [59]	Nachhaltige Entwicklung in Deutschland – Indikatorenbericht 2014
Statistisches Bundesamt – Destatis 2016 [60]	Umweltökonomische Gesamtrechnungen – Nachhaltige Entwicklung in Deutschland – Indikatoren zu Umwelt und Ökonomie – 2016
Expertenkommission zum Monitoring-Prozess 'Energie der Zukunft' 2015 [61]	Stellungnahme zum vierten Monitoring-Bericht der Bundesregierung für das Berichtsjahr 2014
International Atomic Energy Agency, UN Department for Economic and Social Affairs, International Energy Agency, Eurostat, European Environment Agency 2005 [62]	Energy Indicators for Sustainable Development: Guidelines and Methodologies
Institute for Advanced Sustainability Studies (IASS) 2013 [48]	Beiträge zur sozialen Bilanzierung der Energiewende
Kearney, A.T., WirtschaftsWoche 2012 [63]	Energiewende-Index
Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg 2015 [64]	Monitoring der Energiewende in Baden-Württemberg—Schwerpunkt Versorgungssicherheit und Effizienztrends—Statusbericht 2015
Zentrum für Europäische Wirtschaftsforschung (ZEW) 2012 [65]	Indikatoren für die energiepolitische Zielerreichung

issue is that some rules are mainly addressed by classical indicators. For other rules, however, it was necessary to develop and define 'new' and partly provisional indicators, for example for the rule 'participation in societal decision-making processes'. In a few cases, no appropriate indicator could be identified at all. To give an example: Renewable energy technologies have various impacts on biodiversity. The different direct and indirect impacts, however, cannot be merged into a meaningful indicator which can easily be assessed. Thus, the authors have deliberately refrained from proposing an indicator on biodiversity.

The number of indicators addressing the rules can vary widely because no standard exists that one rule has to be addressed by one indicator only. For some rules, it was considered sufficient to define one indicator. For other rules, more than one indicator was needed to adequately and sufficiently address the different facets of the rule. As an example: The rule 'sustainable use of non-renewable resources' is related to different political areas of activity and targets, such as the energy consumption of households, transport and industry as well as the modal split. Therefore, this rule is addressed by nine indicators (Indicator No. 12 to No. 20). It could be argued that any rule with more than one indicator is given a relatively higher weight in the evaluation system. This, however, is not the case because within the evaluation process all rules are defined to be a priori equally weighted. Political and societal decisions about the relevant and relative importance of rules and indicators can only be taken at the level of particular thematic, regional or other contexts.

Indicators for the goal 'securing human existence'

The sustainability goal to secure human existence is defined by five rules and addressed by nine indicators (Table 3). The first three indicators relate to energy-related emissions of particulate matter and emissions of cadmium and mercury, all of them harmful to human health as they cause a wide range of serious health problems. Alternatively, human health could be addressed by the concept of DALY (disability-adjusted life years), which calculates the life years lost due to work-related diseases and lethal and non-lethal occupational accidents in the energy sector. Another option is to calculate the fatality rates of energy technologies based on the Energy-related Severe Accident Database [26, 27]. Both concepts are based on elusive assumptions and system boundaries. As direct health impacts of technologies also cannot be adequately assigned to the energy sector, the most important energy-related emissions were selected as indicators to address the issue of human health.

Table 3 Sustainability indicators for the goal 'securing human existence'

Sustainability rule	Sustainability indicator
Protection of human health	1. Energy-related emissions of particulate matter 2. Energy-related emissions of cadmium 3. Energy-related emissions of mercury
Satisfaction of basic needs	4. Energy import dependency 5. Monthly energy expenditures of households with a monthly net income less than 1300 Euros 6. SAIDI of electricity
Autonomous subsistence based on income from own work	7. Relation of employees in the renewable energy sector to total employees
Just distribution of opportunities to use natural resources	8. Final energy consumption of private households per capita
Reduction of extreme income and wealth inequalities	9. Relation of technician salary to manager salary at the big electricity suppliers

Satisfying the energy demand has not only a physical and technical but also an economic dimension, which are addressed by three indicators. The indicator 'share of imported energy in primary energy use' characterizes one aspect of the physical vulnerability of energy supply by addressing Germany's dependency on imports. Regarding the target of this indicator, it has to be taken into account that a high-technology country like Germany can reduce but not completely overcome its import dependency. To address the technical security of electricity supply, the indicator 'system average interruption duration index' (SAIDI) was selected. The SAIDI sums up the average electricity supply interruption, measured in minutes per year per connected consumer.

The affordability of energy supply was addressed by focusing on the energy expenditures for low-income households. This social group is supposed to suffer from 'energy poverty'. This means that they are not able to adequately heat their homes or use other energy services at affordable costs due to rising energy prices, low income and poor energy efficiency of heating systems or other devices [28, 29]. To adequately measure the unaffordability, the actual expenditures should be related to the expenditures required to meet the existential needs of these households. These 'essential' expenditures still need to be defined for vulnerable household types [30]. It is recommended to replace the proposed indicator by a more sophisticated indicator referring to the relation between energy expenditures for electricity and heat of low-income households and the essential expenditures for the essential provision of these types of energy services.

The rule 'autonomous self-subsistence' refers to the possibility of human beings to secure their livelihood by a freely chosen occupation. The energy sector is an important employer and the continuing growth of jobs in the renewable energy sector is significant because it stands in contrast to trends across the energy sector. This increase is being driven by declining renewable energy technology costs and enabling policy frameworks. The indicator 'share of employees in the renewable energy sector in total employees' is proposed in full knowledge that it cannot represent the rule adequately because jobs in the conventional energy sector will decrease as a result of the energy transition. Moreover, employment levels in other sectors can decline due to higher energy costs resulting from government support for renewable energies. The defined indicator is provisional and needs to be replaced by a more comprehensive indicator including all direct and indirect employment effects of the energy transition as soon as data are available.

The rule 'just distribution of opportunities to use natural resources' implicates the issue of fair allocation of chances, responsibilities and burdens among all people with respect to natural resource use. The less natural resources and absorption capacity of the environment we use in Germany, the more is available for people in other countries. The indicator 'final energy consumption of private households per capita' addresses this issue. A comparison at global level reveals that, for example, household electricity consumption in Germany is four times higher than in India. The sustainability rule 'reduction of extreme income and wealth inequalities' should be adhered to combat poverty and social marginalization. Both are related neither to distinct economic sectors nor to technologies, but rather caused by social and tax regulations. However, huge disparities between the salaries of employees can consolidate or further increase inequalities. Therefore, the relation between technician salary and manager salary at the big energy suppliers was defined as indicator. This relation has worsened significantly in the last years, amounting to 1:79 in 2013 [31].

Indicators for the goal 'maintaining society's productive potential'

The sustainability goal of maintaining society's productive potential is defined by five rules translated into 22 indicators (Table 4). The rule 'sustainable use of renewable resources' is addressed by the classical indicator 'share of renewable energy in gross final energy consumption' and the new indicator 'area under cultivation of energy

Table 4 Sustainability indicators for the goal 'maintaining society's productive potential'

Sustainability rule	Sustainability indicator
Sustainable use of renewable resources	10. Share of renewable energy in gross final consumption of energy 11. Area under cultivation of energy crops
Sustainable use of non-renewable resources	12. Unused renewable electricity due to management measures 13. Use of primary energy 14. Specific final energy consumption of households for heating (temperature-corrected) 15. Final energy consumption in the transport sector 16. Modal split in the transport sector 17. Number of electric vehicles 18. Final energy productivity of the German economy 19. Final energy productivity of the industry 20. Final energy productivity of trade, commerce and services
Sustainable use of the environment as a sink for waste and emissions	21. Energy-related greenhouse gas emissions 22. Energy-related emissions of acid-forming gases 23. Energy-related hazardous solid wastes
Avoidance of technical risks with potentially catastrophic impacts	24. Amount of high-level radioactive waste which has not been transferred to a safe final disposal site
Sustainable development of man-made, human and knowledge capital	25. Installed capacity of renewable energy power plants 26. Number of university graduates in the field of energy sciences 27. Federal expenditures for energy research 28. Number of German patents in the field of renewable energy and energy efficiency 29. Number of start-ups in the renewable energy and energy efficiency sector 30. Added value creation from the renewable energy sector 31. Added value creation from energy efficiency measures in households

crops'. The new indicator was defined due to evidence that energy production with renewables increases the demand for land. The type and extent of land use differs considerably among the energy technologies and therefore cannot be summed up. In Germany, 12.3% of the agricultural area is used for energy cropping [32], indicating a strong impact on land use. There is a controversial debate on land use for energy production in the face of world hunger and evidence on climate impacts and other adverse environmental and social impacts of energy crops [33]. This is why the area under cultivation of energy crops was chosen as indicator.

The sustainable use of non-renewable resources is substantiated by nine indicators. In addition to the classical indicator 'amount of primary energy use', the new indicator 'unused renewable electricity due to management measures' was defined because the installed capacities to produce renewable energy must be used more efficiently, and temporary reductions in production to avoid overloading the grid and blackouts must be reduced.

The indicator 'temperature-corrected specific energy consumption of households for heating' was selected because the existing building stock is a major energy consumer in Germany, aside from the mobility sector for which the indicator 'final energy consumption in the transport sector' was selected. The indicator 'modal split in the transport sector' measures sustainable transport particularly for non-motorized (cycling and walking) and public transport. The indicator 'number of electric vehicles' was defined because of the Federal Government's target to increase the number of electric vehicles to six million until 2030. Another three indicators relate to final energy productivity, the industry sector and the trade, commerce and services sector.

The rule 'sustainable use of the environment as a sink for waste and emissions' is substantiated by three indicators related to energy-related greenhouse gas emissions, emissions of acid-forming gases and hazardous solid wastes. The German energy sector was responsible for about 80% of the greenhouse gas emissions [34], 48% of the acid-forming emissions [35] and 13% of the total amount of hazardous wastes generated in 2012 [36]. The rule to avoid technical risks with potentially catastrophic impacts is substantiated by the indicator 'radioactive waste which has not been transferred to a save final disposal site'. Radioactive waste, especially spent fuel and waste from reprocessing, involves risks and hazards for humans and the environment. In the next years, the amount of radioactive waste will increase due to an increase of spent fuels and the lack of a political decision on a final disposal site.

The first indicator related to the sustainable development of man-made, human and knowledge capital is the 'installed capacity of renewable energy power plants'. To what extent the capacity should be increased depends on the mix of renewables, grid development and electricity storage capacities as well as the electricity demand. Another two indicators address the creation of sustainable added value by the renewable energy sector and energy efficiency measures in households. They are related to the national level and include company profits, taxes and income from wages that are generated, e.g. through planning and implementation of renewable energies or energetic refurbishment.

Well-trained young people with different graduate degrees are needed to support the energy transition in practice, teaching and research. Besides, it is imperative to have enough research funds to boost and sustain human knowledge capital in the field of energy. This is why the indicator 'number of university graduates in the field of energy science' and the indicator 'federal expenditures for energy research' were selected. In 2014, the number of these graduates reached 2171 [37], and the federal research expenditures in the field of energy amounted to 1121 million Euro in 2013 [38]. Another two indicators deal with the development and implementation of knowledge and innovation activities: the 'number of patents with German participation' and the 'number of start-ups in the renewable energy and energy efficiency sector'. The first indicator is more familiar, whereas the second is quite new. The 'start-ups' indicator was defined to measure whether innovations are taken up by entrepreneurs. Start-ups can be considered as drivers and multipliers of innovations which are particularly relevant in young and emerging markets.

Indicators for the goal 'preserving society's options for development and action'

The sustainability goal to preserve society's options for development and action is defined by four rules that are translated into five indicators addressing the socio-technical interface of the energy system (Table 5). The indicators proposed are rather new in the political and scientific debate. The rule 'equal access for all to information, education and occupation' is addressed by the indicator 'gender pay gap in the highest salary group in the energy sector'. In the energy sector, women's salary is about 80% of men's salary in this group [39]. The gender pay gap belongs to the sustainability indicators proposed by the EU [40]. It is linked to a number of legal, social and economic factors which go far beyond the single issue of equal pay for equal work. Nevertheless, the indicator provides a suitable benchmark to measure the achievement of equal opportunities within the energy sector.

The indicator 'share of regulatory tools in the planning of power transmission grids that fulfil regulatory requirements' addresses the sustainability rule 'participation in societal decision-making processes'. This indicator relates to public involvement in decision-making to improve the transparency and quality of decision-making processes and provide legitimation for decisions taken. Ultimately, this is expected to lead to higher acceptance or acceptability of energy infrastructure projects [41].

Energy technologies can be subjectively perceived as impairment of recreational values, spiritual and sensual meanings or aesthetic contemplation of nature [42]. The indicator 'share of tourists who perceive energy power technologies as being disruptive in the vacation area' addresses the sensual perception of leisure travellers and tourists. It substantiates the sustainability rule 'conservation of the cultural function of nature'. While there are ambitious government targets to increase the share of renewable energy, it is recognized that social acceptance may be a constraining factor in achieving these targets. This is particularly apparent in the case of wind energy and grid extension, which has become a subject of contested debates in Germany. Among the different facets of acceptance, the indicators 'acceptance of renewable energies in the neighbourhood' and 'acceptance of grid extension for achieving 100% renewable energy supply' are considered most suitable to address the rule of conservation of social resources.

Indicators for the instrumental sustainability rules

The seven instrumental sustainability rules are translated into nine indicators (Table 6). The rule to internalize external social and ecological costs is addressed by the indicator 'degree of internalization of energy-related external costs'. Internalization of external costs is regarded as essential to both fairly distributing production and consumption costs between involved and non-involved groups and correcting market failures resulting from external costs. The degree of internalization should

Table 5 Sustainability indicators for the goal 'preserving society's options for development and action'

Sustainability rule	Sustainability indicator
Equal access for all to information, education and occupation	32. Gender pay gap in the highest salary group in the energy sector
Participation in societal decision-making processes	33. Share of regulatory tools in the planning of power transmission grids that fulfil regulatory requirements
Conservation of the cultural function of nature	34. Share of tourists who perceive energy power technologies as being disruptive in the vacation area
Conservation of social resources	35. Acceptance of renewable energies in the neighbourhood 36. Acceptance of grid extension for achieving 100% renewable energy supply

Table 6 Indicators for the instrumental sustainability rules

Sustainability rule	Sustainability indicator
Internalization of external social und ecological costs	37. Degree of internalization of energy-related external costs
Promotion of international co-operation	38. Share of development aid expenditure on energy-related projects in relation to total GDP
Society's ability to respond	39. Share of households producing renewable electricity 40. Share of households buying renewable electricity
Society's ability of reflexivity	41. Share of installed smart meters mandatory for large electricity consumers
Society's ability to govern	42. Volume of publicly funded loans for energy-related investments
Society's ability of self-organization	43. Number of energy cooperatives engaged in renewable energy plants 44. Share of population living in regions with the objective to shift to 100% renewable energy
Balance of power between societal actors	45. Market share of the four biggest electricity companies in total electricity production

amount to 100%. In 2010, it amounted to 54% only [43]. The rule 'promotion of international co-operation' is addressed by the indicator 'share of development aid expenditure on energy-related projects relating to total gross domestic product'. This indicator highlights to what extent Germany enhances international co-operation in order to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and to promote investment in energy infrastructure and clean energy technology [43].

The two indicators 'share of households producing renewable electricity' and 'share of households buying renewable electricity' address the sustainability rule 'society's ability to respond'. They highlight the ability of society to react to sustainability challenges caused by the energy system and to support energy transition processes. The energy transition provides new opportunities for citizens to respond and participate, e.g. by becoming producers of energy on their rooftops or by choosing a green electricity provider. By this, they can support the transition process and the use of local renewable resources. The size of PV systems installed by home owners is usually under 10 kWp. Systems in this power range make up less than 15% of the total installed PV power in Germany, while large systems above 500 kWp make up about 30% [44].

The rule 'society's ability to govern' is represented by the indicator 'share of large electricity consumers who have installed smart meters'. Smart metering can contribute to a better control and optimization of the energy system. By providing and exchanging specific information about energy supply and demand, it can facilitate the balancing and improve the mismatch between energy supply and demand occurring in a system that is increasingly based on fluctuating wind and solar energy. A nationwide rollout of smart meters needs to be accompanied by high standards of data protection. The indicator 'volume of publicly funded loans for energy-related investments' relates to the rule addressing society's ability of reflexivity. The indicator shows the overall value of public loans granted for energy-related investments in private households and small- and medium-sized companies.

The rule concerning 'society's ability of self-organization' is substantiated by two indicators. The 'number of energy cooperatives engaged in renewable energy plants' was selected to address civil society activities, in particular by self-organized and member-owned organizations as well as by creating networks and participatory structures. Due to recent changes in the Renewable Energies Act, existing energy cooperatives are increasingly withdrawing from new investment activities [45]. This indicates that energy cooperatives are not active in large-scale renewable energy production, due to both the high upfront investment costs and the trend that the energy sector is gradually being handed back to big providers.

The indicator 'share of population living in regions with the objective to shift to 100% renewable energy' was selected because regions setting ambitious targets to shift their energy supply towards renewable energies support the energy transition by providing space to test innovative technologies and create new organizational forms of co-operation. The instrumental rule 'balance of power between societal actors' requires avoidance or reduction of high power concentration, asymmetric communication and limited access to information and consultation. The indicator 'market share of the four biggest electricity supply companies in total electricity production' was selected to address this rule. As a result of the liberalization of the energy market in 1998, smaller companies and cooperatives producing renewable electricity entered the market. However, the German electricity sector is still characterized by a high degree of vertical and horizontal integration, dominated by the four large electricity providers RWE, E.ON, Vattenfall and EnBW, which generate 54% of total annual electricity production. This value was calculated based on [46].

Discussion

The comprehensive set of sustainability indicators developed has similarities to and overlaps with existing indicator sets such as the monitoring process 'Energy of the Future', but also provides new indicators, mainly related to the socio-technical interface of the energy system. Some of the new indicators are still being developed and discussed in science and policies. Their definition and measurement is at an early stage and information is not always available in the desired way. The discrepancy to other indicator sets is due to different understandings and operationalizations of sustainable development and varying objectives of the indicators. The indicator system is the result of normative decisions and selection processes with participation of experts and stakeholders that cannot be completely justified. The system can be regarded as a picture of the current state of knowledge and awareness that needs to be adapted and improved over time.

The objective of the work was to provide knowledge for the scientific and political debate on indicators in order to assess the sustainability of the German energy system and its transition. The results should be discussed in comparison to other indicator sets focusing on the same objective. For this purpose, the energy transition navigator developed by the Federation of German Industry (BDI) [47] and the indicator sets of the Institute for Advanced Sustainability Studies [48] and the Fraunhofer Institute for Systems and Innovation Research [49] were chosen because they all include approaches to define indicators at the socio-technical interface of the energy system. The BDI navigator considers the acceptance of the energy transition in general and of major projects in particular as well as rising energy prices, but does not address the distribution of benefits and burdens among different social groups or any participatory issues [47]. Besides, the proposed indicators (No. 34, 35 and 36) make a more detailed distinction of acceptance, focusing on the hot spots of the energy transition.

The indicator set developed by the Fraunhofer Institute for Systems and Innovation Research includes only one socio-technical indicator that focuses on energy-related expenses of households in relation to their monthly net income. This indicator is quite similar to indicator No. 5. In politics and science, there seems to be consensus that such an indicator is eligible, if not necessary, because some households cannot afford to adequately heat their homes or pay their electricity bills [30]. Experts assume that between 10 and 17% of German households are heavily burdened by costs for electricity, heat and water heating and vulnerable to energy poverty [50, 51]. However, there is no general agreement about the definition of an adequate indicator for this issue. This is partly due to the lack of information on how much energy is needed by low-income households to meet their demand. Evidence exists that they consume relatively more energy because people usually spend more time at home due to 'mini-jobs' or unemployment and use less energy-efficient electric devices since they often cannot afford more efficient ones. Yet, the situation of energy poverty is not considered as dramatic, due to the German welfare system which partly takes over the heating costs and electricity expenses for benefit recipients [28]. Besides, social subsidies are continuously amended to compensate rising energy prices, and public consultation services are provided to help low-income households to improve the efficiency of their energy consumption and to support energy-related refurbishment.

The Institute for Advanced Sustainability Studies goes much further than just focusing on low-income households [48]. They propose indicators to monitor the distribution of benefits and costs among population groups at household level as well as collaborative aspects of the energy transition and the degree of commitment and participation. More specifically, they suggest recording the share of low-income households that benefit from the feed-in tariffs of the Renewable Energy Act (EEG). This proposal is similar to indicator No. 39. However, the latter focuses on the degree of participation and not at economic benefits which are considered not to be directly relevant for sustainable development. Another indicator proposed by Goldammer et al. [48] is the share of annual power cut-offs per 100 metering points. In Germany, more than 0.75% of all households have their electricity cut-off each year because they failed to pay their electricity bill [52]. In our work, power cut-offs are not regarded as an adequate indicator for addressing energy poverty because this parameter is influenced also by other factors than energy affordability. Besides, power cut-offs are prohibited in cases of households with children or sick persons, though such households can still suffer from energy poverty.

The proposed indicators on gender pay gap (No. 32), the fulfilment of regulatory requirements (No. 33) as well as the indicators addressing society's ability of response, reflexivity, governance and self-organization (No. 39 to 45) are not considered in any of the indicator sets mentioned above. This is remarkable as there seem to be consensus in science and politics that active participation of citizens, for example by buying or producing renewable electricity or becoming involved in energy cooperatives, is essential for a successful energy transition. Although the indicator system was primarily compiled to improve existing indicator sets at the socio-technical interface of the energy system, also new indicators for environmental and economic sustainability issues have been developed. An example is indicator No. 11. The area under cultivation of energy crops is not part of the monitoring system or any other indicator set, although increasing land use competition due to the energy transition has been a debated topic in science and politics for years.

Aside from the adequate selection and definition of indicators to address all sustainability goals, there is a discussion on the appropriate number of indicators for structuring or guiding political debates and decision-making processes. With respect to the number of indicators, there is a clear trade-off between an appropriate substantiation of sustainability aspects and the manageability of analyses, the communicability of results and the applicability in decision-making processes. The final number of indicators (45) is regarded as a suitable compromise between manageability and depth of information. Sustainable development includes the idea of development, i.e. change. Consequently, it is important that the indicator system is updated from time to time in order to maintain its function as an assessment and alert system with regard to undesirable trends and changes. The indicator system is designed to be easily updated and to cope with changes.

Conclusions

The elaborated system of sustainability indicators provides a theoretical link between normative orientation and empirical needs and a holistic and differentiated picture of the complex German energy system and its dynamic transition. It is the first comprehensive and integrated indicator system based on normative values. Several new indicators are proposed that are considered highly relevant. They mainly address the interface between technology and society and the collaborative design and development of the energy transition, going far beyond particular economic aspects such as the costs of electricity supply. The indicator system can help to reveal and eradicate the blind spots and weaknesses of existing indicator sets. Research is required to further improve the system with respect to sustainability issues neglected so far, such as the impact of the energy transition on biodiversity and the distribution of costs and benefits among social groups. Here, methodological and analytical steps are required, besides the definition and selection of suitable indicators. The indicator system shows the strengths and weaknesses of the German energy system and its transition. It enables a systematic analysis of interdependencies and conflicts of goals between sustainability issues and the indicators representing them. Thus, the indicator system can support the development of resilient political strategies to prevent, reduce or solve conflicts occurring in the transition towards a sustainable energy system.

The developed indicator system is more than the sum of individual indicators addressing the different facets of sustainability and goes beyond mere statistical representation to monitor the development of the energy system. It is a key instrument for describing, assessing and managing sustainable development of the complex socio-technical energy system. Its use can help to support policymaking in different ways, for instance through communication, agenda-setting or learning. It can be applied at any stage of the policy process to address information needs or to promote discussion and action. The indicator system can serve as an essential steering instrument for policy and help identify and structure sustainability challenges and conflicts of goals to make them more transparent and thus better manageable. Regardless of the system's possible instrumental, conceptual and symbolic use and influence on the sustainable development of the energy system in Germany, further research is needed to investigate the impact of indicators on politics and decision-making processes.

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For additional information, see https://www.energy-trans.de/

Authors' contributions
All authors designed the objectives and methods of the study and contributed to the development of the indicator system. CR prepared the manuscript with contributions from all co-authors. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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