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1. Abstract

The energy sector plays a key role within the concept of Sustainable Development. However, there is consensus that today's energy system is not sustainable. A transformation towards more efficient structures as well as a shift to renewable sources is needed. To get on the right track, sustainability aspects should be addressed within the scope of technology assessments. This applies in particular to new (renewable) energy systems introduced to the market.

To identify the best technological options, indicators are needed. According to the sustainability concept, they should cover ecological, economical and social aspects. Likewise, they should comprise all steps of a system's life cycle. For practical application, all relevant sustainability issues should be covered by a minimum number of indicators.

Within a research project, seven appropriate indicators were found and applied to wind energy converters, photovoltaic systems and a natural gas fired gas and steam plant. The results of sample calculations show characteristic strength and weakness profiles.

2. Evaluating sustainability for renewable energy systems for electricity generation

2.1 Introduction

Since the report "*Our Common Future*" was published by the UN Commission for Environment and Development ("Brundtland Commission") in 1987 [WCED, 1987], the concept of Sustainable Development was introduced into all relevant social and political areas. As energy builds the basis for almost all social and economical processes, the energy sector plays a key role. Secure, reliable, affordable and ecologically sound energy sources are fundamental for economic and social stability as well as for an intact environment [G8, 2005]. It is evident that sustainability issues are to be considered for upcoming decisions that concern especially the questions 1) how to improve the energy sector and 2) how to distribute the funding for research and development. To find the right answers, the current and future energy technologies have to be thoroughly assessed. Indicators help to identify the best concepts.

2.2 State of the art and motivation

Traditional approaches to evaluate concurrent technical options are the technological impact assessment and life cycle analysis. However, these are commonly restricted to display techno-economic and ecological aspects and often tend to miss the link to the sustainability concept. As a result, existing sustainability indicator systems are indeed frequently characterized by a multitude of figures, but do not cover all relevant aspects. The matters gave reason to launch

the research project “Sustainability Issues of Renewable Energy Systems for Electricity Generation”. It was carried out at the Chair of Energy Systems and Energy Economics at Ruhr-Universitaet Bochum [PETROVIC ET WAGNER, 2005]. The project was funded by the AG Solar, a support programme by the Ministry of Science and Research of the Federal State of North Rhine-Westphalia, Germany.

2.3 Objectives and approach

Within the research project, three main targets were tracked:

- to put the concept of sustainability into concrete terms for the energy sector,
- to find suitable and appropriate indicators for the evaluation of energy systems and
- to design an indicator system and to run sample calculations which results can be used for decision making processes.

The chosen approach is shown in figure 1. The indicator system was developed in three steps: 1) a top-down approach to put the sustainability concept into concrete terms for the energy sector, 2) a bottom-up approach to identify potentially appropriate indicators on the basis of an extensive literature research and 3) a synthesis of the prior, which comprises the design of a sustainability indicator system for the assessment of different options for power generation and its validation by sample calculations for selected renewable energy systems.

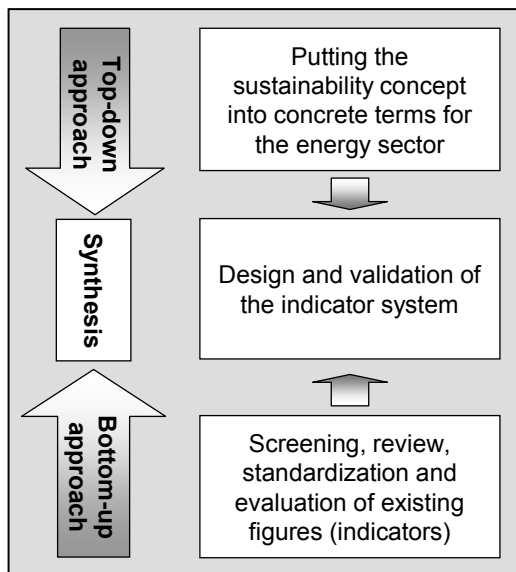


Figure 1: Proceeding within the project “Sustainability Issues of Renewable Energy Systems for Electricity Generation”

3. Development of indicators

3.1 Top-down approach: Putting sustainability into concrete terms for the energy sector

The discussion of the sustainability concept originates from the definition of “Sustainable Development” according to Brundtland [WCED, 1987] and is supported by an extensive literature research and analysis. Focus was put on the identification of the constitutive elements

for the sustainability concept and their interpretation as well as the identification of the relevant sustainability aspects for energy conversion processes. This proceeding was based on important preparatory works performed within the scope of the research project “Global Sustainable Development - Perspectives for Germany“ [KOPFMÜLLER ET AL., 2000].

3.2 Bottom-up approach: Indicator review and evaluation

The indicator review and evaluation is based on preparatory works. At first, already existing indicator systems linked both to the sustainability concept and to the energy sector were screened and analysed. As result, an indicator list reflecting the state of the art in indicator research was compiled. All indicators which seem potentially suitable for the assessment of energy conversion technologies were reviewed and standardized. In the next step, the reviewed indicators were evaluated with regard to their relevance for the sustainability concept, their scientific basis, practical application and other relevant criteria. To find the most suitable figures, a trade off analysis was carried out. Gaps identified with regard to the different sustainability dimensions were filled by the development of new indicators. The last step was to choose seven figures for the designing of an indicator system (see box 1).

4. Validation of the indicator system: Sample calculations

4.1 Reference systems

The system of sustainability indicators created is validated on the basis of its practical applicance concerning selected renewable energy systems for power generation. As examples, the technologies with the currently highest growth ratios regarding installed capacities, namely photovoltaic and onshore wind energy systems, were chosen. Because the wind energy is going to expand towards offshore sites in the near future, additionally a five megawatt three-bladed wind turbine for offshore use was selected. To rank the figures for the renewable energy systems, these were compared with a conventional power plant using fossil fuel for electricity generation. The specification for the systems are summarized in table 1.

Because offshore wind exploitation is associated with significant expenditures for infrastructure, the installation of individual facilities does not seem to be reasonable in economic terms. Therefore, an offshore wind park consisting of 40 wind turbines is being taken into consideration. The wind turbines are built on tripod fundaments in shallow waters. An electric power substation is located on site and the connection to the grid is managed via a 115 km sea cable with alternating current.

Energy security related risks

The indicator summarizes different aspects which are associated to energy security: geopolitical and technological risks as well as risks resulting from a variable energy supply. The geopolitical risk component reflects the stability or instability of energy carrier exporting countries. The second risk component considers the system reliability (technical risk) and fluctuating energy outputs.

Cumulated Energy Demand

The indicator reflects the totality of energetic expenditures which arise in connection with the production, use and disposal of energy facilities. The expenditures are aggregated via primary energy equivalents. The indicator distinguishes between non-sustainable and sustainable energy demands (regenerative energy inputs and energetic expenditures for recyclable materials).

Energy Costs

The calculation of energy costs is based on the annuity method, taking into account replacements and net book values. A 5% discount rate is used.

Gross Employment Effects

The indicator specifies the cumulated gross employment effects that are induced by the additional installation of 1,000 MW capacity of a specific technology in a period of 20 years. The figure is derived from a comparison of two scenarios ("new installation scenario" vs. "reference scenario") using the extended input-output model MARES [ZIEGELMANN ET AL., 2000]. Investment effects, operational effects and effects due to decreased energy imports are taken into account.

Usage of environmental goods (air, water, land)

Air usage: The indicator shows the demand for air volumes which is connected with the production, use and disposal of energy systems. It is calculated via the critical air volume which is necessary to attenuate emissions arising from energy conversion processes accurate to the limits that are defined and regulated by law. Climate affecting gases are treated in the same manner by correlating the greenhouse gas emissions with an atmospheric CO₂ concentration of 550 ppm which is seen as "tolerable" [IPCC, 2001].

Water usage: The indicator is calculated analogically to the previous. It reflects the critical water volume which is needed to attenuate water based pollutants emanating from energy conversion processes accurate to the limits that are defined and regulated by law.

Land use: The indicator displays the spatial-temporal land use which is associated with a) the erection, use and disposal of energy facilities incl. the immediate infrastructure ("direct" land use) and b) the visual disturbance of the environment by technical objects ("indirect" land use). The balancing accounts the different value of varying area types by using a weighting factor. To quantify the indirect land use, a method derived from landscape planning estimating the dimension of a buffer area trading off the visual impact is used.

Table 1: Description of the selected systems

Abbreviation	PV-1	Wind-1	Wind-2	GCC
System specification	Photovoltaic field unit, multi crystal-line modules	Wind energy converter, onshore site	Wind energy converter, offshore site	Natural gas fired gas combined cycle plant
Installed capacity [MW]	0.5 ¹	1.5 ¹	5.0 ¹	353.0
Expected lifetime, facility [a]	20	20	20	30
Expected lifetime, IS* [a]	40	40	40	40
System efficiency [%]	13.2	90.0 ²	80.0 ²	58.0
Capacity factor [h·a ⁻¹]	775	2,200	4,200	7,000
Investment costs [€·MW ⁻¹]	5,110	1,250	1,700	1,330
Operational costs [% of investment costs per year]	0.5	6.0	8.0	3.3
Solar radiation* [kWh·m ⁻² ·a ⁻¹]	1.000	-	-	-
Wind speed in 10 m height (yearly average) [m·s ⁻¹]	-	6.5	9.0	-
Fuel input (NG°) [t·a ⁻¹]	-	-	-	350,000
Fuel price (NG°) [€·kWh ⁻¹]	-	-	-	0.017
¹ MW peak, ² excluding blade efficiency, *IS: infrastructure, °NG: natural gas				

4.2 Backup systems

Renewable energy systems are often characterized by energy security related risks which arise from an inconstant energy supply causing highly volatile energy outputs. For provision of the base load, backup systems covering 80% of the installed regenerative power capacity are necessary for deviation control purposes. This value covers both predictable and non-predictable shutdowns of power supply and is designed for a capacity factor of 7,000 hours per year. As backup device, a GCC plant is chosen.

4.3 Results

4.3.1 Reference systems

The sustainability indicators are evaluated for all systems, including the immediate infrastructure, but excluding measures for grid improvement. For the calculation of the CED it is assumed that 90% of the metals and 80% of the glass components can be recycled. Moreover, it is assumed that for dismantling and disposal of the facilities the same energy is needed as for construction and assembling. The sample calculations show the following results (figure 2a-g):

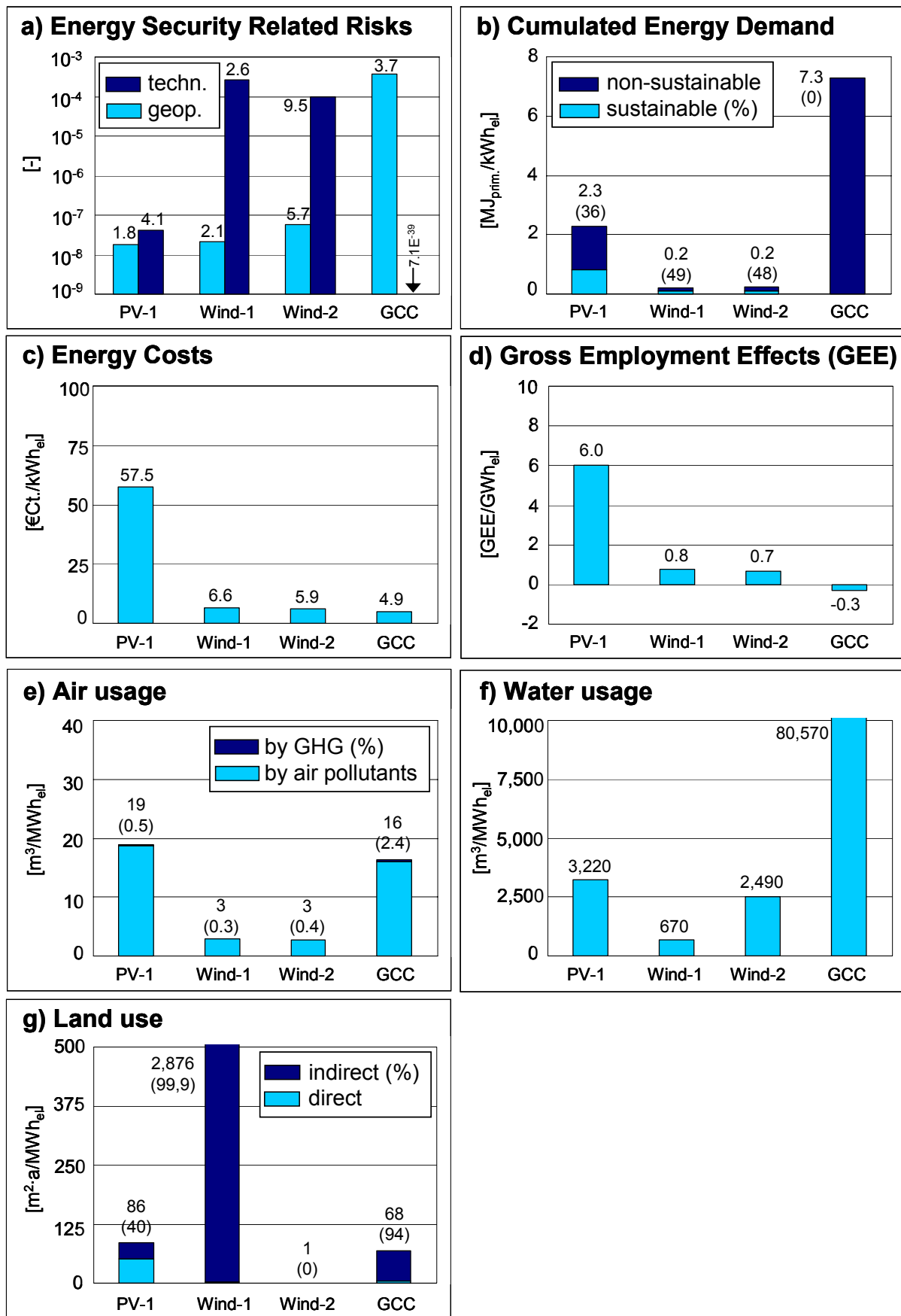


Figure 2: Sustainability indicators for the evaluation of energy systems. Results for several sample calculations (GHG: Greenhouse Gases)

- Energy security related risks: The renewable energy systems are characterized by strongly fluctuating energy outputs and low geopolitical risks. In contrast thereto, the GCC plant is associated with a relatively high geopolitical risk which is due to natural gas transport routes leading through politically instable countries, whilst the technical risk component is very low. In case of the PV system, the relatively low indicator value results from the small proportion of solar energy of the German electricity mix. Bringing more photovoltaic systems onto the market will automatically cause higher values in the range of the wind systems. All in all, the risk dimension is the same for both the renewable energy systems and the GCC plant.
- Cumulated energy demand (CED): The CED is an indicator for resource use and depletion. Renewable energy systems have a clear advantage vis-à-vis conventional, fossil based technologies. In addition, a significant proportion of the energy input for manufacturing the renewable systems can be regarded as “sustainable”, because of a high potential for the recycling of the building materials. In contrast, the fuel consumption of the GCC plant has to be classified as non-sustainable.
- Energy costs: The results show that the PV based power generation is far away from cost effectiveness today, whilst wind energy systems are on the threshold to economic competitiveness. As expected, the indicator displays the lowest costs for the GCC plant, but it has to be taken into account that these are strongly sensitive to the fuel prices.
- Gross employment effects (GEE): The installation of renewable energy systems clearly contributes to the creation and preservation of jobs. The indicator shows that remarkably positive GEE are induced by the PV system. These are caused by high capital costs in correspondence with moderate system efficiencies and comparatively low energy yields during lifetime. The WECs are characterized by slightly positive GEE whilst a negative effect occurs with installation and operation of the GCC plant. This negative effect results from the capital drain due to natural gas imports in the operational phase which overcompensate the positive effects that are associated with the system manufacturing and installation.
- Use of environmental resources (air, water, landscape): With respect to these aspects, the indicators show a heterogenic pattern:
 - Regarding the *usage of air volumes*, the PV systems are characterized by the highest indicator values. This is due to a relatively high energy demand for the module manufacturing that is associated with high “indirect” air emissions by conventional power plants providing the electricity needed. If the PV modules would be manufactured on the basis of regenerative energy inputs only, this would lead to a markedly better performance. The high air demand of the GCC plant is primarily caused by the fuel input for energy conversion. Referring the absolute air emissions to the cor-

responding limits or their threshold values, respectively, it follows that greenhouse gas emissions play a minor role in comparison to “classic” air emission parameters.

- As a result of the steady supply with natural gas for energy conversion, the GCC plant is attributed to the highest indicator value for the *usage of water resources*. The renewable energy systems are characterized by much lower values. Among the WECs, a detailed analysis reveals that the small offshore facility performs significantly poorer on the one hand because of high infrastructure expenditures and on the other hand due to a comparatively low energy yield.
- Taking both the footprints for plants and infrastructure (*direct land usages*) and the visual impairment of nature or landscape by technical objects (*indirect land usages*) into account, the onshore wind facility is characterized by the highest indicator value. However, here the direct land usage accounts only for less than 0.1%. The highest direct land use is associated with the field PV system. For the offshore WEC, the visual disturbance of the surrounding is negligible.

4.3.1 Influence of backup devices

The securing of a high capacity factor for renewable energy systems by a GCC plant shows significant influence on the sustainability indicators. Both systems are regarded integrated in a way that the characteristics of the backup unit, either positive or negative, are allocated on the renewable system (see figure 3a-d).

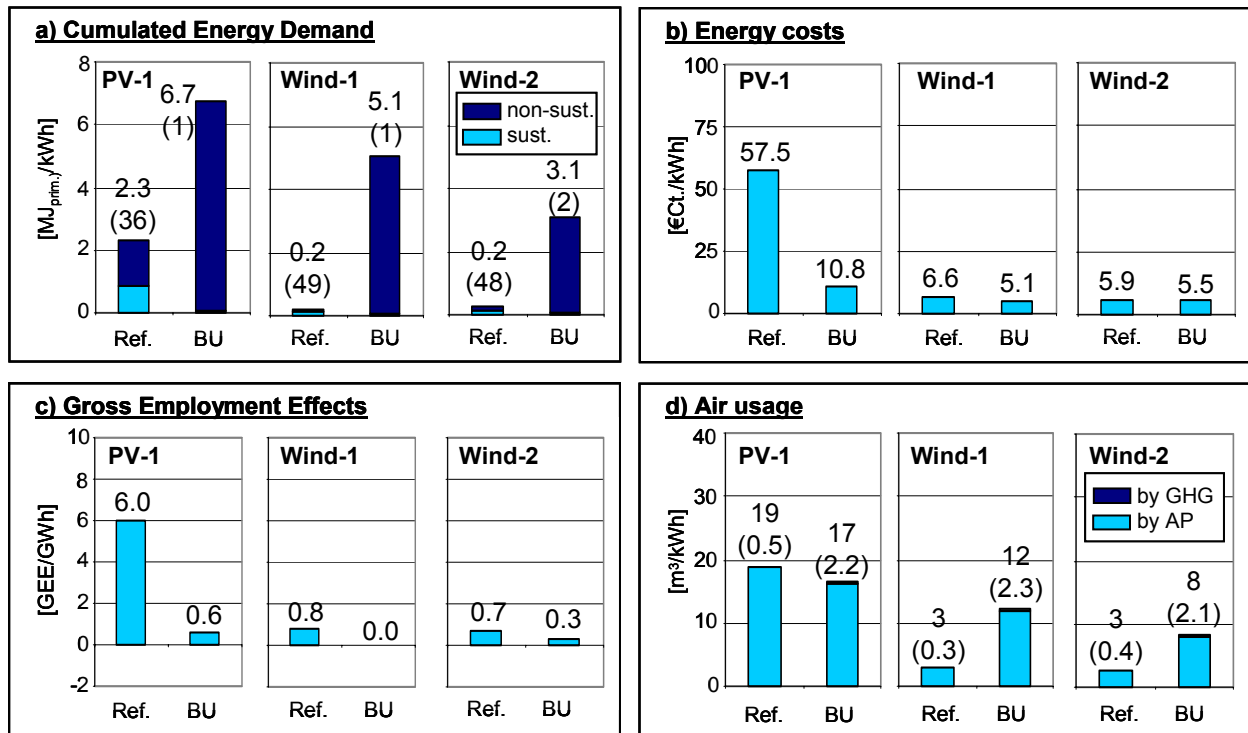


Figure 3a-d: Sustainability indicators for renewable energy systems, incl. an 80% backup by a GCC plant (GHG: greenhouse gases; AP: air pollutants). Due to a lack of space, the visualization of the results is restricted to only four indicators

- Energy security related risks: While the backup system reduces the technical and supply-sided risks that are associated with renewable energy systems, however, this effect is partly or fully traded off by a higher geopolitical risk due to natural gas imports. All in all, the energy security related risks are reduced in case of the wind systems, but increased in case of the PV system.
- Cumulated energy demand (CED): With the integration of a backup system based on fossil fuels, the CED is increased for renewable energy systems. In addition, a shift towards non-sustainable expenditures is induced (figure 3a).
- Energy costs: Concerning costs, the securing of a high capacity factor for renewable energy systems with fluctuating energy output benefits from the good economic performance of the backup unit. The effect is strong in case of the PV system (figure 3b).
- Gross Employment Effects: Enlarging the system boundaries by a backup system diminishes the positive employment effects which are associated with the installation of renewable energy systems remarkably. In contrast to the stand alone GCC plant, however, in all cases still a positive employment effect is preserved (figure 3c).
- Use of environmental resources (air, water, landscape): Concerning the usage of environmental goods, the indicators show a heterogenic picture. For example, the backup of the PV system has a positive effect for air usage and a negative effect for water usage, whilst the backup of the wind systems causes negative effects in both cases. However, in comparison to the stand alone GCC plant, the combination of renewable systems and backup facility is in most cases beneficial.

5. Conclusion

The indicator system is helpful to decide whether a technical option can contribute to sustainability or not. The sample calculations demonstrate its appropriateness for practical use. Due to the results, renewable energy systems can clearly contribute to a sustainable development of the energy sector in many fields. However, strengths and weaknesses regarding individual indicators illustrate the need for a diversified structure of the energy system. A well-balanced mix of electricity generation technologies can prevent negative developments. Enlarging the scope of the study by a backup system (GCC plant) has the effect that its characteristics are partly allocated to the renewable energy systems – with both positive and negative consequences. The impact is dependent upon the backup strategy and the capacity factor to be secured. In the considered case, the backup system is designed to cover base load demands. According to the sample calculations, the sustainability indicators show a significantly poorer performance for the evaluated combinations of renewable energy systems and backup units. However, compared to a stand alone GCC plant, these can still be regarded as beneficial in terms of sustainability.

6. Outlook

The sustainability indicators are, in principle, applicable to other energy conversion technologies. It would be desirable to look at more examples to receive a better benchmark. To enhance the validity of the sustainability indicators and to come to more reliable results for the systems examined, the evaluation should be extended by taking into consideration aspects of grid improvement and extension, renewable backup options and storage technologies.

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