Resource Assessment of Renewable Energy Systems—A Review

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Abstract: The reduction of greenhouse gas emissions by the energy transition may lead to trade-offs with other impacts on the environment, society, and economy. One challenge is resource use impacts due to increasing demand for high-tech metals and minerals. A review of the current state of the art resource assessment of energy systems was conducted to identify gaps in research and application. Publications covering complete energy systems and supplying a detailed resource assessment were the focus of the evaluation. Overall, 92 publications were identified and categorized by the type of system covered and the applied abiotic resource assessment methods. A total of 78 out of 92 publications covered sub-systems of renewable energy systems, and nine considered complete energy systems and conducted a detailed resource use assessment. Most of the publications in the group “complete energy system and detailed resource assessment” were found in grey literature. Several different aspects were covered to assess resource use. Thirty publications focused on similar aspects including criticality and supply risks, but technology-specific aspects are rarely assessed in the resource assessment of renewable energy systems. Few publications included sector coupling technologies, and among the publications most relevant to the aim of this paper one third did not conduct an indicator-driven assessment.

Keywords: energy system; renewable energy; abiotic resources; resource assessment

1. Introduction

Many of the present energy systems depend mainly on fossil resources [1]. The Paris Agreement [2] and the European Green Deal [3] demand high reductions of greenhouse gas emissions, which require switching to renewable energy resources [4] and thus performing an energy transition. Achieving the targets of the energy transition, however, will demand a change in the design of the energy systems and their supporting infrastructure. Energy production will consist of larger shares of renewables and will therefore need supporting infrastructure such as batteries and other storages, more grid infrastructure due to more small producing sites, and sector coupling infrastructure. This leads to a shift in resource use. For example: in 2000 the main resources used by the German energy system were coal, crude oil, oil products and natural gas [1], whereas by 2050 the German energy system will most likely be dependent on copper, aluminum, lithium, nickel, rare earth elements, etc., due to the shift to renewable energies [4]. The needed resources originate from different regions of the world, are available in different amounts and their use might lead to various impacts. Although most publications on resource use of the energy transition do not address threats to the realization of the transition by limited resources [4–11], they do point out impacts on price, environmental issues, social issues, etc. [12–18]. This makes resources strongly intertwined with the success of the energy transition. Integrating impacts of the changing resource demand and its implications within energy system studies could prevent future challenges or at least buffer them. Further, research for possible limited resources technological or material replacements can be better streamlined. Recycling technologies and infrastructure could be enhanced for materials that are likely to become scarce.
Several reviews in the field of sustainability assessment of energy systems are available. The majority did not focus on resource assessment. Only two reviews focusing on the resource assessment of energy systems were identified, but both covered a specific sub-system and not the complete energy systems: Whereas Habib and Wenzel [19] presented a resource criticality assessment of resources for specific types of wind turbines, Leisegang et al. [20] supplied an in-depth review of resource assessment of aluminum-ion batteries. Other reviews such as [21–29] partly included resource assessment but did not focus on it. Romero and Linares [29] for instance, reviewed methods using exergy as a basis for the assessment of energy. Multi-criteria decision analysis methods for the sustainability assessment of energy systems were reviewed by Martin-Gamboa et al. [22], but resource assessment was not explicitly covered. Baumann et al. [21], Peters et al. [23], Jumare et al. [24] and Acar et al. [26] included different sub-systems and did not focus on the resource assessment, while Santoyo-Castelazo and Azapagic [25] presented an overview of general sustainability assessments and Acar et al. [26] covered life cycle assessment (LCA) case studies of energy systems. A systematic literature review concerning the resource use assessment of sub-systems and complete energy systems, however, had not been published to the knowledge of the authors. Therefore, this paper provides such a review of the current state of the art concerning resource assessment of complete energy systems, to identify gaps in research and application.

As the definition of the term “energy system” is ambiguous, clear definitions are needed. In the following the term “complete energy system” is used for a system covering all components needed to run the renewable energy supply of a region. This includes production technologies, the grid as well as energy storage and sector coupling. The term “sub-system” refers to elements of such a system (e.g., a wind turbine, PV panels, batteries, etc.) which are on its own not sufficient to secure the energy supply for a region. Thus, the focus is on complete energy systems, which can deliver a secure energy supply. Due to fluctuations during day and night as well as seasons the secure supply of renewable energy is only given when a complex system of heterogeneous components is implemented [30]. It is therefore not only a matter of up- or down-scaling but rather a balancing act, which should therefore be regarded as one system. Otherwise, burdens might be shifted, and the allocation can be unclear. However, due to the limited number of publications on resource assessment of complete energy systems the scope of the literature review is extended to sub-systems of energy systems as well.

One of the reference systems for the evaluation of the publications is based on Berger et al./Sonderegger et al. [31,32]. They introduced seven questions related to the impacts of mineral resource use (see supporting information, Section S3), based on aspects identified as relevant for resource assessment. For each question, a method was recommended, in order to supply an application-dependent recommendation. A broad range of methods and indicators were introduced to assess the different aspects of resource use, reaching from, e.g., Abiotic Depletion Potential (ADP) [33,34], over Surplus Ore Potential (SOP) [35], LIME [36], Cumulative Exergy Extraction from the Natural Environment (CEENE) [37] to ESSENZ [38,39] and GeoPolRisk [40–42]. The methods consider physical depletion, resource quality, resource quality change and its consequences, (economic) externalities due to overexploitation of resources, thermodynamics and the mid- and short-term supply of mineral resources [31,32]. Some of these methods cover many aspects, e.g., the assessment of the mid- and short-term supply covers company concentration, concentration of production and reserves, primary material use, political stability, price, recycling rates, substitutability and furthermore aspects [39–43].

For the case of energy systems, the technology-specific assessment can be relevant. Recycling rates and substitutability of materials can lead to different outcomes when assessed technology-specific [44]. For substitutability, the technology-specific perspective is even more important, as an average substitutability of a material does not necessarily imply a substitutability for a specific product. Therefore, this review will evaluate the literature concerning the coverage of the relevant aspects identified by Berger et al./
Sonderegger et al. [31,32] as well as the implementation of technology-specific aspects in the identified publications.

In the following section the methodological structure, the scope, and the evaluation steps of the review are introduced. Section 3 presents and discusses the results of the literature. Finally, conclusions drawn from the review are stated in Section 4.

2. Method

In this section the methodological approach of the literature research and its evaluation according to certain aspects will be introduced (see Section 2.1). Next, the clustering of aspects applied for the evaluation will be presented in Section 2.2, followed by assumptions made in this review in Section 2.3.

2.1. Literature Research and Evaluation

The review was conducted in five main steps as described in the following and shown in Table 1. In step 1 a systematic literature research (SLR) based on keywords was conducted. To ensure coherence with the aim of the paper, inclusion and exclusion criteria for the publications were defined (see Table 1). Thus, the identified publications had to assess a complete renewable energy system or a sub-system and cover its abiotic resource assessment with at least one impact category for at least one abiotic resource. If for example only fossil or nuclear resources were included in the assessment, the publication was dismissed.

| Keywords | “energy system” + “resources”/“minerals”/“raw materials” + “sustainable”/“sustainability”/“supply risk”/“criticality”
| Database | Web of Science |
| Inclusion factors | Scope: covering the assessment of abiotic resources in the context of renewable energy systems or sub-systems
| | Type of research: case study and theoretical framework
| | Source: peer-reviewed literature
| | Time period: published between 2010 and 2020
| | Language: English |
| Exclusion factors | Scope: no energy system or sub-system, no resource assessment, only fossil or nuclear technologies regarded
| | Type of research: reviews without own case study
| | Source:
| | Time period: published before 2010 or after 2020
| | Language: any other |

In step 2 (see Figure 1), an intermediate evaluation was conducted (see results in Section 3). The derived sample of publications was categorized by two criteria. The first criterion was, how the resource use assessment was carried out. The publications were divided into two groups: one focusing on the assessment of abiotic resource and, assessing at least two aspects of abiotic resources or at least one resource individually (detailed assessment), and another group treating abiotic resources in one aggregated impact category (aggregated assessment). The second criterion was which type of system was assessed. Here the publications were split again. Therefore, two groups dealing with the assessment of complete energy systems resulted and another two groups assessing sub-systems of energy systems, e.g., a specific battery type, solar panels, grids, etc. This categorization resulted in a division into four groups:

- Complete energy system and aggregated resource assessment
- Complete energy system and detailed resource assessment
- Sub-system and aggregated resource assessment
• Sub-system and detailed resource assessment

![Figure 1. Methodological structure.](image)

As the number of publications in the group “complete energy system and detailed resource assessment” was found to be low after the SLR, the identified publications were complemented by “grey literature”. The grey literature originated from the European Union, Germany and US American institutions. Similar to step 2, the inclusion and exclusion criteria were defined for step 3 (see Table 2). As no database for grey literature is available, a structured keyword driven search could not be conducted. Therefore, publications were directly searched on the publishing institutions websites. The institutions were chosen based on preexisting knowledge and citations in the peer-reviewed literature and the grey literature identified before. This direct targeting of institutions and iterative search process demands preexisting knowledge on possible publishing institutions and leads at the same time to an increasing effort. For these reasons, the geographic scope of the grey literature search was limited to the European Union, Germany, and the USA.

**Table 2. Methodological details on the grey literature search.**

| Sources     | Institutional websites                                                                 |
|-------------|-----------------------------------------------------------------------------------------|
| Inclusion factors | Scope: covering the assessment of abiotic resources in the context of renewable energy systems or sub-systems  |
|             | Type of research: case study and theoretical framework                                     |
|             | Source: grey literature from scientific and political institutions of Germany, the European Union, and the USA |
|             | Time period: published between 2010 and 2020                                             |
|             | Language: English and German                                                              |

| Exclusion factors | Scope: no energy system or sub-system, no resource assessment, only fossil or nuclear technologies regarded |
|                  | Type of research: reviews without own case study                                           |
|                  | Source: grey literature from other regions                                                 |
|                  | Time period: published before 2010 or after 2020                                          |
|                  | Language: any other                                                                       |

For both searches only literature published between 2010 and 2020 was included in the sample, as the technology develops quickly and so did the models of renewable energy systems. Details on the search and keywords, database and sources, inclusion, and exclusion factors (based on the aim of the paper) are presented in Tables 1 and 2.

Like the identified publications of the SLR, also the publications derived from grey literature search were categorized in the four groups introduced above.

In step 4 the publications were evaluated regarding the technologies assessed and the detail of resource assessment, applying the same categories as defined above. An evaluation of the resource aspects and the resources covered in the publications was conducted as well.
Finally, research gaps were identified based on the results of the evaluation in step 5.

2.2. Clustering of Aspects

To better analyze the aspects assessed in the different publications in step 4, the aspects were clustered. The following clusters were introduced:

- Criticality—when supply risk and vulnerability aspects were assessed, following the definition used by Bach et al. [39];
- Demand—when demand forecasts were given without the context of further supply risk or vulnerability aspects;
- Environmental aspects—when any environmental impact was assessed (e.g., climate change impact of material production);
- Economic aspects—when economic impacts were assessed without the context of further supply risk or vulnerability aspects (e.g., energy return on investment);
- Material requirement—when the material requirement was assessed without the context of further supply risk or vulnerability aspects;
- Nexus of material use—when a nexus analysis was applied (a nexus shows among others the impacts of different aspects on one another);
- Political aspects—when political impacts were assessed without the context of further supply risk or vulnerability aspects (e.g., dependence on China);
- Resource depletion—when resource depletion indicators were used (e.g., ADP);
- Resource scarcity—when resource scarcity indicators were used (e.g., Ecoscarcity);
- Social aspects—when any social impact was assessed;
- Supply risk—when supply risk aspects were assessed, following the definition used by Bach et al. [39];
- Thermodynamic aspects—when thermodynamic aspects were assessed (e.g., entropy or exergy).

The clustering could lead to mask certain aspects, e.g., the recycling rate occurred in combination with aspects such as companion metal, company concentration production, demand forecast, political stability, and substitutability. In this review, recycling rates were allocated to the cluster “criticality”; thus, the detailed aspects are not visible anymore. For more transparency on the clustering the originally used aspects can be found in the supporting information, Section S1, Table S1.

2.3. Assumptions

In the evaluation of the assessed technologies, lithium batteries were not treated as sector coupling elements technology, but as storage infrastructure for the grid, as they do not directly transform energy.

Despite the possible benefits of biomass usage as shown by [45], publications focusing exclusively on biomass were dismissed. Biomass is not an abiotic resource, and it is assumed that the reduction of coal firing is correlated with the renewable energy system as a whole. However, when biomass is included in the resource assessment of a broader energy system (including further technologies, e.g., wind turbines) it was included.

3. Results and Discussion

Overall, about 600 sustainability assessments of renewable energy systems or their sub-systems were found during the literature research. Most of the publications did not consider abiotic resources in any way or did not meet the other factors mentioned above (see Table 1). Therefore, the sample included 86 publications. Only three publications covered complete energy systems and a detailed resource assessment (see Section 3.1). Therefore, an additional search in the grey literature was conducted as described in Section 2 and Table 2. Another 6 publications covering complete energy systems and conducting a detailed resource assessment were identified. All together 92 publications were evaluated in this review.
No severe increase of publications over the years could be found (see Figure 2). 22 out of 92 publications were published in 2019. Over 80% of the publications date from 2014 and later. The field of renewable energies and its supporting infrastructure is developing quickly, among others due to its political relevance [2,3]. Additionally, the materials used are changing and being optimized [46–49]. A clear timeframe had to be set for this study to generate and evaluate results. Therefore, publications on abiotic resource assessment of renewable energy systems published after December 2020 were not included.

The results are presented in three sub-sections, evaluating the technologies, the aspects and the resources covered in the literature.

3.1. Technologies Assessed and Level of Detail in Resource Assessment

The results of the evaluation of the technologies assessed and the level of detail of the resource assessment are shown in Figure 3 and Table 3. Forty-six publications were focused on the resource assessment of renewable energy systems or sub-systems (Figure 3 and Supplementary Materials, Section S1, Table S1). This means that they assessed at least two aspects of abiotic resources or at least one resource individually. The other 46 publications covered resources, but only with aggregated indicators. A total of 14 publications considered complete energy systems, and out of these 9 publications covered a detailed resource assessment (see Figure 3). Seventy-eight out of 92 of the included publications treated sub-systems of energy systems (see Figure 3).

Most of the publications in the group “complete energy system and detailed resource assessment” were identified when searching for grey literature [4,5,7,9–11]. As Moss et al. [5] (grey literature) and Moss et al. [6] (literature in peer-reviewed journal) are based on the same project and cover the same results just with different levels of detail, they will be further referred to together, but counted as two publications.

The four groups (see Figure 3) were not equally relevant to the aim of this paper (identify the challenges and research gaps in resource assessment of complete energy systems). As argued before renewable energy systems consist of highly intertwined sub-systems and thus, should be regarded as one product system. Aggregated indicators have the advantage of easy communication, but on the other hand reduce information. The targets of this review demanded a high resolution of the results for each aspect and resource assessed. Therefore, the detailed resource assessments were of importance for this review. In the following sections this group will therefore be given additional focus.
A short overview and a comparison of the publications in the group “complete energy system and detailed resource assessment” in given in Table 4.

![Figure 3. Categorization of the covered publications.](image-url)

As mentioned in the introduction the term “energy system” is used for a variety of technologies. This is also reflected in sample (see Figure 4). Most of the publications (63) assessed either only one specific sub-system of energy systems (“specific power generation technologies” and “grid” in Figure 4) or a homogeneous group of sub-systems concerning the functionality of the technologies: either several storage technologies or several power generation technologies (“storage technologies” and “complete power generation” in Figure 4). The share of publications covering inhomogeneous technologies (e.g., “power generation and grid”, “power generation and storage”, “complete renewable energy system”) was less than one-fourth of the publication sample (see Figure 4). The biggest share of the sample analyzed power generating technologies, either only specific power generation technologies or a power generation mix (here: “complete power generation”). Other technologies were rarely treated, e.g., sector coupling technology. Complete energy systems as regarded most relevant for this work (see Section 1), were only treated in 15% of the publications. This indicates lacking research on abiotic resource assessment of complete renewable energy systems.

Further, 10 out of the 46 publications focusing on resources included at least one sector coupling technology. Sector coupling is hardly avoidable in order to reach a stable renewable energy system [30]. Studies in [8,9,50,51] covered the electrolysis, which is needed for hydrogen production. Meylan et al. [52] included the electrolysis and methanation technology needed for the hydrogen and non-fossil gas production. Ostertag et al. [7] considered among others combined heat and power (CHP) and the electrolysis. The assessments of Koning et al. [53] and Lieberei and Gheewala [54] covered CHP. While Tokimatsu et al. [55] and Purr et al. [4] covered several types of hydrogen production and storage, several types of CHP, a variety of types of liquid fuels. They can therefore be regarded as the only two publications in the sample covering the complete sector coupling infrastructure, as it would be needed for the energy transition to be successful in all sectors. Other publications covered different batteries [13,20,56], which could, in cases such as lithium-ion batteries, be considered as sector coupling technologies for the link between energy and mobility, but as stated above were not regarded as such in this paper.
Further, 10 out of the 46 publications focusing on resources included at least one sector coupling technology. Sector coupling is hardly avoidable in order to reach a stable renewable energy system [30]. Studies in [8,9,50,51] covered the electrolysis, which is needed for hydrogen production. Meylan et al. [52] included the electrolysis and methanation technology needed for the hydrogen and non-fossil gas production. Ostertag et al. [7] considered among others combined heat and power (CHP) and the electrolysis. The assessments of Koning et al. [53] and Lieberei and Gheewala [54] covered CHP. While Tokimatsu et al. [55] and Purr et al. [4] covered several types of hydrogen production and storage, several types of CHP, a variety of types of liquid fuels. They can therefore be regarded as the only two publications in the sample covering the complete sector coupling infrastructure, as it would be needed for the energy transition to be successful in all sectors. Other publications covered different batteries [13,20,56], which could, in cases such as lithium-ion batteries, be considered as sector coupling technologies for the link between energy and mobility, but as stated above were not regarded as such in this paper.

The definition of the energy system assessed within the group “complete energy system and detailed resource assessment” in the different publications was varying. The difference is mainly in the inclusion of sector coupling technology (see Table 4). Purr et al. [4] and Tokimatsu et al. [55] covered the broadest spectrum of technologies in general and, also in particular the broadest spectrum of sector coupling technologies. The spectrum of technologies covered in these two publications is most coherent with the preset energy engineering perspective on the design and composition of renewable energy systems in Germany in 2050 (e.g., [57–61]). Most other publications neglected the sector coupling or regarded it only partly, also it is a crucial element of the energy transition [30].

Overall few publications on complete energy systems supply a detailed resource assessment, most of them origin from grey literature and are therefore not peer-reviewed. Among these publications the definition of the energy system is varying. While two publications [4,55] define a system close to the perspective of current studies for the field of energy engineering [57–61], the other 7 leave out important sector coupling and infrastructure elements. The lack of scientifically reviewed publications assessing the abiotic resource use of complete energy systems becomes apparent.

**Table 3.** List of publications by group.

| Group                                           | Publications                           |
|-------------------------------------------------|----------------------------------------|
| Complete Energy system and detailed resource assessment | [4–11,55]                             |
| Complete Energy system and aggregated resource assessment | [62–66]                              |
| Sub-system and detailed resource assessment     | [12,13,19,20,50–54,56,67–93]          |
| Sub-system aggregated resource assessment       | [24–28,94–129]                        |
| Author | Resources | Aspects | Technology-Specific Aspects | Indicator Type | Sector Coupling | Summary |
|--------|-----------|---------|-----------------------------|----------------|----------------|---------|
| Acatech et al. [11] | Not specified | criticality, demand forecast, environmental impacts, market concentration, material requirement, policy strategies, recycling rate, reserves, social impacts | none | no indicators | not specified | - mainly giving policy recommendations and offering an analysis of the costs and benefits of the different measures recommendations given are not based on an indicator-driven analysis - a possible limitation identified however is the dependance on few suppliers for certain materials |
| American Physical Society [10] | Ag, Ce, Co, Dy, Eu, Ga, Gd, Ge, He, In, Ir, La, Li, Lu, Nd, Os, Pd, Pt, Re, Rh, Ru, Sc, Se, Sm, Tb, Te, Y | abundance, companion metal, environmental impacts, geological concentration, geopolitical risk, response times in production and utilization, social impacts | none | no indicators | not specified | - highlights possible “energy-critical elements” that face potential short-term supply disruptions due to increases in demand combined with the inability of the relatively small global market to respond to these. recommendations for governments include: coordination, dissemination of information, establishment of an research and development effort and increased recycling |
| Moss et al. [5,6] | Ag, Cd, Dy, Ga, Hf, In, Mo, Nb, Nd, Ni, Se, Sn, Te, V | material requirement, limitations to expanding supply capacity, likelihood of rapid global demand growth, country concentration, political risk | none | quantitative indicators | not included | - examines the use of metals in nuclear, solar, wind, bioenergy, carbon capture and storage, and electricity grids - focusing on materials that due to their high relative economic importance and their high relative supply risk, are considered as critical - stresses the importance of market dynamics as they relate to supply chain bottlenecks and offers recommendations relating to the public sharing of data and information, development of supply, international collaboration, research and development investment, recycling, and byproduct production |
Table 4. Cont.

| Author           | Resources                                                                 | Aspects                                                                 | Technology-Specific Aspects | Indicator Type | Sector Coupling | Summary                                                                                                                                 |
|------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|-----------------------------|----------------|-----------------|------------------------------------------------------------------------------------------------------------------------------------------|
| **Ostertag et al. [7]** | Ag, As, Au, B, Ba, Be, Bi, C, Cd, Co, Cr, Cu, Ga, Ge, Hf, Hg, In, Li, Mg, Mn, Mo, Nb, Ni, Pb, Re, Sb, Sc, Se, Sn, Sr, Ta, Te, Ti, Tl, V, W, Zn | country concentration demand forecast limitations to expanding supply capacity political risk | none                        | quantitative indicators | CHP and electrolysis | - based on the method of [5]/[6]; broadening the range of technologies analyzed and updating the results ways of mitigating the supply-chain risks for the critical metals proposed: increasing primary supply, reuse/recycling, and substitution |
| **Purr et al. [4]**  | Explicitly: Ag, Al, C, Co, concrete, Cr, Cu, Fe, Li, Mg, Ni, Pb, PGMs, Si, Zn Implicitly: further | environmental impacts raw material consumption raw material input total material consumption total material requirement | none                        | quantitative indicators, except environmental impacts | complete | - analyzes 6 scenarios for the German energy transition until 2050 regarding CO2-Emissions and raw material consumption in all scenarios a reduction of the raw material consumption is foreseen to decrease until 2050 (comparing to 2010) |
| **Tokimatsu et al. [55]** | Aggr. Presentation and additional details on: Ag, Al, Cd, Co, concrete, Cu, Fe, Ga, Hf, In, Li, Mn, Mo, Ni, Pb, Se, Si, Te, Zn | metal requirement metal production nexus of material use and greenhouse gas emissions | none                        | quantitative indicators | complete | - estimates the metal requirement for various energy scenarios by using a cost-minimizing energy model on the global energy-mineral nexus results conclude a concern regarding the metal requirement and/or availability for certain technologies |
| Author            | Resources                  | Aspects               | Technology-Specific Aspects | Indicator Type  | Sector Coupling | Summary                                                                                                                                                                                                 |
|-------------------|----------------------------|-----------------------|-----------------------------|-----------------|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Viebahn et al. [8] | Cd, Dy, Ga, In, K, La, Li, Nd, Ni, Se, Te, V, Y | critical mineral demand | none                        | quantitative indicators | electrolysis | determines whether the transformation of the German energy system by 2050 may be restricted by a lack of critical minerals; for the relevant technologies roadmaps describing several quantitative market developments in Germany are developed to estimate the current and future demand of specific materials; along these projections potential medium-or long-term mineral resource restrictions are assessed; foreseeable path of the energy transition is generally compatible with the availability and supply of resources, some sub-systems could face a supply risk |
| Wuppertal Institute [9] | Cd, Dy, Ga, In, K, La, Li, Nd, Ni, Se, Tr, V, Y | availability, environmental impacts, material requirement, recycling rate, supply risk | recycling rate | no indicators | electrolysis | assessed the criticality of all technologies referred to in existing energy scenarios in Germany that may be used in the decades ahead; study shows that the geological availability of minerals does not generally represent a limiting factor to the energy transition in Germany; the usage of certain technologies might be limited by the resource availability |
3.2. Resource Use Aspects Assessed

Resource use impacts were assessed considering different aspects. Publications with a detailed resource assessment were especially relevant to the aim of this review and will therefore be evaluated in detail in the following. Among the publications supplying an aggregated assessment of resource impact, 24% applied the SOP [35] and 21% the ADP [33,34]. Details on the resource aspects covered in the publications applying an aggregated assessment can be found in the supporting information, Section 4, Figure S1.

Figure 5 shows resource use aspects covered: the blue bar shows the number of occurrences within the group “complete energy system and detailed resource assessment”. The orange bar shows the occurrences within the group “complete energy system and detailed resource assessment”. Details on the clustering are given in Section 2. Information on which publication covers which aspect, and the corresponding clusters can be found in the supporting information, Section S1, Table S1.

![Figure 5. Number of publications covering specific aspects of resource assessment.](image)

Overall supply risk and criticality aspects were addressed most often, followed by environmental aspects and material requirement. Thermodynamic aspects were covered in two publications [67,91]. Exergy assessment was carried out in the context of sustainability assessment of energy systems [29,130]. Some aspects, e.g., demand and economic aspects, were in most cases also implicitly covered in the aspects of supply risk and criticality. Therefore, the number of publications covering demand, economic aspects, political aspects, material requirement, etc., in Figure 5 have to be interpreted as the number of publications covering these aspects without the context of other broader clusters.

Few technology-specific impact categories were applied, e.g., importance to clean energy (see supporting information, Section S1, Table S1). In three cases the recycling rate was measured specifically for the assessed technologies [9,67,88]. However, the Wuppertal Institute [9] did not apply an indicator, but conducted a qualitative assessment of the recycling rate.

Regarding the group “complete energy system and detailed resource assessment”, aspects of supply risk and criticality were also the most prominent aspects (see Table 4). Five publications covered environmental aspects [4,9–11,55]. However, other aspects considered relevant in the resource assessment presented in the introduction [31,32] are not covered by any of the publications in this group. Thus, only two out of seven questions were addressed, however not using the recommended methods [31,32] ESSENZ [39], GeoPolRisk [43,131] and ADPeconomic reserves [33,34]. The two questions address potential
availability issues related to physico-economic scarcity and relative potential accessibility issues related to short-term geopolitical and socioeconomic aspects.

None of the publications address one of the five questions regarding the access of future generations to the minerals.

Another finding within the group of “complete energy system and detailed resource assessment” is that several of the aspects assessments were not indicator-driven (see Table 4). This means that no indicators are defined for the assessed aspect, but were covered by heterogeneous information, e.g., the Wuppertal Institute [9] supplies the worldwide recycling potential for gallium, but qualitative information on nickel. Clearly defined indicators are applied for the assessment of critical mineral demand, material requirement, metal production, nexus of material use and greenhouse gas emissions, limitations to expanding supply capacity, likelihood of rapid global demand growth, country concentration and political risk [5-8,55]. Purr et al. [4] used quantitative values for assessing material requirement, but qualitatively ones for environmental impacts. [9-11] do not apply clearly defined indicators, and further lack a clear definition of the scope of their case study of complete energy system. The diversity of applied indicators and methods indicates a need for a clear definition and methodological approach, in order to improve the interpretations of the results of different studies.

Helbig et al. [12] discussed the fact, that a sufficient number of indicators, weighted specifically to the technology analyzed, is needed to gain a full picture of the supply risks for certain technologies. None of the publications in this group covered enough aspects and included sufficient indicators to generate a detailed analysis for renewable energy systems.

The evaluation of the aspects assessed shows that to gain a broad and comparable resource assessment (not only concerning the supply risk) more aspects need to be covered, a defined scope and an adequate indicator definition are required, and technology-specific aspects should be developed.

3.3. Resources Assessed

The choice of assessed resources was based on different rationales: most of the publications either identified the most relevant resources based on criteria such as criticality (e.g., [50]), or included all resources used in the assessed technology (e.g., [80]). Only the following publications focused exclusively on one resource identified as relevant to the energy transition: Bustamante et Gaustad [72] assessed the supply risk of tellurium based on byproduct minerals, as tellurium is the scarcest material used in CdTe PV cells. Harmsen et al. [78] focused on copper, because its demand is expected to increase in the future, and deteriorating ore quality as well as increasing gross energy requirement are to be expected. Roelich et al. [87] presented their developed methods for neodymium, because it was defined as facing supply disruptions.

Among the publications in the group “complete energy system and detailed resource assessment” the resources graphite (in eight publications), gallium, indium, selenium (in seven publications), silver, cadmium, nickel, and tellurium (in six publications) were included most often (see Table 4). The varying number of resources included in the publications in this group (see Table 4) arises on the one hand from the different definitions of the energy system and on the other from the scope of the study and therefore makes the results hardly comparable.

In conclusion all publications with a scope on “complete energy system and detailed resource assessment” concluded that the physical availability of minerals and metals is not posing a threat to the energy transition. Some technologies might only be implemented in a limited number due to the inadequate availability of minerals and metals, but substitution technologies exist. Thus, the different publications conclude, that the overall target of achieving energy transition is not threatened by limited resource availability. A summary of the publications content can be found in the supporting information, Section S2.
4. Conclusions

Several reviews of the resource assessment of renewable sub-systems exist, but no review of the assessment of complete energy systems was published so far. The paper identified the challenges and research gaps in resource assessment of complete energy systems by conducting a review of existing publications on the topic. The review presents the publications and evaluates the considered technologies, resource aspects and resources assessed. It was found that many methods for resource assessment of energy system sub-systems exist, but only nine publications were identified covering a detailed resource assessment for complete energy systems. Thirty publications focused on similar aspects mainly criticality and supply risks. Nearly no technology-specific aspects are assessed in the resource assessment of renewable energy systems. Few publications included sector coupling technologies. Among the publications most relevant to the aim of this paper one third did not conduct an indicator-driven assessment.

Based on the results, three main research gaps can be identified: First, only few publications cover complete renewable energy systems. Second, the publications covering complete energy systems are partly not indicator-driven and cover only a limited range of aspects relevant for the resource assessment. Lastly, few to no technology-specific aspects are applied.

Another challenge identified is the lack of a clear definition of the scope for an assessment of renewable energy systems, because they cover a variety of heterogeneous sub-systems with largely varying applications within the system.

Many assessment methods especially for sub-systems of energy systems exist and are applied, but a harmonized, comprehensive assessment and perspective on resource use impacts of renewable energy systems is still missing. Further research should fill this gap. Assessment methods enabling a comprehensive assessment of renewable energy systems should be developed. The applicability to complete energy systems and the accounting for the heterogeneity of renewable energy systems should be a crucial aspect of newly developed methods in this field. A detailed evaluation of the resource assessment methods for sub-systems could support the definition of technology-specific aspects within such a method.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13116107/s1, Table S1: Publications with a focus on the assessment of abiotic resources of sub-systems, Section S2 with summaries of the publications with focus on resources and an assessment of complete energy systems, Section S3 with additional information on Berger et al. 2019, Figure S1: Aspects covered in the publications applying an aggregated assessment.

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