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Ecological Scarcity Based Impact Assessment for a Decentralised Renewable Energy System

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Abstract: Increasing the share of renewable energies in electricity and heat generation is the cornerstone of a climate-friendly energy transition. However, as renewable technologies rely on diverse natural resources, the design of decarbonized energy systems inevitably leads to environmental trade-offs. This paper presents the case study of a comprehensive impact assessment for different future development scenarios of a decentralized renewable energy system in Germany. It applies an adapted ecological scarcity method (ESM) that improves decision-support by ranking the investigated scenarios and revealing their main environmental shortcomings: increased mineral resource use and pollutant emissions due to required technical infrastructure and a substantial increase in land use due to biomass combustion. Concerning the case study, the paper suggests extending the set of considered options, e.g., towards including imported wind energy. More generally, the findings underline the need for a comprehensive environmental assessment of renewable energy systems that integrate electricity supply with heating, cooling, and mobility. On a methodical level, the ESM turns out to be a transparent and well adaptable method to analyze environmental trade-offs from renewable energy supply. It currently suffers from missing quantitative targets that are democratically sufficiently legitimized. At the same time, it can provide a sound basis for an informed discussion on such targets.

Keywords: life cycle impact assessment; distance-to-target weighting; ecological scarcity; renewable electricity and heat generation; decentralized energy system

1. Introduction

Diverse criteria need to be considered when planning future energy systems, such as costs, greenhouse gas emissions, land use, and further environmental impacts. As these criteria are measured in different units, they cannot be directly compared and decision-makers need support to consider conflicting targets adequately. This article, therefore, deals with a systematic analysis of environmental trade-offs to better support the design of decentralized renewable energy systems. It is based on a case study conducted as part of the center for applied research “Urban Energy Systems and Resource Efficiency” (ENsource), an inter-university research network that aims to provide scientific support for the design and operation of sustainable energy systems. The case study took place at Mainau GmbH, a tourist company located on an island in Lake Constance in southern Germany. To become climate neutral, its management decided to further increase the share of renewables in the company’s energy supply. In order to design an energy system that reduces greenhouse gas (GHG) emissions without increasing other environmental impacts, life cycle assessment (LCA) studies for four future energy supply options were conducted, focusing on the choice of an appropriate metric for evaluating environmental trade-offs.
With the Federal Climate Protection Act [1], the German government has committed itself to become greenhouse gas neutral by 2050. As electricity and heat generation account for more than one-third of German GHG emissions [2], the use of renewable technologies in these sectors is an important lever for the German energy transition. Hence, Mainau GmbH’s objectives and strategy are representative of the current efforts of many companies and municipalities in Germany.

Although renewable energies reduce GHG emissions, their construction, disposal, and in some cases, also operation still cause environmental pressures [3,4]. The design of a decarbonized urban energy supply almost inevitably leads to environmental trade-offs. For mineral resources Vidal et al. even point out the danger of a vicious cycle, where “the shift to renewable energy will replace one non-renewable resource (fossil fuel) with another (minerals and metals)” [5]. Hertwich et al. substantiate this concern in an LCA study of a long-term, wide-scale implementation of renewable electricity generation up to 2050 that indicates an increased global consumption of mineral resources like cement, iron, aluminum, and especially copper [6]. As humankind is already at the limits of or even transgressing multiple planetary boundaries [7], a multi-dimensional view of environmental impacts becomes imperative: An energy system design that only takes GHG emissions into account can lead to adverse environmental effects [8].

Hence, methods are required that enable planners and decision-makers to identify energy supply options with a minimal overall environmental impact. LCA provides valuable decision support in this context, as it considers the whole life cycle of power plants and energy carriers [9]. It moreover incorporates a comprehensive environmental impact assessment. Unfortunately, the results of a multi-dimensional life cycle impact assessment (LCIA) are often ambiguous. The main challenge for practical decision support is, therefore, to make impacts in different categories comparable in a meaningful way. Several existing weighting methods can help to solve this dilemma. Even though this approach is generally criticized for necessarily relying on normative value choices [10], it provides valuable decision support in practice [11].

This paper uses the ecological scarcity method (ESM) [12,13] to normalize and weight LCIA results. ESM is a distance-to-target method that weights different environmental pressures based on the ratio of the current situation to the desired policy target. Due to its mathematical simplicity and because the weights depend in a transparent way on publicly available data from laws or environmental authorities [11], it is particularly suitable for communication with practical decision-makers who are usually not LCA experts. For the same reason, it is easier to adapt the ESM to specific decision contexts than other weighting approaches such as, e.g., monetary, panel, or mid-to-endpoint weighting [11,14].

In the present study, we adapt and apply an ESM to renewable energy systems in Germany.

The paper is outlined as follows. Section 2 introduces the main features of ESM and describes essential assumptions and necessary adaptations for the assessment of renewable energy systems in Germany. Sections 3 and 4 deal with the application of the method to the case study of Mainau GmbH. Different energy supply scenarios are ranked regarding their environmental impact and trade-offs between different impact categories are analyzed in more detail. A contribution analysis shows which energy technologies and life cycle processes cause the highest environmental impacts. Based on these results, Section 5 provides recommendations for company management. Section 6 puts the findings from the case study into the broader context of the energy transition, discusses strengths and weaknesses of the adapted ESM, and points out future research needs and fields of application.

2. Materials and Methods

2.1. The Ecological Scarcity Method—Basic Structure and Important Properties

All ESM share the same basic structure [13]: An impact score (IS) is calculated by multiplying elementary flows $e_j$ from a product system’s life cycle inventory by specific eco-factors $EF_j$ (Equation (3))
and adding them up (Equation (1)). Elementary flows are material, and energy flows between the system under investigation and the natural environment.

\[ IS = \sum_j e_j \cdot EF_j \] (1)

Depending on the set of elementary flows covered by the summation index \( j \), the impact score corresponds either to a specific impact category \( i \) (e.g., climate change, mineral resources, water pollution, etc.) or to the total environmental impact. The total impact score \( IS_{\text{total}} \) thus corresponds to the sum of all category impact scores \( IS_i \) (Equation (2))

\[ IS_{\text{total}} = \sum_i IS_i \] (2)

The eco-factor \( EF_j \) combines an external normalization with respect to an appropriate reference value \( N_j \) and a weighting factor: \( w_j = \left( \frac{A_j}{T_j} \right)^2 \) (Equation (3)). The weight depends on the ratio of the current environmental pressure \( A_j \) and the desired target value \( T_j \). ESM thus belongs to the class of distance-to-target weighting methods (cf. [11,15]).

\[ EF_j = \left( \frac{A_j}{N_j} \right)^2 \] (3)

For practical implementation, some specifications and extensions to this basic concept are necessary (Equation (4)): First, most quantities involved in calculating eco-factors refer to a certain region \( x \) (e.g., Switzerland, Germany, the World) and time horizon \( t \) (e.g., 2010, 2020, or 2050). Second, the index \( j \) in Equation (3) refers to single elementary flows, whereas target values, in some cases, only exist on an aggregated level: For instance, greenhouse gas reduction targets apply to different substances and are therefore expressed as global warming potential (CO\(_2\)-equivalents). In this case, Equation (4) integrates characterization, i.e., calculating the contribution of elementary flows \( j \) to specific impact categories \( i \) via the characterization factor \( CF_{ij} \) and carries out both normalization and weighting on the impact level. Finally, a region-specific scaling factor \( s(x) \) usually assures “reasonable” numerical values for the impact \( IS \).

\[ EF_{j, x, t} = CF_{ij} \cdot \left( \frac{A_{j,x,t}}{T_{j,x,t}} \right)^2 \cdot s_x \] (4)

Equation (4) reveals an important feature of ESM: its adaptability. So far, it has mainly been used to adapt the original Swiss ESM [13] to other countries including Germany [16,17], Thailand [18], China [19], and the EU [20,21].

2.2. Compilation of the ENsource ESM

The following section describes the compilation of an ENsource ESM to evaluate environmental trade-offs in the specific context of decentralized renewable energy systems in Germany at the example of Mainau GmbH. To this end, normalization references \( N \), current pressures \( A \), and target values \( T \) of suitable existing ESM had to be adapted to current German conditions. We chose the ESM developed by Ahbe et al. for Germany as a starting point, whose eco-factors basically required a time update (Equation (4)) [17]. In order to further increase the ESM’s coverage of relevant environmental issues, the impact indicators land use, carcinogenic substances into air, heavy metals into air, and ozone layer depletion have been adopted from an ESM developed by Muhl et al. for the European Union [21]. Here, some quantities had to be scaled to German conditions. Eventually, the impact category mineral resources, which is missing in the ESMs of both Ahbe et al. [17] and Muhl et al. [21], was integrated following Frischknecht and Büsser-Knöpfel [13] but applying the latest abiotic resource depletion potentials based on the ultimate reserve according to van Oers et al. [22].
All resulting eco-factors refer to $x = \text{Germany}$. For consistency reasons, the base year is $t = 2017$ for all normalization and current environmental pressures. The time horizon for the target values is $t = 2050$ unless this was not possible due to the lack of data. The attribution of elementary flows to impact categories (classification) follows the impact assessment method “ecological scarcity 2013” as implemented in the ecoinvent v3.5 database [13, 23].

Table 1 provides an overview of all considered impact indicators in the ESM. The asterisks in column “Adapted” indicate that most target values ($T$) have been changed with respect to their respective origins, e.g., if more recent legislative references were available. The column “legitimation” provides a classification of the target value’s degree of democratic legitimation according to the following guidelines: A high legitimation ($+$) is assigned to quantitative targets adopted directly from a national law or a regulation as, e.g., the Federal Climate Protection Act in the case of Global Warming (GW) [1]. Targets based on binding international treaties or guidelines are assigned a medium legitimation (o), e.g., the UN Protocol on Heavy Metals that sets binding targets for Germany for heavy metal emissions into air (HMIA). Eventually, a low legitimation (−) indicates a target derived from a qualitative objective or strategy [24]. This applies, for example, for the targets for mineral resources (MR) and land use (LU), which are deduced respectively from the German resource efficiency program II [25] and sustainability strategy [26]. For a detailed documentation of the eco-factors in the ENsource ESM please refer to the supplementary information (S1_ENsource ESM, S2_ENsouce ESM elementary flows).

Table 1. ENsource ESM impact indicators. Origin: indicates ESM from which indicator was adopted: A = Ahbe et al. [17], M = Muhl et al. [21], F = Frischknecht and Büsser-Knöpfel [13]. Adapted: Asterisks (*) indicate adaptations of target value $T$ with respect to original ESM. Legitimation: Different categories: (+) high (e.g., law, regulation); (o) medium (e.g., binding international treaty, EU directives); (−) low (e.g., derived from qualitative goals, strategies).

| Impact Class   | Impact Indicator                          | Abbreviation | Origin | Adapted | Legitimation |
|----------------|------------------------------------------|--------------|--------|---------|--------------|
| Global warming | global warming                           | GW           | A      | *       | (+)          |
| Ecosystem quality | carcinogenic substances into air         | CSIA         | M      |         | (−)          |
|                 | heavy metals into air                    | HMIA         | M      | *       | (o)          |
|                 | heavy metals into water                  | HMIW         | A      |         | (o)          |
|                 | main air pollutants and PM               | APP          | A      | *       | (o)          |
|                 | ozone layer depletion                    | ODP          | M      |         | (+)          |
|                 | water pollutants                         | WP           | A      | *       | (o)          |
| Resources       | mineral resources                        | MR           | F      | *       | (−)          |
|                 | water resources                          | WR           | A      |         | (−)          |
|                 | land use                                 | LU           | M      | *       | (−)          |
|                 | energy resources                         | ER           | A      |         | (−)          |
| Waste           | non-radioactive waste to deposit         | WTD          | A      |         | (−)          |

2.3. Comparative Analysis of the ESM Weighting Schemes

Figure 1 compares the normalized weights of the ENsource ESM with its predecessor methods. The selection of impact categories corresponds to the ENsource ESM. Particularly striking are the differences with Ahbe et al., as this was the starting point for the development of the ENsource ESM [17].

First, the significantly higher share of GW in the ENsource ESM weighting scheme is conspicuous. It corresponds to the more ambitious target value for GHG emission reductions (−90% of 1990 GHG emissions by 2050 as compared to −80% in the ESM of Ahbe et al.) based on the following consideration: The Federal Climate Protection Act [1] strives for climate neutrality. To avoid the mathematical singularity and because we assume that a complete implementation is not to be expected, we use the mean value between the target value used by Ahbe et al. and a reduction to zero. Even though this
does not correspond exactly to the legal limit, the resulting weight for global warming certainly better reflects the current political priority setting than the original weight in Ahbe et al. [1,17].

![Weighting schemes of the different ecological scarcity methods.](image)

**Figure 1.** Weighting schemes of the different ecological scarcity methods. GW = global warming, LU = land use, APP = main air pollutants and PM, ER = energy resources, HMIW = heavy metals into water, CSIA = carcinogenic substances into air, HMIA = heavy metals into air; WP = water pollutants, MR = mineral resources, WR = water resources, ODP = ozone layer depletion, WTD = non-radioactive waste to deposit.

Furthermore, the large contribution of water pollutants (WP) and heavy metal emissions into water (HMIW) in the weighting scheme of Ahbe et al. is striking. The corresponding target values stem from a personal communication with the Federal Environment Agency [17]. As they could not be updated with publicly available sources, the ENsource ESM uses the original methodology from Frischknecht and Büsser-Knöpfel instead [13]. The target values for HMIW and polycyclic aromatic hydrocarbons (concerning WP) thus correspond to critical concentrations [27]. The remaining WP target values for phosphorus, nitrogen, and chemical oxygen demand correspond to those in Ahbe et al. [17].

3. Case Study: Renewable Energy Supply Scenarios for Mainau GmbH

In the present study, we analyze four scenarios that result from an energy system optimization carried out by the ENsource partner Fraunhofer Institute for Solar Energy systems (ISE) by means of the optimization tool KomMod [28]. All scenarios imply the coupling of heat and electricity sector. First, an analysis of the renewable energy potential is conducted for the island of Mainau to identify relevant constraints. For instance, due to lack of space for wind turbines on the island, wind energy is excluded from the energy supply portfolio. KomMod then minimizes operational and investment costs under the assumption that no energy infrastructure exists. This greenfield approach shall assure a fair comparison of existing with newly installed energy technologies.

3.1. Energy System Scenario Description

The “Business as usual scenario” (BAU) corresponds to the current energy system of Mainau GmbH. Scenario 1 (S1) integrates a power-to-liquid plant to generate methanol as fuel for the company’s
vehicle fleet. It uses surplus energy of a photovoltaic plant (PV) installed on the car park roof on the nearby shore. This requirement corresponds to a constraint of an additional 870 MWh of electric energy (Export in Figure 2) in the optimization model. In order to operate the electrolysis continuously, battery storage is used to compensate for the fluctuations in PV electricity generation. Scenario 2 (S2) exclusively uses the PV potential available on the island. Scenario 3 (S3) additionally comprises the PV potential on the car park but—in contrast to S1—without operating the power-to-liquid plant.

Table 2 summarizes the underlying potentials and constraints. The electronic supplementary material (S3_Parameter and modeling) provides further details on capacity, generation, and full load hours per technology and scenario.

**Figure 2.** Energy supply and storage technology for all scenarios (CHP = combined heat and power plant; PV = photovoltaic plant).

**Table 2.** Potentials and restrictions for optimization of the case study scenarios.

| Potentials/ Restrictions | Technology | BAU | S1 | S2 | S3 |
|--------------------------|------------|-----|----|----|----|
| **Potentials** | Boiler, natural gas [MWh] | 2900 | 0 | 0 | 0 |
| | Boiler, wood chips [MWh] | 2000 | 26,280 | 26,280 | 26,280 |
| | Combined heat and power plant, electricity, natural gas [MWh] | 880 | 880 | 880 | 880 |
| | Combined heat and power plant, electricity, wood gas [MWh] | 600 | 1314 | 1314 | 1314 |
| | Photovoltaic plant [MW] | 0.054 | 3.17 | 0.23 | 3.22 |
| | Solarthermal [MW] | 0 | 0.73 | 0 | 0 |
| **Restrictions** | Grid electricity | not restricted | restricted | not restricted | not restricted |
| | Storages | no | battery, heat | no | no |

Figure 2 illustrates the energy technology portfolios for the target year of \( t = 2050 \) for all scenarios that result from cost optimization. Additionally, Figure 3 provides an overview over the system configurations by means of Sankey diagrams for the energy flows.
3.2. Life Cycle Modelling of the Energy System Scenarios

The functional unit to compare the different scenarios is the provision of 2275 MWh of electricity and 5960 MWh of heat (space heating and hot water) per year. It corresponds to the actual energy consumption in 2015, which the Mainau GmbH deems representative for the future. The system boundary is cradle to grave. The inventory analysis uses the software tools Umberto and openLCA, both relying on the database ecoinvent (v3.5, cut-off system model) for background system modeling [23]. In order to assure consistency, process parameters were, wherever possible, set to the same values as in the optimization model (cf. Table 3: Parameterized processes). For PV plants the site-specific yield is taken into account. The combined heat and power (CHP) plant uses a synthetic gas produced from a wood mix harvested in the surroundings of the island. The wood chips boiler uses the same local wood mix. Wood chips production is modeled using generic datasets. Since no wood gas-fired CHP is available in ecoinvent v3.5 the biogas CHP (adapted with site-specific emission data) is combined with a gasifier dataset (see SI_3_Parameter and modeling for modeling details). The allocation of impacts for heat and electricity follows the ecoinvent approach based on exergy. The battery lifetime is set to 10 years [29]. The energy density corresponds to a common lithium battery [30]. Import electricity corresponds to the process “market for electricity, low voltage (DE)”.

Table 3. Parameterized processes.

| Technology     | Ecoinvent 3.5 Process                                                                 | Parameter         |
|----------------|-------------------------------------------------------------------------------------|-------------------|
|                |                                                                                     | COP   | Energy Density | Lifetime |
| Heat pump      | heat production, air-water heat pump 10 kW                                           | 3.4    | -              | 20       |
| Heat pump      | heat production, borehole heat exchanger, brine-water heat pump 10 kW                | 4.1    | -              | 20       |
| Battery storage| battery production, Li-ion, rechargeable, prismatic                                 | -      | 0.114 kWh/kg   | 10       |

Because of missing inventory data, the power to liquid plant is not explicitly modeled in S1. Instead, a credit is given to the 870 MWh surplus electric energy in order to gain functional equivalency.
between S1 and the other scenarios. As the surplus energy exclusively substitutes fossil fuel combustion in the company’s car fleet, the credit is derived from the fuel consumption and CO₂ emissions of a medium-sized diesel car. An estimated methanol production efficiency of 50% and the heating value of diesel are assumed for credit calculation.

4. Results and Discussion

4.1. Scenario Comparison Based on the Total Environmental Impact

The application of the ENsource ESM leads to an unambiguous ranking of the energy supply scenarios according to their total environmental impact (Figure 4). The alternative renewable scenarios only slightly reduce the total environmental impact compared to BAU. However, this merely reflects the fact that Mainau GmbH’s current energy system already comprises a high share of renewable energies. To obtain a more complete picture, the renewable scenarios (including BAU) are compared with a fictitious carbon scenario (CS), which corresponds to electricity from the German grid and natural gas-based heat generation. Compared to CS, all renewable scenarios have a significantly lower total environmental burden (up to 30% for S1). Furthermore, the relative share of GW in the total environmental impact is significantly smaller in the renewable scenarios (minimum 26% for S1) than in CS (70%). This underlines the necessity of a multi-dimensional environmental impact analysis when comparing the renewable scenarios with each other. Contrary to the partly significant reductions in almost all other impact categories, land use (up to a factor of 20.3 in the case of S1) and mineral resources (up to a factor 3.2 in the case of S1) increase in all renewable scenarios compared to CS.

![Figure 4. Scenario Impacts with ESM ENsource, GW = global warming, LU = land use, APP = main air pollutants and PM, ER = energy resources, HMIW = heavy metals into water, CSIA = carcinogenic substances into air, HMIA = heavy metals into air, WP = water pollutants, MR = mineral resources, WR = water resources, ODP = ozone layer depletion, WTD = non-radioactive waste to deposit.](image)

The renewable scenarios S1 and S3 have the lowest total environmental impact. The slightly more intensive PV use, the increased usage of the wood chips boiler, and the abandonment of the natural gas boiler in scenario S2 lead to a minor reduction in impacts compared to BAU. Scenario S1 is particularly interesting as it leads to the strongest GHG reductions and is the only scenario that explicitly includes the mobility sector. The following section examines which impact categories particularly contribute to the total environmental impact.
4.2. Comparative Analysis of Environmental Impacts

Based on the ENsource ESM, it is possible to analyze the environmental trade-offs between different scenarios. Figure 4 shows absolute differences between the investigated scenarios compared to BAU for the different impact categories. The global warming (GW) reduction in scenario S3 (−36.2 MEP = mega eco-points) is mainly counteracted by increases in land use (LU, 16.2 MEP), mineral resources (MR) and heavy metal emissions into air and other air pollutants (HMIA and APP, together +4.2 MEP), leaving a clear net environmental benefit (−17.9 MEP). The significantly higher GW reduction in scenario S1 (−49 MEP) is offset by correspondingly higher negative environmental impacts in other categories: land use (LU, +19.0 MEP), mineral resources (MR, +2.7 MEP) and heavy metal emissions (+6.3 MEP both into water and air) but also carcinogenic substances (CSIA, +3.6 MEP). Consequently, despite the clearly better climate performance of S1 its total environmental impact (+18.8 MEP) is only slightly lower than for scenario S3.

To better understand the adverse effects of decarbonizing Mainau GmbH’s energy supply and thus to develop context-specific remedies, the following section takes a closer look at critical technologies and life cycle processes that significantly contribute to the increasing impact indicators.

4.3. Hot Spot Analysis: Technologies and Life Cycle Processes

Increasing environmental impacts are mainly due to the additional technical infrastructure required to generate and store renewable energy, which is particularly high for scenario S1 (cf. Figure 5). Precious metals are important drivers of mineral resources (MR): Main consumers are photovoltaic cells (silver for metallization paste), inverters (gold for circuits, copper for converter), the battery (gold for circuits), and the CHP (platinum for catalytic converter). However, the mining and refining processes needed to provide those metals involve other environmental impacts as well, especially heavy metal emissions into air and water (HMIA and HMIW). The battery disposal has significant carcinogenic environmental effects (CSIA). The wood chips boiler and the CHP (both natural and wood gas) contribute mainly to the categories CSIA and other air pollutants (APP). In contrast, increased land use (LU) clearly results from operating the wood chips boiler and, to a lesser extent, the wood gas CHP.

Figure 5. Absolute changes (as differences expressed in MEP = 1e6 EP) of the alternative renewable scenarios compared to BAU, only significant changes considered: GW = global warming, LU = land use, APP = main air pollutants and PM, ER = energy resources, HMIW = heavy metals into water, CSIA = carcinogenic substances into air, HMIA = heavy metals into air, WP = water pollutants, MR = mineral resources.
5. Summary and Recommendations Concerning the Mainau GmbH

The preceding analysis shows that an increased PV use by Mainau GmbH is ecologically beneficial, although GHG savings are partially offset by increased mineral resources and heavy metal emissions (cf. scenario S3 in Figure 6). The inclusion of the mobility sector in scenario S1 makes sense in terms of achieving climate neutrality. However, the continuous operation of the power to liquid system requires a substantial increase of PV capacity, the installation of a heat storage unit, and a battery, as well as the increased use of the wood gasifier. This leads to increases in most of the investigated impact categories that largely offset the GW reductions from substituting fossil fuels. On the other hand, the additional storage capacities entail a completely self-sufficient energy supply. This may be considered an additional advantage in terms of energy systems decentralization, since necessary system services and infrastructure are also partially decentralized. This perspective would put into question the functional unit and system boundaries chosen to compare S1 to the other scenarios.

![Figure 6](image_url)  
**Figure 6.** Share of energy carriers and storage technology for several impact categories, LU = land use, CSIA = carcinogenic substances into air, MR = mineral resources, APP = air pollutants, PM, HMIW = heavy metals into water, HMIA = heavy metals into air.

The hot spot analysis reveals the main drivers of negative environmental impacts associated with an increased use of renewable energies: substantial increases in land use (LU), air pollutants (APP, CSIA), and heavy metal emissions (HMIW, HMIA). The latter is closely linked to the mining activities for raw materials for photovoltaic modules and storage technologies. Land use is increasing due to the use of wood as an energy carrier. These are potential levers for further improving the energy system design: e.g., by switching to CdTe cells instead of multi-silicon cells, which cause lower environmental impacts [31] or by installing PV modules from manufacturers that use secondary raw materials or pay attention to high environmental standards in the extraction of raw materials. For the wood gasifier and wood chip boiler, wood waste or wood from extensive forestry use could be used.
The present analysis suggests extending the set of considered scenarios. In particular, the commitment to local energy production seems unnecessarily restrictive. Imported wind energy could be a resource-saving alternative to photovoltaics. The current scenarios are based on an exclusive cost optimization. The integration of the environmental indicators derived from the ENsource ESM as optimization objectives or constraints could help to identify even more environmentally friendly energy supply scenarios.

6. Conclusions and Outlook

6.1. Environmental Trade-Offs of Renewable Energy Systems

This paper presents an updated ESM for Germany, which includes mineral resource use of renewable energy systems. From a practical point of view, the ENsource ESM quantifies environmental trade-offs between different renewable technologies and scenarios and provides a single score for an unambiguous environmental ranking of different options. Eco-factors that integrate external normalization and distance-to-target weighting make different impact categories comparable in terms of their relevance for a specific decision context. Applying the ENsource ESM to the case of a decentralized renewable energy system confirms the increased demand for mineral resources found by other authors [3,6]. However, it also shows that the major contribution to the total environmental impact stems from pollutant emissions associated with the mining activities. In addition, increasing land use due to biomass combustion is emerging as a potential problem area. The shift in importance from mineral resources to pollutant emissions related categories and land use could be due to extending renewable energy system analysis from electricity production to heating and cooling as well as mobility. To explore the findings’ generalizability from the case study, the ENsource ESM could be applied to other energy systems in Germany.

6.2. Missing Targets—Limitations and Transparency

As for other ESM [17,21], the presented environmental assessment is mainly limited by missing legally binding, quantitative targets for some impact categories (cf. Table 1). In these cases, provisional targets were derived in the most plausible way possible from suitable references, such as EU regulations or directives or governmental strategy reports. However, this clearly limits the democratic legitimacy, which is one of the most important arguments in favor of ESM in general [32]. This study suggests nevertheless that the ESM’s mathematical simplicity makes it a particularly transparent approach that allows for a critical reflection and, if necessary, case-specific adaptation of weights for environmental impacts. It moreover makes it possible to involve practical decision-makers in this process by presenting and communicating key assumptions in a structured way. In that sense, we take in the following a closer look at the weights for heavy metal emissions and land-use, which have been identified in the case study as the main adverse environmental effects of renewable technologies, as well as the weight for global warming, which is without doubt particularly important and involves a legal zero-emission target.

With regard to heavy metal emissions into water, it can be objected that the ENsource ESM does not regionalize weights. This means that policy targets ($T$) and pollutant emissions ($A$) for the Rhine are effectively transferred locally to the Mainau and, more questionably, in terms of representativeness, to the entire world. The latter directly affects the validity of our results because pollutant emissions from mining processes occur outside Germany. As environmental standards are lower in many countries than in Germany or even do not exist ($T = \infty$), regionalized weights would be much smaller or even zero. This would improve the environmental score or the investigated renewable scenarios. However, we follow the argumentation of Frischknecht and Büsser-Knöpfel, who prefer in such cases to apply weights derived from German environmental standards in order to prevent “environmental dumping” [13].
The indicator for land use in the ENsource ESM refers to land occupation. Since land occupation is not limited by law in Germany, the corresponding weight in the eco-factor is based on a limit for land transformation (measured in ha/a) taken from Germany’s sustainability strategy instead [26]. Other approaches to derive the weighting in a more consistent way would be conceivable: e.g., to relate the worldwide land use by German consumption (A) to the usable area available in Germany (T). Regarding our results, this would tend to increase the contribution of land use to the total impact but leave the ranking of the alternative renewable scenarios (S1, S2, and S3) unchanged. Even though methodically appealing, this approach has been abandoned for the present study, as it lacks democratic legitimacy.

The ESM’s transparent way of defining weights is even an advantage where the legal basis is clear. Regarding policies aimed at climate neutrality, the fundamental methodological question arises as to how to deal sensibly with a zero-emission target. Mathematically, this leads to infinite weights (Equation (2)) and, thus, eventually to binary weighting. As pointed out initially, there are good reasons to refuse such a narrowing of the focus. At the same time, the practical way of dealing with this limit within the ENsource ESM provides evidence that a strong emphasis on climate change, does not necessarily lead to neglecting other environmental impacts.

6.3. From Decision to Policy Support

A possible approach to improving the ENsource ESM is the further development of the provisionally derived eco-factors. However, this would contradict the basic idea of ESM, which recommends the use of democratically legitimated target values. Rather than research, a political process is necessary that properly involves science, civil society, and other stakeholders to discuss and finally define such target values for different environmental pressures in a comprehensive and consistent way. As has been pointed out before, the role of science is not to provide normative targets [20]. Nevertheless, science can provide a transparent framework to support an informed discussion on these targets. In that sense, the presented ENsource ESM not only aims at practical decision-support but also at supporting such a political process for developing a consistent set of environmental targets for the necessary transition towards a renewable and sustainable energy supply.

**Supplementary Materials:** The following are available online at [http://www.mdpi.com/1996-1073/13/21/5655/s1](http://www.mdpi.com/1996-1073/13/21/5655/s1), MS Word file S1: ENsource ESM, MS Excel file S2: ENsource ESM elementary flows, MS Excel file S3: Parameter and modeling.

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