

## Solar Energy Demand (SED) of Commodity Life Cycles

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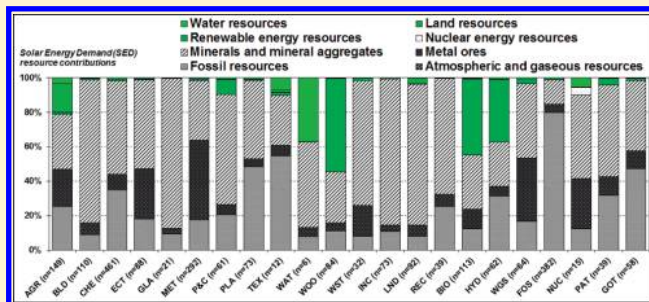
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**S** Supporting Information

**ABSTRACT:** The solar energy demand (SED) of the extraction of 232 atmospheric, biotic, fossil, land, metal, mineral, nuclear, and water resources was quantified and compared with other energy- and exergy-based indicators. SED represents the direct and indirect solar energy required by a product or service during its life cycle. SED scores were calculated for 3865 processes, as implemented in the Ecoinvent database, version 2.1. The results showed that nonrenewable resources, and in particular minerals, formed the dominant contribution to SED. This large share is due to the indirect solar energy required to produce these resource inputs. Compared with other energy- and exergy-based indicators, SED assigns higher impact factors to minerals and metals and smaller impact factors to fossil energetic resources, land use, and nuclear energy. The highest differences were observed for biobased and renewable energy generation processes, whose relative contribution of renewable resources such as water, biomass, and land occupation was much lower in SED than in energy- and exergy-based indicators.



### INTRODUCTION

The life-cycle assessment of energetic flows and resource exploitation is essential for improving the environmental management of natural stocks and their use. Many methods already exist to evaluate resource use and scarcity in life-cycle impact assessment (LCIA). Examples are cumulative energy demand,<sup>1</sup> exergy demand,<sup>2,3</sup> resource depletion,<sup>4–7</sup> and added energy or cost.<sup>8,9</sup>

Solar energy demand is, at present, not included in LCIA approaches. The concept of solar energy formed the basis of the broader *emergy* method, as developed by Odum in the early 1980s.<sup>10,11</sup> In *emergy*, solar energy is chosen as the reference, as it is considered as the primary source that feeds all natural processes and cycles on the Earth. One merit of the *emergy* method is related to its capability to assess very different resources on a common basis, units of solar energy, providing a broad indicator for resource consumption due to human-dominated systems. The system boundaries of *emergy* analysis are similar to those of a life-cycle assessment, as all resources needed during the life cycle of a product or process are accounted for. However, there are also fundamental differences, such as the allocation approaches applied and the number and types of resource assessed. Several studies highlighted the complementary nature of *emergy* and LCA<sup>12–14</sup> or integrated the two methods.<sup>15–19</sup> However, those efforts reveal problems due to lack of consistent data use, fragmented evaluations, limited numbers of processes included, and an absence of build-up and maintenance of an overall solar energy data set for commodity production. Recently, a National Environmental Accounting

Database (NEAD) was developed,<sup>20</sup> which aims at a global standardization of *emergy* calculation. NEAD contains highly aggregated data for industrial and agricultural sectors and can be used for the *emergy* analysis of different countries. However, NEAD shows inconsistencies in the gathering and aggregation of raw data and conversion factors (Supporting Information S1). On the contrary, some life-cycle inventory databases (e.g., Ecoinvent) contain large amounts of consistently collected inventory data on a unit-process level. Thus, the latter databases appear to be solid foundations for the implementation of solar energy calculations of products and processes.

In this paper we (a) introduce a solar energy-based indicator for resource consumption (i.e., solar energy demand, SED), (b) apply solar energy life-cycle-based impact factors to the large number of production processes from the Ecoinvent database v.2.1,<sup>21</sup> and (c) compare the solar energy indicator scores to the corresponding scores assessed with previous energy- and exergy-based LCIA methods.<sup>1–3</sup> The aim is to provide data and a comprehensive method for the evaluation of resource use of commodities within life-cycle assessment. This method can be used, for example, for assessing and improving the environmental management of natural resources.

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**Table 1. Overview of the Solar Energy Factors (SEFs) Coupled to the Ecoinvent v2.1 Resources**

| key elementary flows and groups of resource<br>( <i>n</i> = number of total resources within each group) | units               | type <sup>a</sup> | solar energy<br>factors <sup>b</sup> MJ <sub>se</sub> •unit <sup>−1</sup> | source for original unit energy values<br>(UEVs) and corresponding original flow |                                     |
|--|---------------------|-------------------|---|--|-------------------------------------|
| atmospheric and gaseous resources (4 reference flows)  |                     |                   |   |  |                                     |
| He   | kg                  |                   | 0   | d.c. <sup>d</sup>  |                                     |
| CO <sub>2</sub> ; Kr; Xe;  | kg                  |                   | 0   | g.s. <sup>c</sup> + d.c. <sup>d</sup>  |                                     |
| land resources (91 reference flows)  |                     |                   |   |  |                                     |
| carbon in organic matter   | kg                  |                   | 0   | d.c. <sup>d</sup>  |                                     |
| occupation (e.g., arable; forestry; urban; <i>n</i> .24 flows)   | m <sup>2</sup> year | R                 | 6.17 × 10 <sup>4</sup>  | ref 11   | empower density Earth               |
| occupation (benthos area, <i>n</i> .2 flows)   | m <sup>2</sup> year |                   | 0   | g.s. <sup>c</sup>  |                                     |
| transformation (e.g., from forestry to urban; <i>n</i> .60 flows)  | m <sup>2</sup>      |                   | 0   | d.c. <sup>d</sup>  |                                     |
| volume occupied (in m <sup>3</sup> , <i>n</i> .3 flows; in m <sup>3</sup> a, <i>n</i> .1 flow)           |                     |                   | 0   | d.c. <sup>d</sup>  |                                     |
| renewable energy resources (10 reference flows)  |                     |                   |   |  |                                     |
| geothermal energy  | MJ                  | R                 | 6.06 × 10 <sup>3</sup>  | ref 11   | convective earth heat               |
| wind energy  | MJ                  | R                 | 1.47 × 10 <sup>3</sup>  | ref 11   | surface wind                        |
| potential (in hydropower reservoir) energy   | MJ                  | R                 | 2.72 × 10 <sup>4</sup>  | ref 11   | physical stream energy              |
| solar energy   | MJ                  |                   | 0   | d.c. <sup>d</sup>  |                                     |
| energy in biomass ( <i>n</i> .2 flows)   | MJ                  |                   | 0   | d.c. <sup>d</sup>  |                                     |
| wood resources ( <i>n</i> .4 flows)  | m <sup>3</sup>      |                   | 0   | d.c. <sup>d</sup>  |                                     |
| fossil resources (8 reference flows)   |                     |                   |   |  |                                     |
| peat   | kg                  | N                 | 3.53 × 10 <sup>5</sup>  | ref 11   | peat                                |
| natural gas  | Nm <sup>3</sup>     | N                 | 1.47 × 10 <sup>6</sup>  | ref 29   | natural gas                         |
| coal ( <i>n</i> .2 flows)  | kg                  | N                 | 1.42 × 10 <sup>6</sup>  | ref 11   | metamorphic rock                    |
| crude oil  | kg                  | N                 | 2.32 × 10 <sup>6</sup>  | ref 29   | oil                                 |
| sulfur   | kg                  | N                 | 4.45 × 10 <sup>6</sup>  | ref 11   | volcanic sediment                   |
| natural gas; coal mine off-gas   | Nm <sup>3</sup>     |                   | 0   | d.c. <sup>d</sup>  |                                     |
| metal ores (71 reference flows)  |                     |                   |   |  |                                     |
| ranges:  |                     |                   |   |  |                                     |
| Al; rare earth metals ( <i>n</i> .7 flows); Fe   | kg                  | N                 | 3.26 × 10 <sup>6</sup> —7.07 × 10 <sup>6</sup>                            | ref 30   | <sup>e</sup> (cerium/rare earths)   |
| Ga; Zr; Ti; Zn; Cu; Pd; Co; Cr; Ta ( <i>n</i> .22 total flows)   | kg                  | N                 | 1.04 × 10 <sup>7</sup> —9.89 × 10 <sup>7</sup>                            | ref 30   | <sup>e</sup>                        |
| Ni; Mn; Pt; In; Ag; Pb; Au; Mo; Rh; Sb (tin) ( <i>n</i> .36 total flows)                                 | kg                  | N                 | 1.18 × 10 <sup>8</sup> —9.89 × 10 <sup>8</sup>                            | ref 30   | <sup>e</sup>                        |
| Re; Cd; Cinnabar (Hg); Te  | kg                  | N                 | 5.26 × 10 <sup>9</sup> —2.97 × 10 <sup>10</sup>                           | ref 30   | <sup>e</sup>                        |
| minerals and mineral aggregates (39 reference flows)   |                     |                   |   |  |                                     |
| basalt   | kg                  | N                 | 1.46 × 10 <sup>5</sup>  | ref 23   | oceanic basalt                      |
| granite  | kg                  | N                 | 4.90 × 10 <sup>5</sup>  | ref 11   | granitic rocks                      |
| <i>n</i> .15 flows (e.g., feldspar, gravel, kaolinite)   | kg                  | N                 | 1.25 × 10 <sup>6</sup>  | ref 23   | continental sediment                |
| pyrite; metamorphous rock  | kg                  | N                 | 1.42 × 10 <sup>6</sup>  | ref 11   | metamorphic rock                    |
| clay ( <i>n</i> .2 flows)  | kg                  | N                 | 1.98 × 10 <sup>6</sup>  | ref 11   | soil clay                           |
| shale  | kg                  | N                 | 2.36 × 10 <sup>6</sup>  | ref 23   | shale                               |
| perlite; pumice  | kg                  | N                 | 4.45 × 10 <sup>6</sup>  | ref 11   | volcanic sediment                   |
| sand   | kg                  | N                 | 4.95 × 10 <sup>6</sup>  | ref 23   | sandstone                           |
| calcite; dolomite  | kg                  | N                 | 5.50 × 10 <sup>6</sup>  | ref 23   | limestone                           |
| <i>n</i> .11 flows (e.g., anhydrite, borax, sodium chloride) <sup>f</sup>                                | kg                  | N                 | 9.89 × 10 <sup>7</sup>  | ref 23   | evaporites                          |
| stibnite   | kg                  | N                 | 2.47 × 10 <sup>9</sup>  | ref 30   | antimony                            |
| nuclear energy resources (1 reference flow: uranium)   |                     |                   |   |  |                                     |
| U  | kg                  | N                 | 9.36 × 10 <sup>7</sup>  | ref 30   | <sup>e</sup>                        |
| water resources (9 reference flows)  |                     |                   |   |  |                                     |
| water, lake  | m <sup>3</sup>      | R                 | 2.22 × 10 <sup>5</sup>  | ref 32   | freshwater lakes                    |
| water, river   | m <sup>3</sup>      | R                 | 3.09 × 10 <sup>5</sup>  | ref 32   | rivers and streams                  |
| water, well  | m <sup>3</sup>      | R                 | 1.10 × 10 <sup>6</sup>  | ref 32   | fresh groundwater                   |
| water, unspecified ( <i>n</i> .2 flows)  | m <sup>3</sup>      | R                 | 5.44 × 10 <sup>5</sup>  |  | avg of lake, river, and well waters |
| salt water ( <i>n</i> .2 flows); Mg (in kg, in water); water in turbines                                 | m <sup>3</sup>      |                   | 0   | g.s. <sup>c</sup>  |                                     |

<sup>a</sup> R = Renewable resource; N = nonrenewable resource. <sup>b</sup> Values refer to the baseline  $9.26 \times 10^{18}$  MJ<sub>se</sub>/year. <sup>c</sup> Ground-state resource. <sup>d</sup> Not included to avoid double counting. <sup>e</sup> Corresponding specific metal. <sup>f</sup> Noncarbonate salts.

## METHOD

**Solar Energy Framework.** The solar energy demand (SED) of a given process can be defined as

$$\text{SED}_p = \sum_i \text{SEF}_i \cdot M_{p,i} \quad (1)$$

where  $\text{SED}_p$  represents the total solar energy required to produce the good or service  $p$  ( $\text{SED}_p$  in  $\text{MJ}_{\text{se}}$ -equiv, megajoules of equivalent solar energy),  $\text{SEF}_i$  is the solar energy factor of the  $i$ th reference flow of resource ( $\text{SEF}_i$  in  $\text{MJ}_{\text{se}}/\text{kg}$ ,  $\text{MJ}_{\text{se}}/\text{Nm}^3$ ,  $\text{MJ}_{\text{se}}/\text{m}^3$ ,  $\text{MJ}_{\text{se}}/\text{m}^2\text{a}$ ,  $\text{MJ}_{\text{se}}/\text{MJ}$ ), and  $M_{p,i}$  is the quantity of the resource flow  $i$  ( $M_{p,i}$  in  $\text{kg}$ ,  $\text{Nm}^3$ ,  $\text{m}^3$ ,  $\text{m}^2\text{a}$ ,  $\text{MJ}$ ) involved as input in the production of  $p$ .

In general, the solar energy factor can be calculated via eq 2

$$\text{SEF}_i = \frac{S}{F_i} \quad (2)$$

where  $S$  represents the annual baseline of energy that flows in the geobiosphere, i.e., sum of emergy in sun, tide, and crustal heat,<sup>22</sup> and  $F_i$  is the annual flow of the resource  $i$  (e.g.,  $\text{kg}/\text{year}$ ), estimated by the ratio of the stored quantity and its turnover time.<sup>11</sup> Various values for  $S$  have been put forward in the literature.<sup>11,23</sup> Differences in these baseline values are related to the degree of connectivity and equivalence among the three primary sources (i.e., sun, tide, and crustal heat) that drive two global processes: (i) the annual production of geopotential energy in the world oceans and (ii) the Earth cycle of uplift and subsidence.<sup>22–24</sup> In this paper, SEFs were derived from the  $9.26\text{E}18 \text{ MJ}_{\text{se}}/\text{year}$  baseline assuming that tides do not contribute to the Earth cycle and the Earth's deep heat does not contribute to the annual production of geopotential energy in the world oceans.<sup>24,25</sup> Therefore, SEF can be calculated for land, waters, minerals, energy carriers, and so forth, by assuming the baseline as 'free' energy that feeds and sustains each of the resource flows. The turnover time is used to make a distinction between renewable resources (e.g., water, biotic elements) and nonrenewable resources (e.g., fossil and metal/mineral resources).<sup>11</sup> Since the baseline is defined on an annual basis, resources for which the turnover time is more than 1 year are considered nonrenewable in this study (Supporting Information S2).

SED is not equal to emergy, although they share the same conceptual rationale. First, SED includes allocation between coproducts of different nature, while emergy is defined by special algebra rules that, in the case of coproducts, assign the complete burden of multioutput processes to all coproducts.<sup>11,26</sup> Although there are methods to enable calculations according to emergy algebra, these have mainly been implemented manually on relatively simple product or process systems;<sup>11,27</sup> consistently avoiding allocation is not feasible for LCA databases of several thousand interconnected data sets with circular cycles. The allocation approaches taken in the Ecoinvent database (e.g., economic, exergy, or mass allocation) are a more straightforward and consistent procedure in this regard, as they are conceptually simple and ensure that all emissions are assigned to products/processes without any double counting. Second, SED does not account for a number of process inputs usually included in emergy analysis, i.e., human labor, information, and most ecosystem services (e.g., provisioning and regulating services such as rain, tide, and evapotranspiration or supporting services such as soil formation and photosynthesis).<sup>28</sup>

**Grouping of Elementary Flows.** The elementary flows of the Ecoinvent database v2.1 were grouped into 8 resource categories: (1) atmospheric and gaseous resources; (2) land resources; (3) renewable energy resources; (4) fossil resources; (5) metal ores; (6) minerals and mineral aggregates; (7) nuclear energy resources; (8) water resources. Categories 2, 3, and 8 refer to renewable resources, while those included in the other categories were considered nonrenewable.

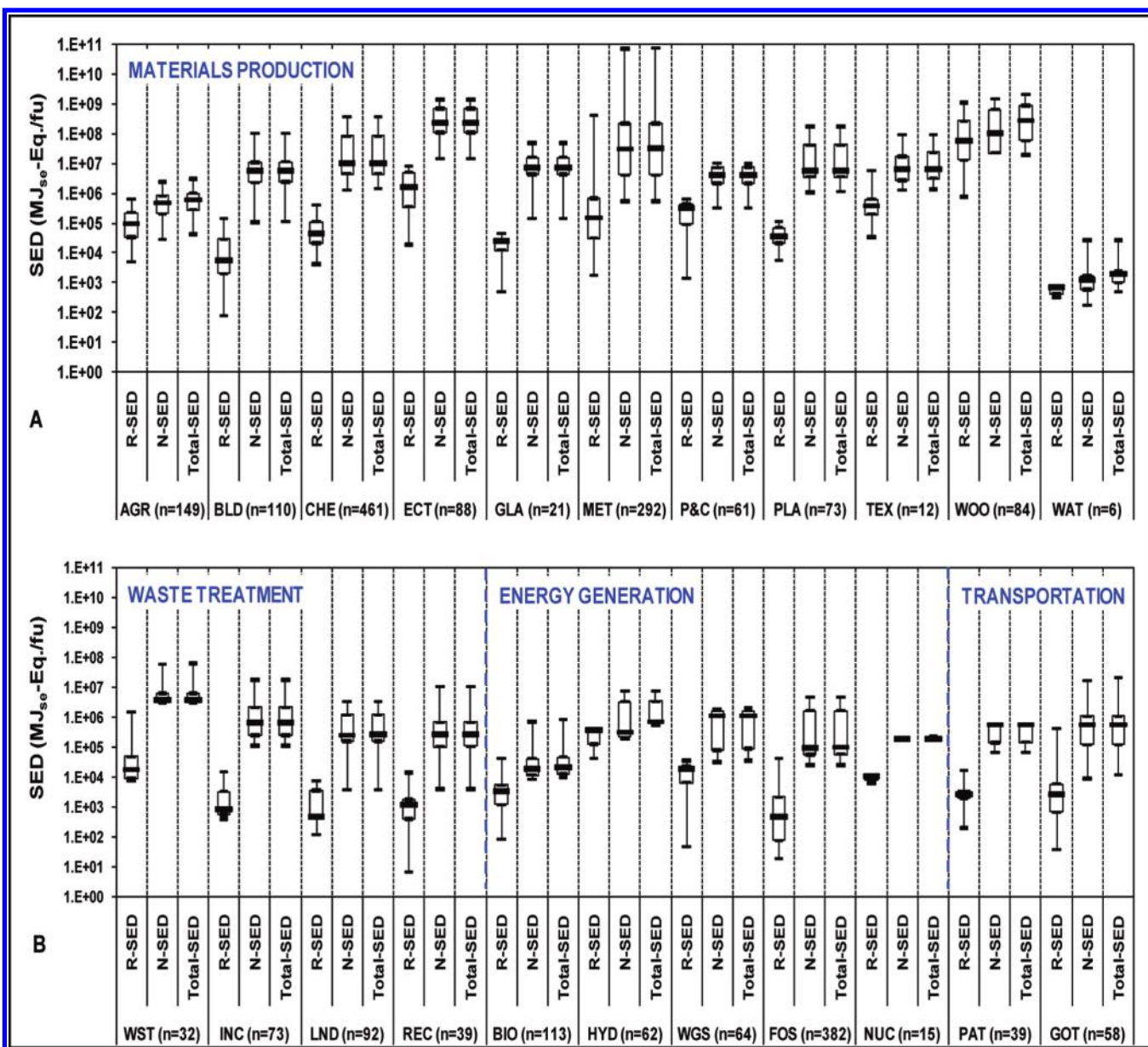
SEF values were derived from the emergy literature and correspond to reference unit emergy values (UEVs: transformities or specific emergies<sup>11</sup> included in previous emergy analyses and methodological reports). The SEF has a metric of  $\text{MJ}_{\text{se}}/\text{unit}$ . Table 1 provides an overview about SEFs assignment and R/N figures to the grouped elementary resources. The complete list of SEFs is available in Table S1 of the Supporting Information, while a detailed description of all SEFs calculation is reported in the Supporting Information S2.

**Atmospheric and Gaseous Resources.** SEFs of carbon dioxide, krypton, and xenon (in air) were set to zero, since they were considered as ground-state (largely spread resources of reference, with no solar energy potential) resources of the atmosphere. SEF of the gaseous resource of helium, which is inventoried as an elementary flow occurring with natural gas in ground deposits, was also set to zero to avoid double counting with natural gas.

**Land Resources.** Ecoinvent v2.1 accounts for (i) occupation of land (in  $\text{m}^2\text{-year}$ ), (ii) transformation of land (in  $\text{m}^2$ ), and (iii) volume of land occupied (3 flows in  $\text{m}^3$  and 1 in  $\text{m}^3\text{-year}$ ). To characterize land occupation, an average value was used for all land use classes, which is the emergy equivalent to land area-time units.<sup>11</sup> As only the global continental surface is included in the calculation (Supporting Information S2), SEFs for two flows of benthos area occupation were set to zero.<sup>32</sup> Moreover, SEFs for land transformation and land volume flows were set to zero to avoid double counting with land occupation flows. Finally, the SEF for carbon in soil organic matter was also set to zero to avoid double counting with land use.

**Renewable Energy Resources.** For wind, hydro, and geothermal energies, the Ecoinvent database accounts for the fraction useful to produce electricity, i.e., the fraction of kinetic energy converted from wind by wind mills, of potential energy in hydropower reservoir, and of geothermal energy extracted by borehole heat exchangers, respectively. In this connection, SEFs (in  $\text{MJ}_{\text{se}}/\text{MJ}$ ) referred to average global data<sup>11</sup> were coupled to each energy carrier. For agricultural products and renewable energy generation from biomass crops, Ecoinvent provides the elementary flow "Energy, gross calorific value, in biomass", in  $\text{MJ}$ , in addition to land occupation and inputs from the technosphere (e.g., fertilizers). The flow of "Energy, gross calorific value, in biomass" is only used to add a calorific value to the specific crop. From a solar energy perspective, this flow would be not an input but, instead, an output used for conversion of an agricultural product of interest. Thus, SEF for this flow was set to zero, and a solar energy factor was only assigned to land flows that are necessary for the growth of crops. For wooden materials, Ecoinvent provides not only land and biomass energy content but also the volume of wood (in  $\text{m}^3$ ) that grows in the specific area (forest land) of interest. In analogy to the approach used for crops, SEF was set to zero for the flows of wood resources (see Table 1), avoiding double counting with land occupation (Supporting Information S1). Similarly, the SEF of the elementary flow of solar energy that is converted by solar panels in technological systems was also set to zero, because solar energy is already included in the SEF of occupied land surface.



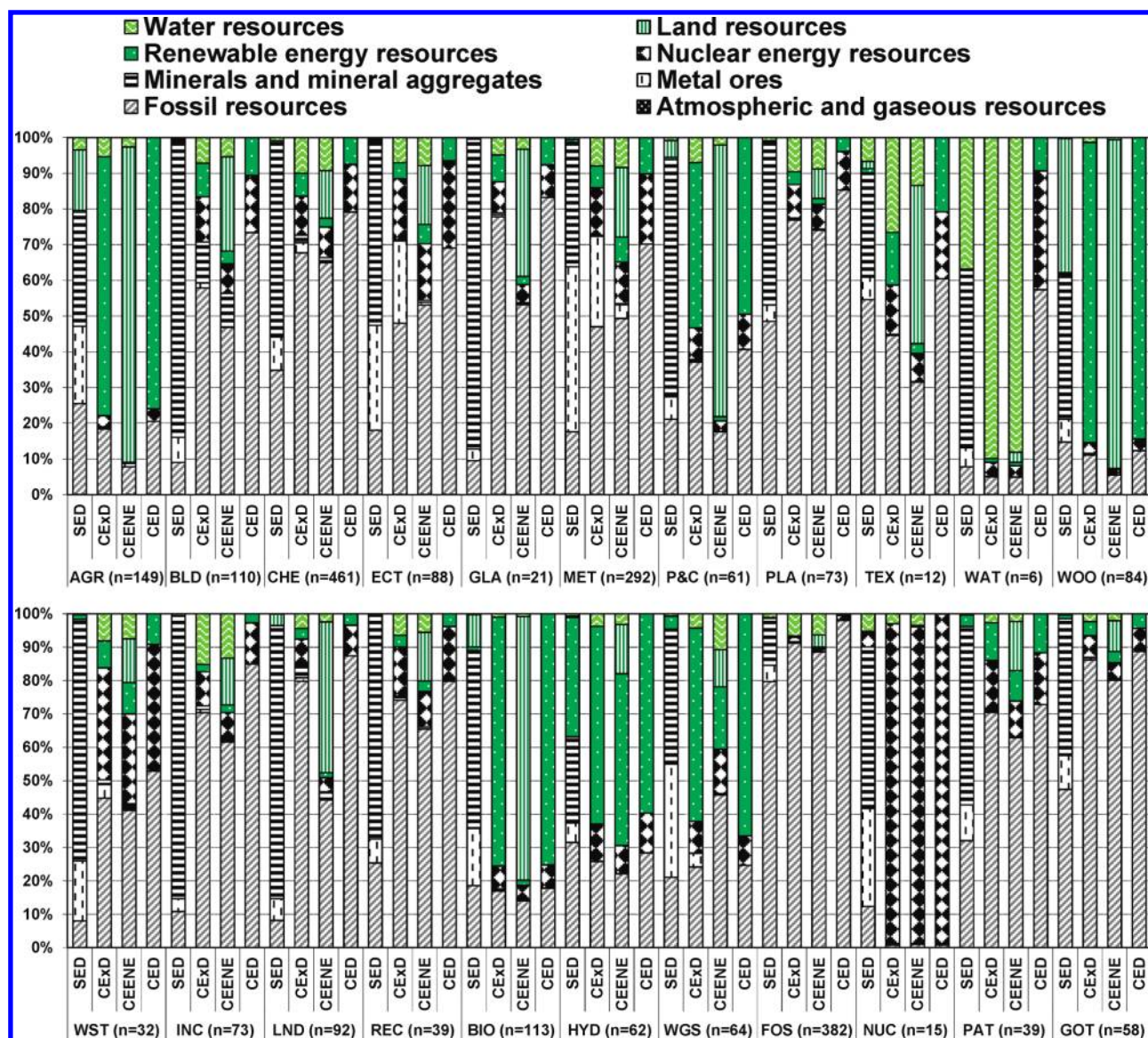


**Figure 1.** Box plots of renewable (R) and nonrenewable (N) portion of the total solar energy demand (SED) scores (in MJ<sub>se</sub>/fu, where se = solar energy; fu = functional unit) for class of service or product in the Ecoinvent database v2.1: (A) materials production (agricultural products (AGR), building materials (BLD), chemicals (CHE), electronics (ECT), glass (GLA), metals (MET), paper and cardboard (P&C), plastics (PLA), textiles (TEX), wooden materials (WOO), water supply (WAT)) and (B) waste treatments (wastewater treatment (WST), incineration (INC), landfill (LND), recycling (REC)) are in MJ<sub>se</sub>/kg, except WOO and WST, which are in MJ<sub>se</sub>/m<sup>3</sup>. Energy production processes (biomass energy (BIO), hydroenergy (HYD), wind, geo energy, and solar energy (WGS), fossil energy (FOS), nuclear energy (NUC)) are given in MJ<sub>se</sub>/MJ, passengers transport (PAT) in MJ<sub>se</sub>/pkm, and goods transport (GOT) in MJ<sub>se</sub>/tkm. The center of the box represents the median value, the edges of the box indicate the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles of the distributions.

**Fossil Resources.** This category includes nonrenewable fuel resources (gas, oil, coal, peat, sulfur). The SEF of “Gas, mine, off-gas, process, coal mining” was set to zero since this flow can be regarded as a waste (emissions to air) occurring when mining coal. The SEF for peat was directly taken from Odum,<sup>11</sup> while SEF for coal (both hard and brown) and sulfur were assumed to be those of the corresponding stock of resource in ground, i.e., metamorphic rock and volcanic sediment, respectively.<sup>11</sup> Finally, SEFs for natural gas (originally in seJ/g and then converted in MJ<sub>se</sub>/m<sup>3</sup> using an average density of gas equal to 716.82 g/m<sup>3</sup>),

and oil refers to specific energies calculated on the basis of the biogeochemical processes that contribute to their formation (from photosynthesis through catagenesis).<sup>29</sup> Such a perspective differs from that of other SEFs, since the baseline is not taken as reference. Although this alternative thermodynamic approach addresses some of the main criticisms in SEFs calculation,<sup>25</sup> its wider application to all resources is currently limited to a few resources for which the corresponding SEF factors and data are available.

**Metal Ores.** Solar energy factors (in MJ<sub>se</sub>/kg) of metal ores were taken from Cohen et al.,<sup>30</sup> who provided specific energies



**Figure 2.** Comparison of the relative contribution of renewable (R, i.e., water, land, renewable energy) and nonrenewable (N, i.e., nuclear energy, fossil, mineral, metal, atmospheric and gaseous) resources in SED, CExD, CEENE, and CED scores for 22 product/service groups of the Ecoinvent database v2.1 ( $n$  = number of processes): agricultural products (AGR), building materials (BLD), chemicals (CHE), electronics (ECT), glass (GLA), metals (MET), paper and cardboard (P&C), plastics (PLA), textiles (TEX), wooden materials (WOO), water supply (WAT), wastewater treatment (WST), incineration (INC), landfill (LND), recycling (REC), biomass energy (BIO), hydro energy (HYD), wind, geo and solar energy (WGS), fossil energy (FOS), nuclear energy (NUC), passengers transport (PAT), and goods transport (GOT).

for 26 elements concentrated in ores based on published ore grade cutoff (OGC) and average crustal concentration values. With regard to 24 other metal ores for which OGC values were not available, an OGC regression model based on existing data about price and crustal abundance was applied<sup>30</sup> (Supporting Information S2). For rare-earth elements (i.e., europium, gadolinium, lanthanum, neodymium, praseodymium, and samarium), the SEF of cerium was used as a first approximation.<sup>30</sup>

**Minerals and Mineral Aggregates.** Since the high variability and number of elements included in each mineral and mineral aggregate's composition, average values related to corresponding rocks were used (SEFs in MJ<sub>se</sub>/kg), as provided by Odum<sup>11,23</sup> (Supporting Information S2). The self-organizational processes of the Earth circulation generate many kinds of rock:

the total energy of the Earth was then assigned to all these components, since rocks can be conceived as coproducts and necessary components of the Earth cycles.<sup>23</sup> The only exception was stibnite, for which the specific energy of the reference metal (i.e., antimony) was used<sup>30</sup> due to the high concentration of antimony in the mineral ( $Sb = 71.68\%$  in  $Sb_2S_3$ ; ref 31).

**Nuclear Energy Resources.** This category included the reference flow of uranium in ground, for which the SEF was derived from Cohen et al.<sup>30</sup>

**Water Resources.** All solar energy factors were derived from a comprehensive energy evaluation of global and regional water uses.<sup>32</sup> Transfinites of global water storages and flows are calculated by assuming these as coproducts, respectively, of the baseline. Accordingly, SEFs (in MJ<sub>se</sub>/m<sup>3</sup>) for different types of water (e.g., river, lake, ground waters) can be obtained (Supporting Information S2).



According to Buenfil,<sup>32</sup> SEFs equal to zero were assigned to 'seawater flows' (including the resource of magnesium, in water), since seawater is considered "ground state" with no chemical potential energy. The SEF of water in turbines of hydropower plants was also set to zero to avoid double counting for hydroelectric power.

**SED Calculation.** Specific solar energy demands were first calculated for 3865 products, processes, and infrastructures of the Ecoinvent database v.2.1 (specific SED in MJ<sub>se</sub>-equiv/f.u., where f.u. = functional unit of each unit process, e.g., 1 kg, 1 Nm<sup>3</sup>, 1 MJ). From this sample, 2326 processes were grouped in 22 rather homogeneous product/service groups, including various types of energy carriers, materials, transport systems, and waste treatment. For commodities related to multiple locations (e.g., chemicals production), only the process with the largest geographical coverage was further included in the analysis (e.g., between the production of 'ammonia, liquid, at regional storehouse' in Switzerland (CH) and Europe (RER), only this latter was considered). This helped to minimize the interdependency between commodities. An evaluation of the distribution of SED scores among the grouped processes was made, splitting each score between its renewable (R-SED) and nonrenewable (N-SED) portion. The composition of category resources in the average SED score of each product/service group was then calculated.

**Methods Comparison.** To compare the relative importance of resource groups across various methods implemented in Ecoinvent, SED was compared to cumulative energy demand (CED),<sup>1</sup> cumulative exergy demand (CExD),<sup>2</sup> and cumulative exergy extraction from the natural environment (CEENE)<sup>3</sup> (Supporting Information S1). The comparison was done in terms of renewable (R) and nonrenewable (N) resource contributions.

## ■ RESULTS

**SED Scores.** The box plot in Figure 1 shows the ranges of renewable (R-SED) and nonrenewable (N-SED) indicator scores calculated for 2326 Ecoinvent processes. All specific SEDs per unit process are given in Table S3 of the Supporting Information. It appears that the portion of renewable SED is systematically lower than the nonrenewable SED. On average, N-SED is 2 orders of magnitude higher than R-SED. In some cases their difference is, however, lower (e.g., wooden materials, agricultural products).

In materials production, the lowest SED scores are found for water supply products (e.g., tap water). Higher SEDs are observed for biobased materials, such as agricultural products, and paper and cardboard, followed by chemicals and building materials. The highest SED scores are found for the production of electronics and metals (note that wooden materials are accounted in m<sup>3</sup> and not in kg). With regard to energy generation processes, renewable solar and hydroenergy production have a higher SED than nonrenewable energy production while biomass and geothermal (included in the WGS group in Figure 1) display the lowest SED (see Table S4 and Figure S4 of the Supporting Information). The main reason for the high SED score of solar and hydropower is the consumption of mineral and fossil resources for the construction of the plants, while the direct input of renewable energy in the form of solar radiation and water is irrelevant in the case of solar and about 30% of the total SED score of hydropower (Figure S4, Supporting Information). Moreover, since the SEF for uranium is relatively low compared with other energy-based characterization factors (Table S1, Supporting Information), SED of nuclear energy is also

relatively small (note that nuclear waste management is not included). Finally, the typical SED for waste incineration processes is higher than that of other types of waste treatment.

**Resource Contributions and Methods Comparison.** The contribution of each resource category to the SED score is presented in Figure 2. Within the 22 Ecoinvent product/service groups analyzed, it appears that the nonrenewable resources and, in particular, metals, fossil, and mineral resources have a dominant contribution to the SED scores of most product groups. For the majority of the product groups, SED is dominated by the consumption of minerals and mineral aggregates (mainly gravel, calcite, and sodium chloride), with contributions between 31% (i.e., agricultural products) and 87% (i.e., glass materials). Exceptions are found in the groups of fossil energy, textiles, plastics, and goods transport, where consumption of fossil resources prevails (between 47% and 80%). Other exceptions are found in metals production and the group of renewable energy generation from hydropower. The former is dominated by the solar energy of metal ore resources (about 47%), while the latter is by renewable energy resources (about 36%, i.e., potential energy in hydropower reservoir) (see Figure S4 of the Supporting Information for further details about composition of the SED score for energy production).

Figure 2 also compares SED with the CEENE, CExD, and CED indicators. The composition of resource demands show that SED scores have typically lower renewability than the other indicator scores. In particular, for biobased product groups (i.e., agricultural products, paper and cardboard, and wooden materials) and renewable energy processes (i.e., wind, geo, solar, and biomass energies) the nonrenewable resource contribution to the SED scores is relatively high. For non-biobased processes such as metals, chemicals, plastics, transportation, and fossil energy, where the demand for nonrenewable resources is usually dominant, differences between the four indicators are much lower. However, while for SED the minerals are most important concerning nonrenewable resource use, in the fossil resources are weighted very strongly according to CEENE, CExD, and CED.

## ■ DISCUSSION

The solar energy demand (SED) indicator quantifies the equivalent solar energy necessary to sustain and provide a product or service along its life cycle. It assesses resources required by processes and enables the systems comparison by converting all inputs to a common solar energy unit. In this study, specific SEDs for a large set of processes from version 2.1 of the Ecoinvent database were calculated.

**Uncertainty.** The SED calculations are, however, not without uncertainty. For land occupation flows, a typical global SEF was used without distinguishing between different land resources (e.g., cropland, forestry, urban). A SEF based on site-specific data, accounting for the free solar energy in different parts of the globe, would decrease the level of uncertainty for land occupation flows. In addition to spatial variation, another uncertainty comes from the choice of coupling SEFs to land occupation and not to the biomass (see Methods section and Supporting Information S1). A sensitivity analysis showed that the influence of this choice on renewable resource score is rather low with regard to the average of the complete database. However, the variation for biobased commodity groups can be significant, i.e., for wooden materials and biomass energy, the renewable SED portion increases from 38% to 55% and from 11% to 45%, respectively, when applying a

SEF to wood resources instead of land occupation (Supporting Information S5). The SEFs of minerals are uncertain as well. Average transformities of rocks, considered as coproducts of the same earth process, were assigned to minerals without following compositional characteristics. For instance, the solar energy factor of the widely used resource 'sodium chloride', which is a non-carbonate salt, was arbitrarily set equal to the SEF of the larger group of evaporite rocks. Since this is the highest SEF for minerals, assigning a SEF 1 or 2 orders of magnitude lower (being at the same of the rest of mineral SEFs) would allow for an average decrease of about 11% of the total contribution of the minerals category among the Ecoinvent product groups (see Supporting Information S5). For metal resources, SEFs were based on ore grade cutoff (OGC) values and enrichment ratios.<sup>30</sup> However, those are uncertain values, depending on economic demand and extraction technology.<sup>34,35</sup> Because of the large spread in OGC values (see Table S2 in the Supporting Information), metals have the highest variability in SEF among all resource categories (Table 1) as well as in SED scores among all materials (Figure 1). Furthermore, the weighing of metals with factors that are always larger than 1, according to the enrichment ratio,<sup>30</sup> enlarges the cumulated solar energy of the resource category "global land cycle" beyond the solar energy available on earth, when summing up all global land resources. Uncertainty is also associated with SEFs of some fossil (sulfur, peat, and coal) and nuclear (uranium) resources, since they are calculated with the same approach used for the SEF of minerals and metals, respectively. Conversely, the approach behind the SEF calculation for oil and natural gas seems to be less uncertain, since it is specifically addressed to include the biogeochemical efficiency of all natural steps of the oil formation.<sup>29</sup> In this regard, only the solar energy that was needed to form oil and gas resources was accounted for, while for minerals the complete baseline (sum of equivalent (solar) energy embodied in sunlight, geothermal heat, and tidal energy) was divided by the formation rate, independently of whether this energy input was really necessary to form these resources.

**Method Comparison.** SED and CEENE account for the majority of resources included in Ecoinvent. In particular, they both account for the solar energy and exergy, respectively, on land, and avoid double counting of biomass. Conversely, CED and CExD, respectively, focus on the energetic and exergetic content of biotic elements and do not account for land resources. Additionally, CED does not account for minerals and metals, covering a much lower set of resources than all other methods. While CExD provides information about the current state of the system and its future ability to do work,<sup>2,28,33</sup> SED envisions providing information about total energy used in the formation of resources. Although this is not yet fully implemented, for example, because the quality of SEFs are compromised by a rather simplistic calculation procedure based on the baseline (see last paragraph in Uncertainty section and Outlook), this can represent a significant advantage to the other methods in the future. For example, the solar energy required for a piece of wood is about 1000 times larger than the exergy of the same, since the efficiency of the photosynthesis is around 0.1%. SED's capability to account for these losses is an advantage in terms of consistency, e.g., when electricity production systems such as biomass and photovoltaic are compared, since both occupy land to capture solar energy. Thus, compared to cumulative energy and exergy, SED gives a more comprehensive overview of the resource requirements along a life cycle, since it expands the system boundaries from the primary resources (i.e., reference states in exergy and energy) back to the primary energy of the sun. However, it is not clear whether SED and

formation rates are correlated to the actual availability or scarcity of resources. Instead, SED intends to provide the memory of the basic energy (solar) spent to make a resource available at a given quality.

**Outlook.** One promising pathway for further research is to refine the transformity of all primary resources according to the approach proposed by Bastianoni et al.<sup>29</sup> or other thermodynamic approaches to quantify the formation energy of resources. This would allow for calculating SEFs in a consistent way and independent of the baseline, which is one of the main sources of uncertainty and inaccuracy in conventional emergy evaluations.<sup>22,24,25</sup> In this case, SED would represent a very interesting and consistent approach for the assessment of a large amount of resources within life-cycle assessment.

## ■ ASSOCIATED CONTENT

**Supporting Information.** SED characterization factors vs CExD, CEENE, and CED methods, details about NEAD database and SEFs calculation, framework to avoid double counting of SEF, specific SED scores for 3865 unit processes, SED average values and resource contributions, and sensitivity analysis for SEFs of sodium chloride and wood resources. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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