# Powering a Sustainable and Circular Economy— An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries

**Harald Desing *** , **Rolf Widmer** , **Didier Beloin-Saint-Pierre** and **Roland Hischier** and **Patrick Wäger**

Empa – Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, CH-9014 St.Gallen, Switzerland; rolf.widmer@empa.ch (R.W.); didier.beloinsaintpierre@empa.ch (D.B.-S.-P.); roland.hischier@empa.ch (R.H.); patrick.waeger@empa.ch (P.W.)

* Correspondence: harald.desing@empa.ch

**Abstract:** This study proposes a method to estimate the appropriability of renewable energy resources at the global scale, when Earth system boundaries/needs and the human demand for chemical energy are respected. The method is based on an engineering approach, i.e., uncertainties of parameters and models are considered and potentials calculated with 99% confidence. We used literature data to test our method and provide initial results for global appropriable technical potentials (ATP) that sum up to 71 TW, which is significantly larger than the current global energy demand. Consequently, there is sufficient renewable energy potentially available to increase energy access for a growing world population as well as for a development towards increasingly closed material cycles within the technosphere. Solar energy collected on the built environment (29%) and in desert areas (69%) represent the dominant part of this potential, followed in great distance by hydro (0.6%), terrestrial heat (0.4%), wind (0.35%), and biomass (0.2%). Furthermore, we propose indicators to evaluate an energy mix on different levels, from an energy mix in single products to the mix used by the global economy, against the estimated RE potentials, which allow an evaluation and consideration in the design of sustainable–circular products and systems.

## 1. Introduction

A circular economy (CE) aims at decoupling economic growth from natural resource depletion and environmental degradation, acknowledging the finite nature of the planet [1,2]. However, merely closing material cycles, as is often suggested in publications related to CE, does not prevent the violation of Earth system boundaries, as the magnitude of the induced material and energy fluxes remains unquestioned. Indeed, the discourse on circularity is mainly focusing on material cycles, neglecting that such cycles will require large-scale development of renewable energy (RE) resources to be powered in a sustainable manner. Fully closed material cycles are only possible in theory given that infinite exergy is available [3]. Moreover, the effort to recover materials (i.e., required exergy) increases nonlinearly with improved recycling yield [4,5], making a CE potentially very energy-intensive and raising the question of how much energy a CE may appropriate within Earth system boundaries.

Over the last two centuries, fossil energy resources, which are stored solar energy, have been the main power source for the linear industrial economy. Although they contribute little to Earth's energy budget (0.003% in 2016 [6]), burning fossil fuels is depleting these resources at an alarming rate (considering that they have been built up over millions of years) and is also one of the main

drivers for global environmental disruption [7], for example triggering a climate crisis [8–11]. Nuclear energy harvested in today's fission reactor fleet, though contributing little to the climate crisis, rapidly depletes the uranium stock, poses catastrophic risks for human and ecosystem health in case of accidents, increases the possibility for development and proliferation of nuclear weapons, and leaves radioactive waste to be managed for millennia by future generations [12]. Both fossil and nuclear energy resources are therefore incompatible with the notion of sustainable development, since it is defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [13]. Consequently, a sustainable CE can only be powered by RE fluxes in the future.

The Earth system is powered by three incoming RE fluxes: solar irradiance, terrestrial heat, and tides. The latter two contribute very little to the Earth's energy budget, i.e., 0.03% and 0.002%, respectively [14–17]. Solar irradiance is therefore the pivotal power source for the circulation of natural and anthropogenic materials in an otherwise closed Earth system. The Earth system balances these energy inflows mainly with infrared emittance, which is adjusted by the Earth's surface temperature [18]. All material cycles within the Earth system, be they natural or anthropogenic, are enabled by these energy fluxes, which are approximately five orders of magnitude larger than the current human demand for technical energy (i.e., energy used to power technical processes, such as electric energy) [6]. Throughout the Earth's history, these energy fluxes had been completely used by the Earth system (e.g., to power the water cycle). Human appropriation of RE fluxes, for example through the demand for chemical energy (i.e., energy used to supply humanity with food and biogenic materials, such as fodder, fibers and timber), has become a driving force in the Earth system. Hence the question is, how much of the theoretical RE potential can we safely appropriate without transgressing Earth system boundaries?

Studies on RE potentials that have been published so far can be classified as (A) having limited their scope on the theoretical potential reduced by thermodynamic limits for conversion to free energy (e.g., Carnot efficiency for thermal energy conversion, Betz' limit for wind conversion, …) [19–23]; (B) including also the technical conversion, i.e., the amount of energy that can be harvested on physically suitable sites with available technology (e.g., [24,25]); or (C) considering, in addition, political and economic feasibility in the assessment (e.g., [26–30]). Calculations according to (A) likely overestimate RE potentials, as they can neither be achieved with available technologies nor do they necessarily respect Earth system boundaries; those according to (B) reflect what is practically achievable but do not ensure that Earth system boundaries are respected; and those according to (C) likely underestimate potentials, because they extrapolate the limits of current markets. Furthermore, uncertainties in these estimations are rarely explicitly provided, making a confidence evaluation of the reported RE potentials difficult.

This manuscript thus proposes a new method to estimate the global appropriable technical potential (ATP), which considers and respects Earth system boundaries and the human demand for chemical energy while relying on current technology without looking into economic or legal restrictions. The method thus provides a technically and environmentally attainable estimate (in contrast to (A) and (B)) and, at the same time, sets targets transcending the current economic and political limitations (in contrast to (C)). It builds on a precautionary approach to consider uncertainties in all input parameters and estimates appropriable RE potentials that can be reached with high confidence. Such an approach is standard in engineering but also applied, for example, in environmental policy [2]. Initial ATPs are calculated for demonstration of the method based on literature data and indicators are developed to evaluate an existing or hypothetical energy mix against the ATP mix. This new method allows answering the question: How much technical energy from RE fluxes is available on a global scale to power a sustainable circular economy?

## 2. Method Development

The method developed in this paper follows incoming global RE fluxes to the level of ATPs only (see Figure 1). Issues regarding their distribution over time and space, energy demand, transition from conventional to RE resources or societal and economic costs are not within the scope of this investigation. Though not addressed here, these are important issues necessitating further research.

Figure 1 gives a conceptual representation on how the ATPs are calculated in this study. The theoretical potential comprises all incoming energy fluxes, i.e., solar irradiance, terrestrial heat flux, and energy flux from planetary motion. In the unperturbed Earth without human influence, all of this theoretical potential drives Earth system processes (e.g., climate system, water cycle, ocean currents, and biomass production) and is finally radiated back into space, partly as short wave radiation (i.e., reflected solar irradiance, albedo) and mainly as long wave radiation after exergy is consumed.
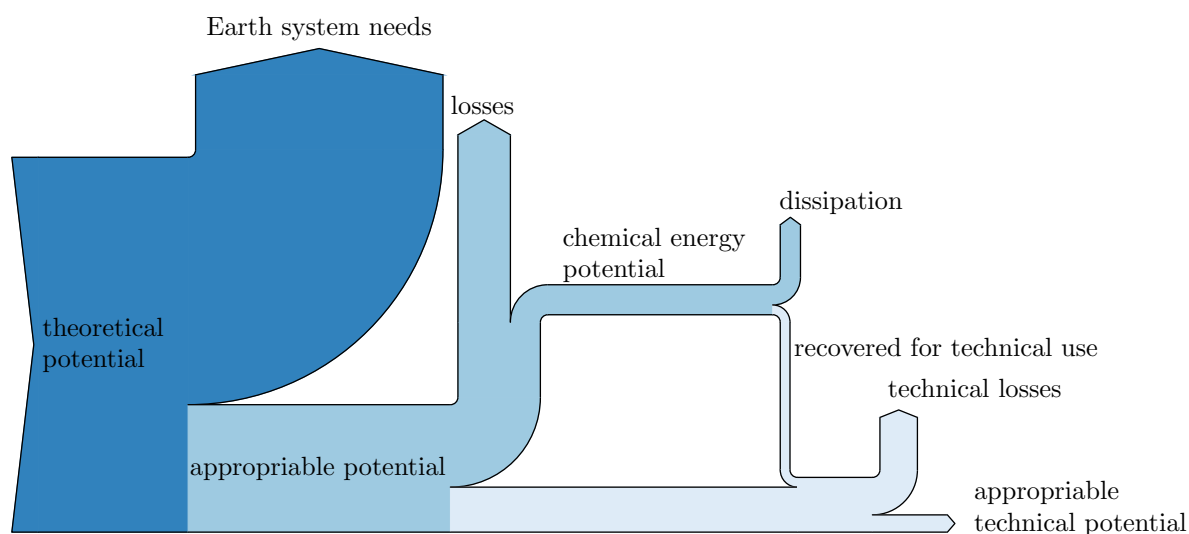


**Figure 1.** Schematic representation of the concepts of theoretical potential (i.e., incoming energy flux), appropriable potential (i.e., minus Earth system energy needs), and appropriable technical potential (ATP) (i.e., minus what is needed to provide appropriable chemical potential plus what can be recovered for technical use after chemical use and minus the technical conversion losses to electric energy). Fluxes are not to scale.

Human appropriation of energy fluxes in the Earth system essentially reduces their availability for Earth system processes. The Earth system has the ability to tolerate such disturbances to a certain extent while keeping its functionality [8,9]. However, crossing these thresholds runs the increasingly higher risk of triggering fast and irreversible environmental change towards new and likely less hospitable states [31]. Therefore, we define here the *appropriable potential* as the energy flux that can be diverted from the Earth system without crossing Earth system boundaries (Section 2.2.2), i.e., subtracting Earth system needs from the theoretical potential.

The appropriable potential satisfies the human demand for chemical energy (Section 2.2.1)—i.e., through net primary production (NPP) of biomass—and for technical energy. Providing this chemical energy implies losses, for example due to inefficiencies of photosynthesis or inevitable harvest residues. Part of this energy dissipates, for example through respiration in the case of food and fodder. The remaining appropriable NPP—such as fuel, waste and residues—together with the appropriable potential from the other RE resources are available for technical energy conversion. Conversion losses deducted, the remaining potential is defined here as *appropriable technical potential*.

*2.1. Core Modeling Principles*

The method is based on a common unit of comparison (Section 2.1.1), a simplified system model (Section 2.1.2) and explicitly deals with uncertainty to allow an assessment in line with the precautionary principle (Section 2.1.3).

2.1.1. Quantities and Units of Comparison

Energy is conserved, as stated in the first law of thermodynamics. However, there are more and less useful forms of energy–making it difficult to compare the quality, or usefulness, based on the energy value alone.

For the purpose of this study, electric energy is used to compare all energy resources as most RE technologies convert their harvested energy into electric energy. It is pure exergy, convertible to any other energy form and thus extremely versatile. We use a time resolution of one year (Section 2.1.2), and therefore, energy fluxes are reported as annual average power and ATPs as annual average electric power output in units of watt (not to be confused with installed capacity; $1\,W = 1\,J/s$; conversion $1\,EJ/a = 3.17 \times 10^{10}\,W$). The electrification of the energy system is often seen as key for a post-fossil society [32], making electric energy a relevant universal currency for energy in the future. For example, in RE-based mobility, electric energy is the main input energy stored in batteries, e-fuels (synthetic hydrocarbons), and hydrogen, or used directly in grid-connected electric vehicles (such as trains or trolleybuses).

In addition to electric energy, low temperature heat is another common output of RE systems (e.g., terrestrial or solar heat). It is relevant, for example, for indoor heating in higher latitudes and altitudes, domestic water heating, or in crop processing (drying). Even though direct conversion to low temperature heat may in many cases be more efficient and thus preferable, it is theoretically possible to convert to electric energy first and, using a heat pump and ambient heat, to low temperature heat later with a similar overall efficiency. Thus, for this assessment, technologies to provide low temperature heat are not considered.

2.1.2. System Model

For this study, we built a zero-dimensional steady-state model for the Earth system with a time resolution of one year. The system is driven by three constant incoming energy fluxes: (1) solar irradiance at the top of the atmosphere (5700 K, $TSI_{p=0.997} = (1360.9 \pm 6.1)\,W/m^2$ [16,18,33]; the uncertainty of values is reported for a specified level of confidence of the interval $p$, the geometric mean, and the lower and upper deviation from the mean that confine the interval); (2) rotational inertia of celestial bodies; and (3) terrestrial heat resulting from crystallization, cooling, and radioactive decay in the Earth's core and mantle. High-entropy long wave terrestrial radiation (255 K) to space is assumed to balance all inflows to maintain an average surface temperature of approximately 288 K. This model addresses neither transitions (e.g., how to get from the current energy system to a 100 % renewable one) nor temperature changes. As a consequence, stock levels within the system are considered to remain constant (e.g., forest biomass) and transformations cannot occur (e.g., land transformation). RE resources are available with great regional and seasonal variation (e.g., consider the difference of solar irradiance between summer and winter or equator and poles), requiring seasonal storage and geographic distribution in order to level out these variations. However, all of this, as well as long-term geological (e.g., Earth core cooling) and astronomical changes (e.g., increased solar luminosity), are not considered in this model.

The ATPs result from conversion in state-of-the-art technologies that reflects practically achievable conversion efficiencies (see Section 2.1.3). However, they neither consider environmental impacts from production, installation, and decommissioning nor resource requirements for any specific technology. Life cycle impacts depend on specific technologies, production routes, and energy mixes, which are

subject to change. Therefore, the potential indicates an upper limit that is independent of environmental impacts from the life cycle of specific technologies.

### 2.1.3. Precautionary Approach, Uncertainty, and Assumptions

Models are, by definition, abstractions from reality, inevitably leading to uncertainties [34]. Parameter uncertainties, stemming, for example, from measurement errors or temporal variability, are consistently considered throughout the model, whereas model uncertainties—e.g., due to assumptions and abstractions—are only considered in scenarios (see Supplementary Materials Section 4 for more details). Despite the often large uncertainties, their evaluation allows estimating results with high confidence, i.e., in a precautionary way. This is in analogy to engineering, where systems have to be designed that are functional and reliable over time with high confidence [2]. For example, the exact strength of a bridge is unknown; still, it needs to be designed to withstand loads that may occur with very low probability (worst-case). Acknowledging the challenges of building precise models at the global scale, we chose an engineering approach by looking at worst-case (in the sense of precautionary) estimates to describe key Earth system and technical processes, calculate results as probability distributions, and report the final value with a selected confidence level.

To demonstrate the method, we set this level of confidence to 99%, i.e., there is a 1% chance that the ATP is ecologically or technically not viable. This level of confidence is higher than what is applied to emission pathways to reach climate targets ($p = 0.66$ for $2\,^\circ$C [10] and $p = 0.5$ for $1.5\,^\circ$C [11]) and lower than in many engineering fields (e.g., for aviation, ships, power plants, etc. $p > 0.999$ [35–37]). Furthermore, this approach is also in line with the concept of planetary boundaries (PB) [8,9], which set the boundaries at the lower end of their uncertainty range. More precise models and data may allow decreasing the uncertainty range, increasing the value with a confidence of 99% when its mean value stays unchanged.

The conversion efficiency from Earth system power (e.g., kinetic power of wind) to technical power (e.g., electric power) depends on available technologies. Due to innovation, the efficiency may improve over time; however, it cannot surpass physical limits (e.g., Betz' limit for wind energy conversion [21,38]). As future development of technologies is uncertain, we consider here, in concordance with the precautionary approach, the efficiency for current state-of-the-art technologies. Potential improvements seen at lab scale as well as emerging technologies are not considered, as their market penetration may be delayed or fail.

Various assumptions are necessary, for example, concerning the accessibility of an area for energy conversion. Assumptions are generally made with a large uncertainty range across what is judged to be practically feasible. All assumptions and technological values behind this model are described in detail in the Supplementary Materials.

### 2.2. Limits to the Appropriation of RE

According to Figure 1, the appropriation of RE fluxes is limited by available technologies (see Section 5 in Supplementary Materials), the human demand for chemical energy (Section 2.2.1), and the environmental sustainability criteria (Section 2.2.2). Detailed descriptions of values and calculations can be found in the calculation worksheet and accompanying code provided online (see Supplementary Materials).

### 2.2.1. Human Need for Chemical Energy

Plants are the first trophic level that convert solar irradiance into chemical energy, mostly as glucose and other sugars [14,39], which subsequently support all other life forms along the food chain. Net primary production (NPP), a measure for biological productivity, is limited by production factors such as sunlight, nutrient, and water availability [40]. Human appropriation of NPP (HANPP) has become a major factor in biological systems [41–43]. HANPP should be limited by ecosystem requirements, interference with water and biogeochemical cycles, biosphere integrity, and land

transformation [40,44,45]. The latter three are already beyond safe limits [8,9,46], and water use trespasses safe limits in some regions [47,48]. The appropriability of NPP is further lowered due to ecosystem degradation (e.g., soil loss) [49,50] and will be exacerbated by the climate crisis [51].

Currently, HANPP is dominated by food production [41]. As the world's population is expected to grow and stabilize at $N_{p=0.95} = \left(10.87^{+1.79}_{-1.45}\right) \times 10^9$ in 2100 [52], the production of sufficient and healthy food is a key challenge for sustainable development [49,53,54], necessitating a more efficient use of the resources *land* [55] and *nutrients* [56]. This could be achieved, for example, through shifting diets towards 'less meat', increasing resource efficiency (mainly nutrients and water), closing yield gaps, reducing harvesting losses and food waste, as well as reducing demand for nonfood biomass [54,57–63]. Willett and colleagues [54] showed that a combination of all these measures is necessary to feed humanity within Earth system boundaries. Food production is therefore of top priority among all human chemical energy demands.

Nonfood biomass (e.g., wood, fibers or residues from food production) is important as raw materials (for construction, clothing) and/or fuel (for cooking, space heating, and more recently for propelling mobility [6]). Materials can partly be used in cascades ending in incinerators for energy recovery and possibly carbon capture and storage (CCS). Sustainable wood harvest is limited by the regrowth of forests, sustainable forest management, and the exclusion of protected and not accessible areas [64]. In contrast to wood, most fibers (e.g., cotton) and agrochemicals (including fuel/energy crops) are grown on cropland and therefore compete with food production. Bioenergy with carbon capture and storage (BECCS) is expected to become a large sink for atmospheric $CO_2$ [11,49]; however, this could result in a significant increase of HANPP, which is already beyond safe limits [41,65,66]. Transforming food into an energy crop production area, as suggested in some scenarios [49], is delicate in the face of the food challenge described before. Inevitable residues, food waste, and feces may be available for technical energy conversion. However, it remains to be proven whether these residues should not be applied on croplands to regain soil quality and close nutrient cycles [19,49,67]. We thus exclude all biomass of agricultural origin from being an appropriable energy resource.

### 2.2.2. Environmental Sustainability Criteria

Various attempts have been made to describe Earth system boundaries with key parameters that are representative and measurable [68]. For our proposed method, we use relevant limit values from the PB framework [8,9], which are specified for nine key Earth system processes (climate change, change of biosphere integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows, land system change, freshwater use, atmospheric aerosol loading, and novel entities). The dominant boundary for RE resources is *land system change*, since harvesting RE fluxes mostly depends on the available land surface. In case of hydro power and power from the salinity gradient between fresh- and saltwater, the *freshwater withdrawal* boundary is limiting. Agricultural production of biomass is, in addition to land, further limited by the *freshwater consumption* and *biogeochemical cycle* boundaries. As bioenergy from agricultural production is excluded in this assessment (Section 2.2.1), these boundaries are not discussed here. Since there is no land transformation in the model (Section 2.1.2), no effects on climate nor biodiversity may occur. Moreover, impacts on the remaining boundary categories that would result from production and EoL treatment of specific technologies are not considered for the estimation of ATP.

### 2.2.2.1. Land System Change

The Earth surface of $5.1 \times 10^{14}\,\mathrm{m^2}$ is divided between 28% of land and the rest for ocean surface [69–71]. Without human disturbance, the land would mainly be covered with climax vegetation, which is classified into various biomes, such as tropical forest or savanna [69]. Removing the climax vegetation has an effect on the climate system [70] as well as on biodiversity [72]. The PB for *land system change* [9] is based on simulating its effect on climate system only [70]. It specifies the maximum sustainable removal of forest biomes, as deforestation is the most pressing driver for land system

change [9]. It does not, however, specify any boundary values for the other biomes (e.g., grasslands), which seems arbitrary for two reasons: (1) In the simulation, removing the climax vegetation in the other biomes results in similar effects on albedo and evapotranspiration although restricted to the region [70]; (2) appropriating much of the nonforest biomes would severely reduce their biodiversity, which would violate the biosphere integrity boundary [45,73].

In order to maintain the functional diversity, Dinerstein and colleagues argue that at least half of each terrestrial biome needs to be intact [74]. We use this estimate and combine it with the original PB (see Table 1). Polar land and the rest of land (RoL) (i.e., mountain ranges, wetlands, etc.) are assumed not to be appropriable at all due to the fragility of the ecosystems and the geographical remoteness.

**Table 1.** Combination of planetary boundaries (PB) [9] and biodiversity conservation targets [74] to form a boundary for land system change across all biomes. Intervals are expressed in this paper in their mathematical form, i.e., $x = [x_{\min}, x_{\max})$ meaning $x_{\min} \leq x < x_{\max}$. This notation implies a level of confidence of the interval of $p = 1$.

| Biome | Appropriable Share of Land Area Biome | | | Appropriable Land Area $A_{\mathrm{appr}, p=0.98}/10^{12}\,\mathrm{m}^2$ |
| --- | --- | --- | --- | --- |
| | According to [74] | According to [9] | Combined | |
| tropical forest | 0.5 | $[0.15, 0.4]$ | $[0.15, 0.5]$ | $6.22 \pm 2.77$ |
| temporal forest | 0.5 | $[0.5, 0.8]$ | $[0.5, 0.8]$ | $11.1 \pm 2.51$ |
| boreal forest | 0.5 | $[0.15, 0.4]$ | $[0.15, 0.5]$ | $4.31 \pm 1.92$ |
| others (excl. polar and RoL) | 0.5 | ? | 0.5 | $36.6 \pm 0.18$ |
| sum | | | $[0.35, 0.48]$ | $60.1 \pm 9.24$ |

For the calculation, the appropriable land needs to be allocated to three land use types: cropland, pasture, and built environment. This can be done according to historic data or different scenarios [46,49,64,75–81]. For the purpose of this study, we used three exemplary scenarios: (1) *proportional:* Appropriable land is divided according to the relative share in the year 2000 [46,75–80]; (2) *reduce pasture:* The area of built environment and cropland is kept at the level of 2010 and pasture scaled to fit the PB [60], and in deserts, tge built environment is allowed to expand as it is considered not suitable for pasture expansion; (3) *maximize cropland:* Starting from scenario (2), cropland is maximized wherever possible at the cost of pasture to increase possible food supply for a growing population [52]. The scenarios are described in detail in Section 4 in the Supplementary Materials.

2.2.2.2. Freshwater Withdrawal

The annual global river runoff is $\dot{V}_{\mathrm{global}, p=0.68} = (1.46 \pm 0.14) \times 10^6\,\mathrm{m}^3/\mathrm{s}$ [71]. Annual variation is significant ($\frac{\dot{V}_{\mathrm{monthly}}}{\dot{V}_{\mathrm{global}}} = [0.31, 1.85]$ [82]); however, there are on average as many low as high flow months [82]. The PB specify the maximum monthly river withdrawal as:

$$\frac{\text{monthly withdrawal}}{\text{mean monthly river flow}} < \begin{cases} [0.25, 0.55] & \text{low flow months} \\ [0.30, 0.60] & \text{intermediate flow months} \\ [0.55, 0.85] & \text{high flow months} \end{cases}$$

As temporal and spatial variability is not considered in our global model, the boundary is approximated with the lowest and highest values, i.e., the total withdrawal needs to be smaller than 25% to 85% of the annual river runoff. This withdrawal from the rivers consists of two components, consumptive and temporal. The consumptive water use is further restricted by the PB framework to $[1.26, 1.90] \times 10^5\,\mathrm{m}^3/\mathrm{s}$ and, for example, used for irrigation in agriculture. The temporary withdrawal is released back into the river after use, for example, in a hydro power plant. Subtracting the consumptive withdrawal, we get a boundary for the temporary withdrawal of $\frac{\dot{V}_{\mathrm{withdrawal,temporary}}}{\dot{V}_{\mathrm{global}}} = [0.13, 0.75]$.

### 2.3. Indicators to Evaluate a Given Energy Mix against ATP

The pressure on each resource *i* can be calculated as the power used from each resource divided by the resource's ATP.

$$\tilde{\tau}_i \;=\; \frac{P_{\text{required},i}}{ATP_i} \tag{1}$$

The required power needs to be converted to electric energy equivalents by applying average energy conversion efficiencies between fuel and electric energy (see Table S3 in the Supplementary Materials). The indicator $\tilde{\tau}_i$ can be interpreted as the fraction of ATP necessary to provide the required power. A value of $\tilde{\tau}_i > 1$ means that more power is required from the resource *i* than is available in an ecologically sustainable way. High values of $\tilde{\tau}_i$ indicate a high pressure and vice versa. The indicator can also be calculated for required energy (e.g., to produce one product), resulting in a time necessary to provide the energy demand from the ATP $\tau_i = \frac{E_{\text{el},i}}{ATP_i}$.

Another useful indicator is the RE fraction *REF*, indicating how much of the total energy demand is provided from RE resources. It can be measured using the cumulative energy demand (CED) converted in electric energy equivalents $CED_{\text{el}}$ (see Supplementary Materials). An $REF = 1$ indicates a purely RE mix, whereas $REF = 0$ corresponds with a purely non-RE mix.

$$REF = \frac{\sum_{i=1}^{n_{\text{RE}}} E_{\text{el},i}}{CED_{\text{el}}} \tag{2}$$

An optimal use of all RE resources is achieved when the actual energy mix is the same as the potential energy mix. The RE index *REI* is comparing the energy mix in a product to the potential RE mix. The comparison is based on the Bravais–Pearson correlation coefficient, which measures the correlation between two datasets. In the case of *REI*, one data set is the actual energy mix from renewable resources, the other the ATP mix. The absolute of the co-variance index is multiplied with *REF* to include the effect of renewable vs. non-RE used.

$$REI \;=\; REF \cdot \left| \frac{\sum_{i=1}^{n_{\text{RE}}}(\alpha_i - \overline{\alpha})(\beta_i - \overline{\beta})}{\sqrt{\sum_{i=1}^{n_{\text{RE}}}(\alpha_i - \overline{\alpha})^2 \sum_{i=1}^{n_{\text{RE}}}(\beta_i - \overline{\beta})^2}} \right| \quad \in (0,1] \tag{3}$$

$$\alpha_i = \frac{E_{\text{el},i}}{CED_{\text{el}}} \qquad \beta_i = \frac{ATP_i}{\sum_i ATP_i}$$

The index has a value of $REI = 1$ if the energy mix equals exactly the potential RE mix. For a fully non-RE mix ($REF = 0$), *REI* is not defined, as the denominator becomes zero. The lower the value of *REI*, the less correlated the energy mix is with the potential mix, and thus, the less well it is utilized.

These indicators can be applied at different levels, from products and services to a global scale. Uncertainty distributions can be included in the calculation (performing a Monte Carlo simulation). Alternatively, 99% confidence values can be used for the calculation. Depending on data availability, the RE potentials can be aggregated (e.g., *solar on desert* and *solar on infrastructure* can be aggregated to *solar*).

## 3. Results

We tested the introduced method with data from the literature. In Figure 2, we follow the low-entropy energy fluxes from their point of entry into the Earth system to the point where their exergy is consumed. From the incoming solar energy flux from space ($1.7 \times 10^{17}$ W, i.e., 100%), an ATP of $7.1 \times 10^{13}$ W (or 0.04%) can be harvested without violating land system change or water withdrawal boundaries with a confidence of 99% (see Table 2). In other words, 99.96% of the theoretical potential is essential to maintain Earth system stability or provide chemical energy or is lost in technical conversion.
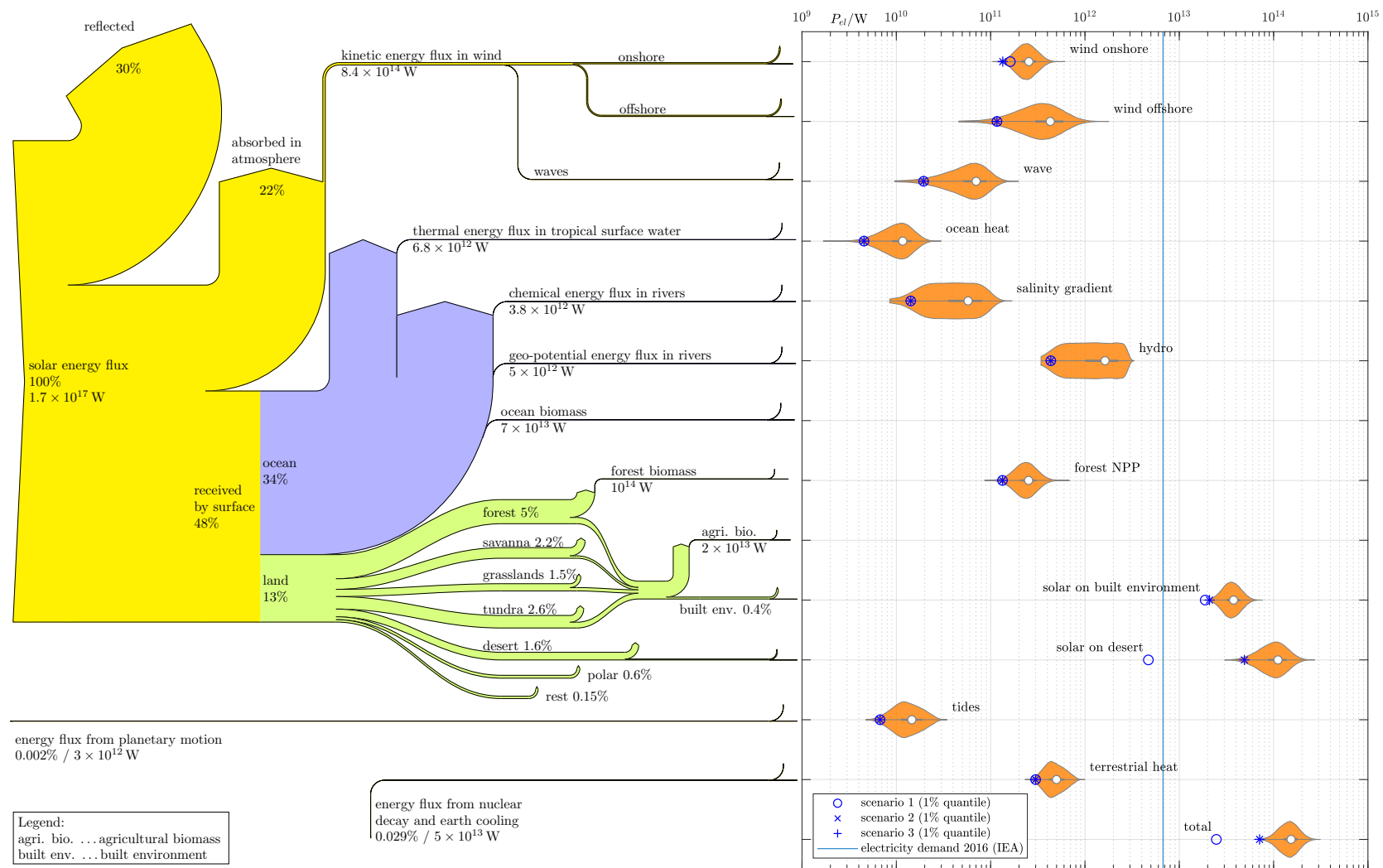
**Figure 2.** Sankey diagram of renewable energy (RE) flows from incoming energy flux to appropriable technical potential (ATP) with the limits (1% quantile) for the three land use scenarios (see Section 2.2.2.1).

Since losses are minimal when solar irradiance is directly converted to electric energy, the lion's share of RE can be provided through direct solar energy conversion on the built environment and desert surfaces. Hydro power is the second largest ATP, as geopotential energy in rivers can be converted into electric energy very efficiently. It is, nevertheless, two orders of magnitude smaller than the ATP from solar. Terrestrial heat also has a significant ATP similar to on- and offshore wind and forest NPP. Waves and the salinity gradient have ATPs that are three orders of magnitude smaller than solar. ATP from ocean temperature gradients and tides are four orders of magnitude smaller and at best of local importance. Moreover, there are no state-of-the-art technologies available to utilize the gradients of ocean temperature and salinity. However the analysis with prospective technologies shows that they can, at best, contribute very little to the overall ATP.

The chosen land use scenarios have little influence on the results, except for solar in desert. In scenario 1, the built environment in deserts is allocated according to its share in the year 2000, which is small. Scenarios 2 and 3 allow built environment to significantly expand in the deserts, which explains the difference. For the rest of this paper, results from scenario 3 are used.

**Table 2.** ATP results for scenario 3 (maximize cropland) with a confidence of $p = 0.99$ for the various RE resources and the resulting electric energy mix. The appearance in the table corresponds to Figure 2. Resources marked with * are based on prospective technologies.

| RE Resource | Technology | Appropriable Technical Potential ATP/TW | Energy Mix |
|---|---|---|---|
| wind onshore | wind turbine | 0.13 | 0.19% |
| wind offshore | wind turbine | 0.12 | 0.16% |
| wave | WEC | 0.019 | 0.03% |
| ocean temperature gradient * | OTEC | 0.0045 | 0.01% |
| salinity gradient * | forward osmosis | 0.014 | 0.02% |
| freshwater runoff | hydro turbine | 0.43 | 0.61% |
| ocean NPP | combustion | 0 | 0.% |
| forest NPP | combustion | 0.14 | 0.19% |
| agricultural NPP | combustion | 0 | 0% |
| solar on built environment | PV | 21 | 29.43% |
| solar on desert | PV / CSP | 49 | 68.94% |
| tides | hydro turbine | 0.0067 | 0.01% |
| terrestrial heat | geothermal power | 0.30 | 0.42% |
| total | | 71 | 100.% |

## 4. Discussion and Conclusion

### 4.1. Comparison to Current Energy Demand

The total RE potential is about an order of magnitude larger than the current energy demand $P_{el,2016} = 6.72 \times 10^{12}$ W (data from [6] converted to electric energy equivalents), so there is room for a substantial increase. While demand was not assessed in this study, we expect that vast amounts of energy will be necessary:

- to supply the still growing population with adequate energy;
- to balance the unevenly distributed RE in space and time; and
- to enable the massive restoration and mitigation efforts required to unwind past environmental impacts (e.g., $CO_2$ DAC).

Therefore, this increase will not solely be available to improve circularity. Dividing ATP by the expected world's population ($N_{p=0.95} = (10.87^{+1.79}_{-1.45}) \times 10^9$ in 2100 [52]) results in 7760 W average power potential per capita (99% confidence), or in 2300 W when ATP of solar in deserts is not used. The average power supplied in 2016 was approximately 900 W per capita. Thus, the energy demand could increase up to the guidance value of the 2000 W-society [83] without appropriating deserts.

However, raising the energy demand worldwide to, e.g., the Swiss average of 5000 W per capita in 2016 [83] would require development of solar in deserts.

When comparing the ecological potentials to the current electric energy production for each RE resource (red squares in Figure 3), biomass use is already beyond the ecologically safe limit ($\tilde{\tau}_{\text{biomass}} = 4$, see Section 2.3). This is explainable through the wide usage of charcoal and wood for cooking and low temperature heat production [6,19]. According to our findings, this usage cannot be considered environmentally sustainable. Current hydro power is close to its ATP ($\tilde{\tau}_{\text{hydro}} = 0.96$), which is reasonable considering the number of large-scale hydro installations. Consequently, there is no (significant) development potential for large-scale hydro power. All other RE resources are significantly underdeveloped today, especially direct solar energy conversion ($\tilde{\tau}_{\text{solar}} = 0.0002$). As a consequence, the total current RE usage can and needs to be increased substantially, placing the primary focus for development on solar energy conversion on the built environment and secondly on deserts, as this is the largest, though technically more challenging potential.
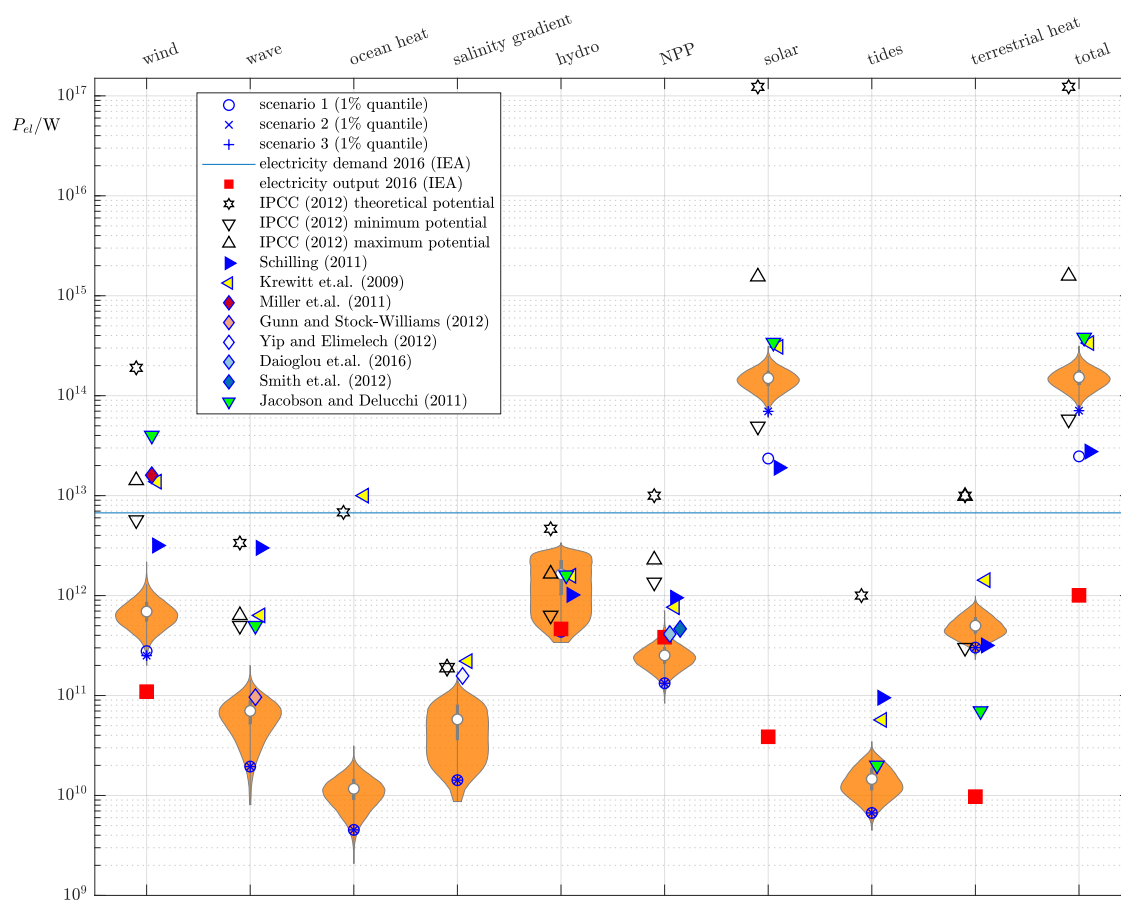


**Figure 3.** Comparison of ATP to other estimates: IEA [6], IPCC [19], Schilling [21], Krewitt et.al. [20], Miller et.al. [22], Gunn and Stock-Williams [84], Yip and Elimelech [85], Daioglou et.al. [67], Smith et.al. [66], and Jacobson and Delucchi [12].

In 2016, renewable resources were utilized to $\tilde{\tau}_{\text{RE,global,2016}} = 0.015$ globally, meaning there is a potential to increase RE provision by a factor of 66. The global energy mix of 2016 has $REF_{\text{global,2016}} = 0.22$. Despite the relatively high REF, the RE index is $REI_{\text{global,2016}} = 0.04$. This is mainly due to the fact that the current renewable fraction is dominated by hydro and biomass [6], whereas the potential mix is dominated by solar.

### 4.2. Comparison with Other Studies

In Figure 3, we compare the ATPs calculated with our method to values from ten studies that mostly report on technical potentials [6,12,19–22,66,67,84,85]. As expected, our results are generally lower than the technical potentials from other studies, as we include environmental sustainability criteria as well as the chemical energy demand described above. One exception to this trend is solar, as other studies find smaller technical potentials than the ATP estimated in this study. This is due to differences in land area considered for solar energy conversion (e.g., including/excluding deserts). Another is terrestrial heat, where one study indicates a much lower technical potential [12]. At the same time, we see that wind power is overestimated in these studies compared to our study. This is due to the area requirement, both on land and offshore. Wave power is similarly overestimated, except in one study [84], which specifically estimates wave power resource potentials and lies within the uncertainty range of our results. Ocean thermal energy conversion is only included in two of the studies; one quoting the theoretical potential, the other a technical potential which is, however, higher than the theoretical potential indicated in the other study. The potential for forward osmosis is estimated on the upper end of the uncertainty range of our study. The potential estimates for hydro power spread throughout the uncertainty range of our results. For biomass, other studies offer more optimistic potentials than our model, except one that specifically focuses on residues only [67] and another one that is constrained by biological reproduction rates [66]. While tide power is again overestimated, geothermal power corresponds to our results. In summary, it could be concluded that our results are either more restrictive or lie within the results from the compared studies; hence, the comparison confirms that our method provides precautionary estimates.

### 4.3. Limitations and Further Developments

The results presented in Section 3 are preliminary in nature since they are produced from literature data combined with, whenever necessary, estimates, which are based on conservative assumptions. Uncertainty in data and assumptions are included over their entire range that could be judged reasonable. We acknowledge that this judgment is subjective and restricted to the selected data sources. Refined and policy relevant results could be obtained with more data, more detailed models and experts' knowledge in the respective fields of energy options. For this purpose, all calculation sheets and Matlab code files are made available in the Supplementary Materials.

Currently, the model does not consider spatial and temporal variations. The resulting ATPs are therefore global and not necessarily representative for specific locations (e.g., Norway) or season (e.g., winter). To extend the method for such a regionalized and time-explicit assessment, more detailed data and models will be necessary as well as the integration of distribution network and energy storage options to level out possible variations.

The precautionary approach applied necessitates the use of a cut off criterion, or level of confidence for the results. We have chosen a level of confidence of 99%, i.e., 99% of plausible potentials are above the boundary set for each resource. This choice is normative, as it reflects the confidence in the viability of a system that we as a society require. Our proposed value is to be seen as a starting point for a public and political debate [86].

Furthermore, the assessment method does not take into account the environmental impacts caused by production, installation, and decommissioning of the necessary technologies. Developing the ATP with current technology may actually not respect other Earth system boundaries (e.g., biodiversity). Life cycles impact assessments for state-of-the-art technologies could be added to the current method to offer a broader perspective. Such life cycle assessments could also help to understand if there are enough natural resources to build the necessary technologies and infrastructures to harvest the full ATP, especially from solar energy [87,88]. Likewise, our method assesses neither societal nor economic costs for building and operating the necessary infrastructure.

*4.4. Relevance to the Circular Economy*

Taking the initial results as input for a global CE, we find that the total ATP is large enough to fulfill the energy demand of a growing population and still leaves some room to increase the energy intensity of a CE, e.g., to increase recycling of technical materials. However, the ATPs are not evenly spread among different resources and geographic regions. When designing circular systems, products and solutions, the energy mix, as well as its magnitude, can—to a certain extent—be defined. It is preferable to demand more energy from a large ATP and vice versa. For example, buildings cause a high demand for energy (i.e., heating/cooling and electric energy) and can at the same time be designed as power plants (i.e., building integrated energy systems). As the largest ATP is solar energy on the built environment and deserts, it would be ideal to power the entire life cycle of the building with solar energy harvested on its envelope. Energy for construction, refurbishment, and deconstruction cannot be reduced to zero but can be compensated by a net surplus energy supplied by the building during its service life. Hence, such a building uses the largest ATP and scores high on the RE index ($REI = 0.99998$ with $REF = 1$). On the other hand, powering the same building with biomass, i.e., using a renewable resource that is much more limited in the global mix, reduces the index to $REI = 0.125$ with $REF = 1$. In addition to the proper selection of the RE resources, this approach also provides incentives to reduce and actively manage energy demand, another aspect of the building's design (e.g., heat storage, passive cooling) to optimally use the daily and seasonally changing availability of RE resources and reduce the demand for storage capacities.

For many products, the use phase energy mix cannot be influenced by the product design. For example, the electric energy mix of a washing machine depends on the building and the choices of the operator rather than the design of the machine. Aside from energy efficiency in the use phase, only the energy mix for production and distribution can be influenced and designed by the washing machine's manufacturer. Powering a manufacturing facility with rooftop photovoltaic (PV) might then give economic incentives to plan energy-intensive processes during peak sun hours.

Beyond product and service design, the proposed method can be used, amongst others, to evaluate scenarios for nations and society as a whole. Questions such as "can the current food waste be a significant RE resource?" or "how would an improved conversion technology increase ATP?" could be addressed. Furthermore, the method, refined with additional data and robust assumptions, could inform policy relevant questions for a transition towards a sustainable CE by exploring questions like "what are priority RE resource for investments?" or "what maximum levels of circularity are achievable with the appropriable RE?"

**Abbreviations**

The following abbreviations are used in this manuscript:

| | |
|---|---|
| ATP | Appropriable technical potential |
| BECCS | Bioenergy carbon capture and storage |
| CCS | Carbon capture and storage |
| CE | Circular economy |
| CSP | Concentrated solar power |
| DAC | Direct air capture |
| EoL | End of life |
| FO | Forward osmosis |
| GIS | Geographical information system |
| HANPP | Human appropriation of net primary production |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life cycle assessment |
| NPP | Net primary production |
| PB | Planetary Boundaries |
| PV | Photovoltaic |
| RE | Renewable energy |
| RoL | Rest of land |

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