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To Zulaa,
Markus and Julius

ABSTRACT

Products and services are at the heart of the economy, satisfying needs and desires of a growing and more prosperous humankind on the one hand, but their excessive consumption is destabilising the Earth system on the other. Acknowledging that the Earth is our life support system, an awareness is rising globally calling for a fundamental change in the way we live, consume and treat planet Earth, our common home.

Circular economy is hoped to bring this change towards a truly sustainable economic system. Closing material cycles, as nature shows us, is perceived as the vehicle to make humanity independent of the restrictions and environmental consequences of primary resources, enabling continuous economic growth. However, can such an idealised concept be implemented in practice? It is the motivation for this thesis to investigate the conditions a circular economy has to fulfil in order to be sustainable and to translate these insights into guidance for product and service design.

To bring circular economy and sustainability together, a conceptual framework is developed. The environment is seen therein as the un-negotiable and irreplaceable frame for all human activities. Within these boundaries, a limited amount of materials and energy can be appropriated without disturbing the integrity and functioning of the Earth system beyond its safe limits. Since the carrying capacity of the Earth and environmental impacts of societal activities are uncertain, the framework calls for a precautionary approach, that is to ensure system viability with high confidence. The highest utility from the sustainable resource base can be obtained for society, if it is used as intensively as possible within the socio-economic system. This can be achieved by designing slow as well as small material cycles and – most importantly – by minimizing the entropy produced in the socio-economic system.

Driving sustainable material cycles requires clean energy, which is a limited resource on our limited planet. In order to estimate, how much renewable energy can be safely appropriated from the Earth system without compromising ecosystems and food supply, the *appropriable technical potential* (ATP) method is presented. The method provides estimates of renewable energy potentials that can be made available to power a sustainable circular economy with a chosen high confidence. Global ATP with 99 % confidence is ten times larger than energy demand in 2016, suggesting that there is

enough energy available to increase energy access for a growing population and to power increasingly closed – and therefore potentially more energy intensive – material cycles. However, the global ATP is provided to 98 % from solar energy, requiring the circular economy to be powered almost exclusively by the sun.

Material cycles can not be fully closed in practice, due to inevitable losses. Therefore, sustainable raw material extraction and safe final sinks are necessary parts for a circular economy. The *ecological resource availability* (ERA) method aims at answering the question of how much primary materials can be made available as input to sustainable material cycles, without crossing vital Earth system boundaries. In this way, environmental boundary conditions can be translated into resource budgets. The method can serve as a scenario tool, modelling the effect of different allocation procedures, technological advances and substitutions (e. g. renewable instead of fossil plastics) on the sustainable resource base. First results are presented for metals with a grandfathering approach and 99 % confidence. The sustainable production of metals is thereby 40 times smaller than the production in 2016, when the socio-economic system is rescaled equally to fit within Earth system boundaries.

The design of products and services is essential to define their subsequent environmental performance. It is therefore important to guide designers to make most use out of the limited sustainable resource base. The *resource pressure* method aims to offer decision support for this challenge, both in qualitative guidelines and a quantitative indicator. Pressure on primary resources is exerted by the product system twofold: directly thorough the intake of primary materials and indirectly through the generation of final losses, which can no longer be used elsewhere in the socio-economic system. Therefore, the resource pressure method aims at identifying and quantifying the circular strategies reducing the pressure on primary inputs as well as final losses most effectively.

In conclusion, a sustainable circular economy needs to build on the sustainable resource base and aim at making best use of these limited resources. This thesis provides methods to both estimate the sustainable resource base as well as guide towards a higher utilisation in products and services.

ZUSAMMENFASSUNG

Produkte und Dienstleistungen sind die Basis unserer Wirtschaft. Einerseits befriedigen sie die Bedürfnisse und Wünsche der stetig wachsenden und wohlhabenderen Menschheit, andererseits führt jedoch ihr exzessiver Konsum zur Destabilisierung des Erdsystems. In Anbetracht der drohenden Zerstörung unseres Lebenserhaltungssystems steigt das Bewusstsein weltweit, dass wir unsere Lebensweise, unser Konsumverhalten und unseren Umgang mit unserer gemeinsamen Heimat Erde fundamental ändern müssen.

Die Kreislaufwirtschaft ist ein Hoffnungsträger für einen solchen Wandel zu einem nachhaltigen Wirtschaftssystem. Geschlossene Materialkreisläufe, wie uns die Natur es vormacht, sollen uns von den endlichen Ressourcen und den Umweltauswirkungen, die bei deren Nutzbarmachung entstehen, unabhängig machen, was wiederum unbeschränktes wirtschaftliches Wachstum erlauben soll. Das wirft jedoch die Frage auf, ob so ein idealisiertes Konzept auch tatsächlich in der Realität umgesetzt werden kann. Die Untersuchung der Bedingungen, die eine Kreislaufwirtschaft erfüllen muss um nachhaltig sein zu können, ist die Motivation für diese Doktorarbeit. Darüber hinaus gehe ich der Frage nach, wie man dieses Wissen für die Gestaltung von Produkten und Dienstleistungen verwenden kann.

Im ersten Schritt wird ein konzeptioneller Rahmen entwickelt, um die Kreislaufwirtschaft und Nachhaltigkeit zusammen zu bringen. Die Umwelt wird darin als nicht verhandelbarer und unersetzbarer Rahmen für alle menschlichen Aktivitäten gesehen. Innerhalb dieser Grenzen kann ein beschränktes Maß an Materialen und Energie für die Menschheit nutzbar gemacht werden, ohne die Integrität und funktionale Einheit des Erdsystems fundamental zu stören. Aufgrund der zum Teil großen Unsicherheiten in der Bestimmung der Belastungsgrenzen der Erde sowie die Umweltauswirkungen menschlicher Aktivitäten, soll ein nachhaltiges sozioökonomisches System auf dem Vorsorgeprinzip aufbauen, d.h. die Überlebensfähigkeit des Systems muss mit hoher Vertrauenswahrscheinlichkeit sichergestellt sein. Der höchste Nutzen aus der nachhaltigen Ressourcenbasis kann für die Gesellschaft dann erreicht werden, wenn die Ressourcen so intensiv wie möglich im sozioökonomischen System genutzt werden. Dies kann durch langsame sowie kleine Materialkreisläufe und vor allem durch die Minimierung der dabei entstehenden Entropie erreicht werden.

Der Antrieb nachhaltiger Materialkreisläufe benötigt saubere Energie, eine limitierte Ressource auf unserem limitierten Planeten. Die Methode des *aneigenbaren technischen Potentials* (ATP) erlaubt es abzuschätzen wie viel erneuerbare Energie sicher aus dem Erdsystem entnommen werden kann, ohne dabei das Ökosystem oder die Lebensmittelversorgung zu beeinträchtigen. Die Potentiale werden dabei mit einer wählbaren, hohen Vertrauenswahrscheinlichkeit berechnet. Das globale ATP mit 99 % Vertrauenswahrscheinlichkeit ist zehnmal so groß wie der Energiebedarf im Jahr 2016. Daher scheint es möglich den Zugang zu Energie für eine weiterhin wachsende Erdbevölkerung zu erhöhen und gleichzeitig zunehmend geschlossene und damit potentiell energieintensive Materialkreisläufe anzutreiben. Allerdings besteht das globale ATP zu 98 % aus Solarenergie, weshalb die nachhaltige Kreislaufwirtschaft fast ausschließlich von der Sonne angetrieben werden muss.

Aufgrund von unvermeidbaren Verlusten lassen sich Materialkreisläufe nicht vollkommen schließen. Die nachhaltige Extraktion und sichere Endlager sind daher notwendige Bestandteile einer Kreislaufwirtschaft. Die Methode der *ökologischen Verfügbarkeit (ecological resource availability, ERA)* erlaubt die Bestimmung der Jahresproduktion für Primärressourcen, welche ohne die Überschreitung von kritischen Erdsystemgrenzen möglich ist. Auf diese Weise werden Erdsystemgrenzen in Ressourcenbudgets übersetzt. Die Methode ist ein Werkzeug um den Effekt von verschiedenen Zuteilungsmechanismen, technologischen Entwicklungen und Substitutionen (z.B. erneuerbares anstelle von fossilem Plastik) in den jeweiligen Szenarien zu beurteilen. Erste Ergebnisse unter Annahme heutiger Technologie, Zuteilung nach dem Bestandsschutz-Prinzip und einer Vertrauenswahrscheinlichkeit von 99 % ergeben, dass die nachhaltige Produktion von Metallen 40-mal kleiner sein müsste als im Jahr 2016. Dies würde gelten, wollte man das heutige sozioökonomische System gleichmäßig so skalieren, dass es innerhalb der Erdsystemgrenzen möglich wäre.

Das Design von Produkten und Dienstleistungen ist für die Definition der späteren Umweltauswirkungen maßgeblich. Daher ist es entscheidend die Designentscheidungen dahingehend zu lenken die beschränkte nachhaltige Ressourcenbasis möglichst optimal zu nutzen. Die *Ressourcendruck*methode schlägt sowohl qualitative Richtlinien sowie einen quantitativen Indikator als Hilfestellung für diese Herausforderung vor. Ein Produktsystem übt dabei auf zweierlei Art Druck auf Primärressourcen aus: direkt durch die Verwendung der Primärressource und indirekt durch die Erzeugung von finale Verlusten, welche nicht weiter für die Verwendung im sozioökonomischen System zu Verfügung stehen. Aus diesem Grund identifiziert und quantifiziert die Ressourcendruckmethode zirkuläre Strategien, welche effektiv den Primärinput und die finalen Verluste reduzieren.

Eine nachhaltige Kreislaufwirtschaft baut daher auf der nachhaltigen Ressourcenbasis auf und zielt darauf ab, die beschränkten Ressourcen bestmöglich zu nutzen. Diese Doktorarbeit stellt Methoden dafür zu Verfügung, die sowohl die Abschätzung der nachhaltigen Ressourcenbasis erlauben als auch Richtlinien für die Nutzung der Ressourcen in Produkten und Dienstleistungen formulieren.

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CONTENTS

1

INTRODUCTION

Be the change you wish to see in the world.
— Arleen Lorrance

Circular economy (CE) is a buzzword, frequently used among business leaders, policy makers and academia. It spreads the hope that an industrial society is possible without the major environmental problems caused by the current "linear economy" by building a perpetual mobile for material cycles [1].

This introductory reflection of CE already raises many questions, such as: What is actually possible considering physical limitations? Would it really free society of its environmental burdens? And if so, how can this be achieved?

1.1 MOTIVATION

Life is an ongoing experiment by nature, running since several billion years. It is continuously inventing and testing a huge variety of different designs and is selecting the ones best fit for life on Earth. The results of this ongoing optimisation are almost perfectly closed material cycles. Natural organisms have evolved over millions of years and perfected a complex interplay of exchanging nutrients and energy in ecosystems [2]. All parts in the ecosystem are built according to very similar blueprints [3], however, resulting in the great diversity of life. From a material view, almost nothing goes to waste because every organism is built of the same (limited) set of elements (i.e. mainly C, O, H, N, P and trace elements such as Fe or Mg). These elements can be re-utilized by a myriad of different organisms in a decentralized way. The energy driving these nutrient cycles comes almost exclusively from the sun[1], either directly through photosynthesis or indirectly through burning organic compounds (mostly sugar) that had been previously built up by photosynthesis.

Natural material cycles (see figure 1.1) are thereby not closed from the perspective of one individual organism. An algae, for example, will most

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[1] There are very few organisms which utilize geothermal energy at deep sea hot smokers.

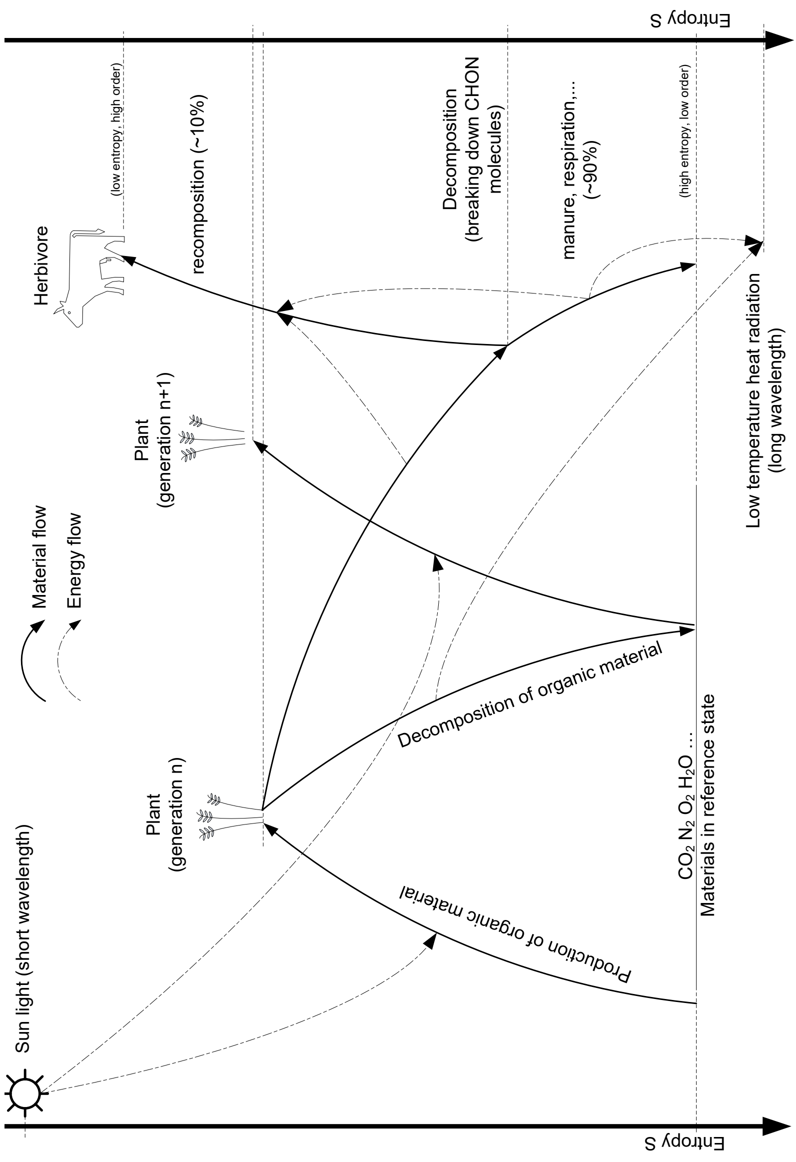

FIGURE 1.1: Conceptualisation of natural material cycles as a function of entropy.

likely not become an algae again after it dies, but its elements will make up many different organisms (e. g. fish). From a global mass balance perspective, however, the algae is build from the same elements, though as it evolves, may require a little different amounts and lead to slightly different combinations. The natural material cycle describes therefore rather a change in the elements' state from their basic form of appearance (also called reference state [4], e. g. carbon as CO_2) with high entropy into biomolecules arranged in a specific way in a cell (low entropy). The reduction of entropy is powered by solar energy. Decomposition of organic materials back into their basic form increases entropy and releases low temperature heat. Elements are stored in their reference state in reservoirs of biologically available but inactive mass (e. g. CO_2 in atmosphere) that is vastly larger than the active and circulating mass [5].

Technical systems are, in contrast, built on very different design principles. Natural resources are extracted from the environment, transformed into useful products, which are replicated millionfold and thrown away after use, too often even prematurely. The socio-economic metabolism relies heavily on a few key technologies (e. g. silicon chips for computing, telecommunications, controls, . . . ; or fossil heat engines for mobility), rendering it vulnerable to disruption in regard to these technologies (e. g. political instabilities in countries where key materials are extracted or the climate crisis). The industrial engine is running predominantly on fossil fuels to extract elements across the periodic table [6] and put them into products. Since the industrial revolution, the stockpile of materials in the technosphere is continuously growing [7]. Even though there is a time lag between the time when a material is put into the socio-economic metabolism and when it becomes an output, the system is largely unable to extract the elements back again from end-of-life products. As a result, the industrial metabolism is able to circulate only less than 10 % [8, 9][2], whereas in ecosystems close to 100 % of materials are kept in the loop. The human appetite for consuming resources puts the whole planet at stake through massive destruction of natural ecosystems [10, 11], depletion of resources [12, 13] as well as pollution and deterioration of our life support system [14–16]. Man has become, in fact, a driving force in the Earth system [17, 18].

So, what is a viable strategy to design sustainable and circular products, avoiding the negative consequences of the current technical system yet still providing for needs of human civilisations? Can the circle of life serve as a

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[2] This value, however, includes biological nutrients that are composted, recovered from waste water treatment and biogasification. The cycling of technical materials is even much lower.

blueprint for product life cycles? Table 1.1 provides a non-exhaustive list of differences between natural and current technical design principles.

It may suggest that the solution lies in imitating nature (i.e. biomimicry [19]) or in making technical artefacts "edible", i. e. being digestible by the socio-economic metabolism in order that the materials remain available in the system, as suggested by cradle-to-cradle^{TM} design [20]. It leads further to the widespread perception, that everything based on biological materials is *per se* circular and sustainable (e. g. biobased plastics). For example, the "butterfly" diagram depicting the circular economy in the eyes of the Ellen MacArthur foundation [21] distinguishes between biological and technical nutrients. Cycling of biological nutrients is suggested to be outsourced as a free service to the biosphere and seemingly doesn't require technical intervention or care by society. However, this is likely not the case, as technical applications of biological materials change its availability in the food chain. For example, consider the difference of wood in a fallen tree in the forest and in furniture. Technical processes and societal requirements lead to modifications that render bio based materials into technical waste (e. g. surface finishing on furniture, ink on paper,. . .).

Furthermore, the biosphere shall not be misunderstood as a production facility for human needs; biological organisms are existing in their own right and not for the purpose of utilization by humanity [22]. As humans, we ourselves are a part of the biosphere. However, we have become a dominant force across all domains of life (e. g. crops, livestock, fisheries) [11, 18, 23], which puts us in a precarious situation. On the one hand, we are dependent on biomass for food [24, 25] and increasingly non-food use (e. g. agrofuels, bio-based materials) [26] as well as for recreation and health [27, 28]; on the other hand, we are eroding the resilience and functionality of natural ecosystems (e. g. loss of habitat [29–33], biodiversity [10], soil quality [34]). Thus shifting material use from technical to biological materials and letting nature do the job of closing material cycles is not necessarily sustainable. On the contrary, there is reasonable doubt that it can be sustainable at scale.

To my experience in industry, product design and engineering is centred around the development of technology to fit the requirements of the customer. This has to be achieved under the constraints of time and money. Everything else was left to personal motivation and frequently rejected when in conflict with the previously mentioned objectives. During my time in development cooperation, I realized how important and in fact unavoidable it is, to change the way we make things fundamentally for both environmental and social reasons. This brought me to the question of how

Nature's design principles	**Technical design principles**
Built on a limited number of elements (C,H,O,N,P,...) that are used in all organisms	Using the majority of elements in the periodic table and different ones for different devices (e.g. a smartphone uses very different elements than a bicycle)
Infinite combinations (consider the difference between a tree and a whale, still they are built with (almost) the same elements)	Standardized technologies (e.g. internal combustion engine)
Nutrient cycles: elements and compounds are passed through many organisms until they are becoming available at the same trophic level again	Linear flow of resources from extraction through utilization back into the environment as degraded waste
Powered by the sun: all energy driving biological organisms (with very few exceptions) comes from the sun into the food chain	Powered mainly by fossil energy
Diversity: every individual is different	Uniformity: products of a kind as exact duplicates
Distributed	Centralised
Self-reproducing	Produced in a complex and purpose-built machinery
Self-repairing/healing	If repair is at all possible, needs special external infrastructure.
Existence of every organism in its own right	Existence of technical artefacts purpose related
Every organism has a will	Every artefact has a purpose / utility

TABLE 1.1: Comparison between natural and technical design principles

to design sustainability into technical systems. Applying circular strategies can contribute to achieving this goal, however, it is not necessarily sufficient. The question is therefore to find out when and to what scale circularity is sustainable.

Through this thesis, I am trying to find answers for these questions. The aim of my thesis is to relate global environmental boundary conditions to restrictions for the economy and provide guidance to product and service design that takes these restrictions into account.

1.2 BACKGROUND

Circular Economy (CE) recently gained popularity in policy and business circles [35, 36], even though at the same time there is no consent on what CE actually means and encompasses [37, 38]. The underlying idea is to close material cycles and become independent from primary raw materials (i.e. economic benefit) as well as avoid the associated environmental repercussions (i.e. environmental benefit) (see e. g. [21, 39–45]). This idea continues the schools of thought of *clean technology* [46, 47], *industrial ecology* [41, 48, 49], *performance economy* [50–52], *bio-mimicry* [19] or *industrial symbiosis* [53] under a new heading [54, 55]. But it also expands beyond material and environmental concerns by including business models [56–59] and legislation [36, 60] as crucial aspects for the successful implementation of CE. This, in turn, leads to the hope of continuous economic growth at simultaneously decreasing material and environmental footprints [61].

Despite its motivation in the current economic logic, the question is, whether a CE can grow, needs to be in a steady state [62] or even has to shrink [63, 64] in order to reduce the environmental pressure to what the Earth system can tolerate in the long run. So far, CE is mostly investigated for bottom-up initiatives (e. g. business models, products or supply chains). The promoted strategies of material cycling don't necessarily lead to a net environmental benefit [65–67] as closing material cycles alone doesn't touch the question of how large and fast such cycles can be to be sustainable [1, 68]. E. g. Grosse [65] argues that in an economy where resource use is growing by more than 1% per year, the positive effects of recycling on resource depletion are negligible. CE is seen as an enabler to economic growth [61], but in order to result in an absolute decoupling of resource use from GDP growth [62], the growth would need to be linked to observed resource efficiency improvements [69]. As shown by Zink and Geyer [67], it is commonly assumed when promoting CE that cycled material will replace

1:1 primary production, neglecting the dynamics of raw material, second hand or repair markets and stakeholder behaviour, which can eventually lead to a rebound effect [67, 70, 71]. What has not been explored is a top-down approach to CE, identifying necessary conditions for when a CE is also sustainable and connect the bottom-up initiatives with the top-down perspective.

To identify such conditions for environmental sustainability, an absolute benchmark (sometimes also called "context") is necessary [72]. Throughout the past century, the human society has become a driving force in the Earth system [17, 18, 23, 73], with the potential of shifting the Earth system to new and less hospitable states [74]. Avoiding such a shift requires to limit the human pressure on critical Earth systems to their carrying capacities, which is termed in this thesis Earth system boundaries (ESB). Several proposals exist in literature to identify and quantify these limits [75]. Two prominent examples are the ecological footprint [76], which compares the required area for regeneration to the total surface area of the planet, and the planetary boundaries (PB) framework [77–79]. The latter is a set of nine boundary categories[3], each of them with one or more indicators and respective boundary values. Specific boundaries had been formulated in more detail by other authors (e. g. land [29, 30, 80] or freshwater [12, 81–84]) and others are contested (e. g. biodiversity [85]). Even though it has to be refined, it nevertheless is already useful (and used) for policy guidance (e. g. analysing Swiss consumption footprint [86]), analysing a country's or region's environmental performance [87–92] and modelling scenarios of how to achieve the sustainable development goals within PB [93, 94]. Achieving such a society within ESB requires transformational change [95]. The CE can be seen as a vehicle for such a transformation when in combination with other measures, e. g. demand reduction [96, 97]. In order to evaluate societal activities in regard to the PB, several PB impact assessment methods have been proposed for LCA [98–109]. Besides the aforementioned examples, there are also proposals for limits to specific indicators. For example, Dinerstein and colleagues [33] propose that "nature needs half" of the area of each biome to guarantee the biome's integrity and provision of ecosystem services; or that the human appropriation of net primary production [11, 110, 111] does not cross a certain value [112].

In theory, materials can be cycled indefinitely given that infinite exergy is available and hibernating stocks are large [5]. In reality, closing material

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[3] I.e.: climate change, biodiversity integrity, landsystem change, freshwater use, biogeochemical flows, ocean accidification, atmospheric aerosol loading, stratospheric ozone depletion, novel entities.

cycles is subject to physical limitations [5, 35, 45, 113], degradation and unavoidable losses [114–120], which makes it practically impossible to neither become totally independent from primary production nor avoiding losses to the environment. A sustainable CE would thus need to include sustainable raw material extraction [40] and safe final sinks [121]. The pressure on ESB is caused by the use of energy and resources (incl. food and fuels) in society to a significant extent [122]. In order to remain within ESB, material and energy flows have to be limited based on their environmental consequences. In literature, however, limitations to resource use are discussed mainly in regard to other factors. Studies on the potentials for renewable energies (RE), for example, mostly focus on theoretical [123–125] or technical potentials [126–130], disregarding competing land use [131], soil quality preservation [34, 132] or the material demand to build the necessary infrastructure [133, 134]. As a result, these potentials are often too optimistic. Other studies, in contrast, estimate economic potentials (e. g. [135, 136]), which can be realized under current or future economic and societal constraints. Such studies tend to underestimate the sustainable potential. Similarly, restrictions to the availability of primary materials are commonly defined through physical, political, economic or societal reasons [137–142], but not due to environmental repercussions. What is needed, is therefore a method to evaluate the availability of primary materials and energy within ESB as an input to be utilized in the CE.

Many studies deal with the material cycling either at the level of material flow in society or waste management of products and product groups. Material flow analysis of the current socio-economic metabolism show the gap for closing material cycles ("circularity gap" [8, 9, 143]). For materials with a well established recycling system (e. g. Al [144–146], Cu [147], steel [148]), this gap can be explained as resulting from growing in-use stocks [7]. For other materials the gap is even larger, due to lacking recycling performance in addition (e. g. plastic [119, 149], critical raw materials [150]). Materials are often not recycled for the same function but cascade towards lower quality applications [151–153]. The quality that can be achieved as an output of the recycling process, depends – among many factors – on the material combination at the input to recycling [154] and the thermodynamics of the processes themselves [154–160]. Whether or not cascading is counted as recycling and on what level the recycling rate is measured (e. g. input, intermediate or output recycling rate [153, 161, 162]) is, however, often unclear.

Design of product systems plays a key role in determining environmental impacts [163–167]. Therefore it is important to consider sustainability criteria in design from the very beginning. This requires guidance on material selection [168–170] and choice of (circular) design strategies (e. g. lifetime, repairability, recyclability) [171, 172]. A multitude of eco-design tools have been proposed to this end (see for an overview [166, 171, 173–177]) in forms of checklists [171, 174, 178], diagram tools [179], *design for X* tools [166, 180, 181] and tools based on (simplified) life cycle assessment (LCA) [182, 183]. *Eco-design* or *Design for Environment* focus on reducing life cycle environmental impacts relative to the current situation [171, 173], however, circular design requires new or adapted methodologies to guide to the ideal state of CE [184]. Several tools target specific aspects of CE (e. g. life extension [165, 184], repairability [185], active disassembly [186, 187]). Circular design can unfold its potential best in combination with an adapted business model [58, 188] and *vice versa* [189]. The *cradle-to-cradle* framework [20] offers decision support regarding material selection for a product system through a categorization of materials regarding human and environmental health. Within a category, however, there is no distinction made (i.e. according to other environmental dimensions such as e. g. climate change) and it therefore is not sufficient to guide design towards environmental sustainability. Furthermore, in the cradle-to-cradle concept wastes are seen as resources (also called nutrients), suggesting that perfectly closed cycles allow for infinite growth, lacking to acknowledge final wastes and emissions as well as to address the size and speed of material cycles.

Most of the described tools are not commonly applied in industry, mainly because of time-consuming complex procedures requiring specific knowledge [166, 167], often resulting in trade-offs for which the tools provide insufficient support [174, 190]. It is further difficult to choose the appropriate tool from the variety of possibilities for the specific requirements of the company [166]. LCA [191, 192] based methodologies can inform about the relative environmental performance of design alternatives as well as the resource requirements over the whole life cycle. However, they require detailed data which is available in later design stages only and is thus not useful to guide design from the very beginning [166, 174, 182]. Consequently, there is a need to develop eco-design methodologies that are easily applicable [166] and support product design for a sustainable circular economy [184] from early design stages on [167, 182].

Multiple indicators have been proposed to promote CE [193–197], focusing on economic [198, 199] or material aspects [200–204], which measure the performance in regard to the objective of closing material cycles. E. g. the Circular Economy Index [198] measures the economic value recovered; the Material Circularity Index [202] measures mass-based recycling fractions and utilization intensity. Beyond CE specific indicators, several attempts have been proposed to measure the degradation in the socio-economic system [114], which assess the quality of (secondary) resources based on entropy [205–207] and/or exergy (e. g. [208–211]). These indicators capture the efficiency of resource use and need to be accompanied by indicators measuring the environmental impacts in order to allow sustainability evaluations [153, 161]. All these indicators are developed for the measurement and analysis of existing systems, which makes it difficult to use them for design guidance. For the design of circular and sustainable products, there is a need to develop an indicator that combines the measurement of resource utilization based on circular strategies with the performance in regard to environmental sustainability.

1.3 PROBLEM STATEMENT AND RESEARCH QUESTIONS

When is an economic system actually sustainable? In the widely used "weak" sustainability conceptualisation where the three pillars – people, profit, planet – are of equal importance, this question is very difficult to address, as it depends on the trade-offs and management between the three spheres [212]. Furthermore, the weak sustainability does not guarantee inter- and intragenerational justice, as it allows, for example, the trade between (short term) economic benefit for (long term) environmental stability [212, 213]. Safeguarding the environmental capital as the life basis for future generations (intragenerational equity), requires to see the environmental sustainability criteria as the non-negotiable and non-tradeable frame for all human activities ("strong" sustainability) [214]. Therefore, I will focus the work in this thesis on environmental sustainability. More in detail, the thesis addresses the following research questions (RQ):

RQ 1 Under which boundary conditions are CE initiatives and strategies environmentally sustainable?

RQ 2 How do these boundary conditions translate into the availability of energy and materials to society?

RQ 3 How can environmental boundary conditions inform early stage product design in regard to selection and utilization of resources?

RQ 4 How to measure the utilisation of limited resources through circular strategies of a product/service or company?

The main idea and novelty of this thesis is to find conditions under which a CE can be considered environmentally sustainable and use this top-down knowledge for guidance in design of new products and services as a first step to connect the top-down and bottom-up perspectives. To my knowledge RQ 1 and RQ 3 are addressed for the first time in this thesis. RQ 2 has been treated for specific sets of resources before (e. g. food [24, 215], timber [216]) and is re-addressed in this thesis for resources in general. RQ 4 is a commonly posed question, however, it will be treated in this thesis in order to develop indicators consistent with the approaches dealing with RQ 1-RQ 3.

1.4 ORGANIZATION OF THE THESIS

In this thesis, I address the research questions by developing a conceptual framework (chapter 2) and several methods, presented in the chapters 3 to 5. The overview of the structure can be seen in figure 1.2.

The first step in this thesis was to develop a conceptual framework to find conditions a CE has to satisfy to be sustainable (RQ 1). This framework provides further a common understanding, framed as a definition, of CE for the inter- and transdiciplinary partners of the LACE project[4]. In this framework, the environment is seen as the non-negotiable and overall frame for human activities (strong sustainability). This justifies the further focus of the thesis on environmental sustainability. Furthermore, the framework calls for a precautionary approach, which is implemented in the methods developed thereafter.

Based on the proposed framework, CE needs to operate within ESB to be environmentally sustainable. It needs energy to power the material cycles and primary materials to compensate unavoidable losses (RQ 2). The first question arising is, if there is enough renewable energy available to power such material cycles? Since existing studies on RE potentials do not take ESB into account and neither follow the precautionary approach, I have developed a method to calculate *appropriable technical potentials* (ATP) for RE resources (chapter 3). ATP provides precautionary estimates for energy that can be harvested while respecting Earth system needs and

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[4] This thesis is embedded in the project “Laboratory for applied circular economy” (LACE), funded by the Swiss national science foundation (SNSF). `http://www.nfp73.ch/en/projects/circular-economy/laboratory-for-circular-economy`

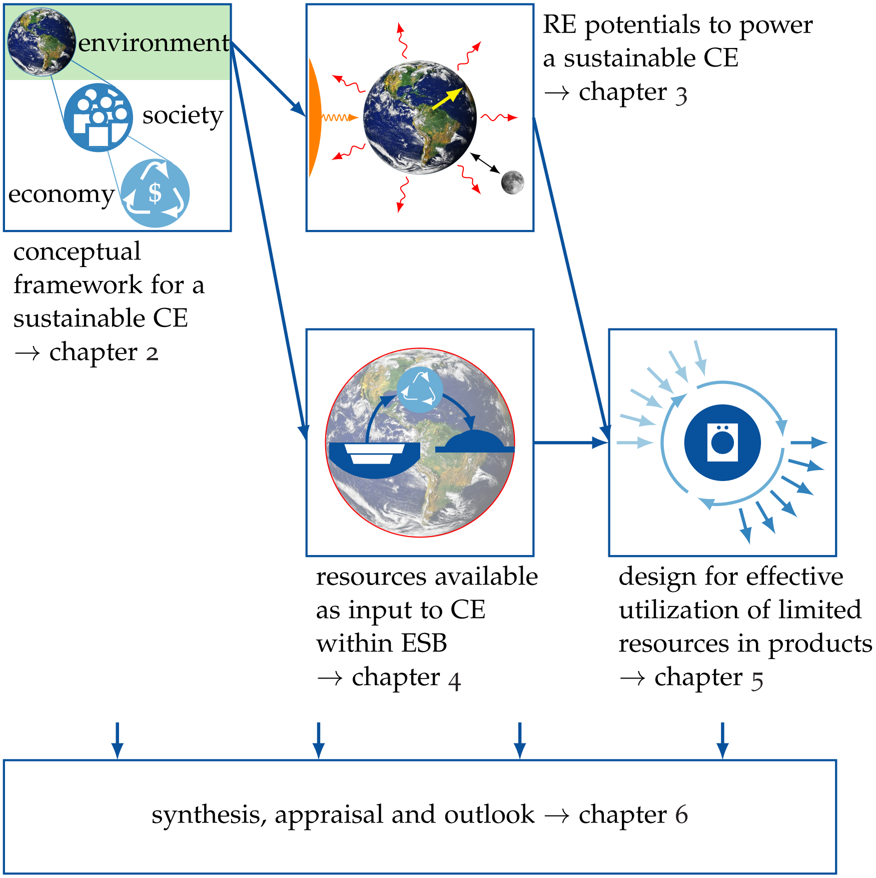

FIGURE 1.2: Overview of the structure of chapters in this thesis.

boundaries, considering the human demand for chemical energy (e. g. food, fodder, fiber) and technical conversion losses to electric energy when using state-of-the-art technology. The ATP method does not consider material requirements and impacts of specific technologies, as these may change with technological progress and with the change in the energy system, and thus provide a maximum ecological potential.

For material resources, in contrast, impacts from the production are crucial and therefore require consideration. For this, I have developed the *ecological resource availability* (ERA) method (chapter 4). The central idea behind the ERA method is that resource use is limited by environmental consequences, rather than their physical availability. Staying within ESB, therefore, requires to limit the availability of resources to an environmentally sustainable level, which is ERA. The method is not limited to materials, but can be applied to all kinds of natural resources, e. g. RE. The ERA method requires several allocation steps, which need further research to define desirable ERA. To test the method, a grandfathering allocation is applied, which reflects the idea of rescaling the current economy to fit within ESB.

After identifying the sustainable resource base, the last part of the thesis is concerned with the effective utilization of resources in products and services. For this, I propose the *resource pressure* method (chapter 5). As resources are limited, the objective for the design is to reduce the pressure on these resources through circular strategies. The method is both an indicator (RQ 4) and provides design guidelines (RQ 3). As the grandfathered ERA budgets do not provide a meaningful design objective, I adapted the ERA method to calculate *ecological resource potentials* (ERP) (section 5.8, [217]), which depend only on the impacts on ESB and do not require allocation.

Chapter 6 offers a synthesis of the four papers and an extended discussion on the relevance and underlying assumptions. Potential future research topics are identified to further develop the presented methods, address shortcomings and make the approach easier to apply in practice.

1.5 METHODOLOGICAL APPROACH

To address the research questions, the methods developed in this thesis are based on the precautionary principle (section 1.5.1). Section 1.5.2 introduces the concept of Earth system boundaries, which demarcate the safe operating space for humanity. In section 1.5.3, methodologies are described, which are the basis for the methods developed in this thesis and commonly used in industrial ecology.

1.5.1 *Precautionary approach*

The methods developed during this thesis are built on the precautionary approach. It is widely used in engineering, but also applied in other fields of societal actions, for example environmental policy [218], risk assessment of chemicals [219, 220] or public health and health care [221, 222]. The core idea is that despite uncertainty, system viability, functioning and safety must be ensured. In other words: nothing is certain, still future generations and remote people need to be protected [213].

Scientific theories and models try to explain observed phenomena, however, they are only valid to a certain degree of applicability and accuracy [223]. They further evolve over time with scientific progress, providing more accurate and precise descriptions for observations. Even though knowledge gaps can be reduced, uncertainties still remain either stemming from measurement errors, interference of the measurement device with the phenomena to be observed, stochastic nature of real world problems or incomplete knowledge. All of this makes precise predictions theoretically impossible [223].

Despite these uncertainties, engineering applies scientific theories and models to build reliable and functional products and systems. One principle to handle the uncertainties and incompleteness of scientific knowledge for the creation of new technology is the *precautionary approach*. This means that uncertainties are explicitly taken into account and systems built with high confidence. For example, as the exact strength as well as the occurring loads of a bridge are unknown, the structure needs to be oversized to withstand all possible load cases with confidence. This oversizing needs to be larger when the uncertainties of the strength and loads are large and *vice versa*. Disregarding this principle can have catastrophic consequences (e. g. collapse of the bridge).

The simplest way to consider the precautionary approach in engineering is to apply a safety factor. For example, if a structural component has to withstand a certain load, it will be sized so that it can theoretically withstand a load multiplied with the safety factor. In this way, the uncertainties in determining the loads as well as the strength of the components are considered. Safety factors have been defined for many applications through experience and empirical observations. This approach often leads to largely oversized structures, which can become a problem, e. g. in weight sensitive applications (e. g. aircraft components or connecting rods in piston engines [224]).

In such cases, a statistical approach can be taken. The probability of occurrence for loads are determined as a load profile, i. e. a probability distribution of loads. For example, loads on structural car components arising from standard driving at standard speed occur with a high probability, whereas extreme loads resulting from driving over a pothole occur with very low probabilities only [225]. Similarly, the strength of a component is determined by a statistical analysis of test results. Samples are tested at specified loads until failure (fatigue testing) or at increasing loads until failure (strength testing) [224]. The distribution of the results can, for example, be due to differences in material (e. g. composition, impurities, defects), geometrical deviations from design shape (e. g. manufacturing tolerances) or measurement errors. Knowing the distribution of loads and strengths, it is possible to calculate the probability of failure, i. e. the probability that a load is higher than a strength. As a design criterion, a certain probability of failure shall not be crossed, i. e. the component or system needs to have a certain (high) probability of survival in real world application. Such probabilities of survival are usually $> 99.9\,\%$ [226].

For example, an aircraft (or any other transport technology) has to be reliable and a safe means of transport with a very high probability. System failures may lead to catastrophic accidents, endangering the life of passengers. The probability, that such events can occur, needs to be at a chosen and experimentally proven low probability. In aeronautics, such probabilities usually range between $[10^{-7}, 10^{-8}]1/\mathrm{h}$ [227] (incidents per flight hour) for critical system failures. Looking at flight accident statistics, there had been 11 fatal accidents[5] in 2018 [228], which translates to an approximate $1.1 \times 10^{-7} 1/\mathrm{h}$, confirming the effectiveness of the design probability. The probability of death is lowest for air transport ($\approx 10^{-11}$ per passenger kilometre) [228] in comparison to rail (10^{-10}) and road (10^{-8}) [229], even though the risk perceived by individuals may be the other way round.

As a society, we require technologies to be reliable and safe. In contrast, when it comes to designing the societal system, this principle seems to be forgotten. For example, uncertainties in climate modelling remain large [230, 231]. Still, the targets to reduce greenhouse gas emissions (i. e. environmental “loads”) to limit global warming (i. e. the “strength” of the climate system) are set with a confidence of 66 % in the case of 2 °C target [232] and 50 % for the 1.5 °C target [15]. That means, there is a chance of one in three (one in two, respectively) that despite adhering to compatible emission pathways, the global warming targets will be transgressed.

Growing evidence suggests, that humanity has become a driving force in the Earth system [17, 18, 73], leading to a new geological epoch, the Anthropocene [233]. Our actions and decisions do influence and shape the planet significantly. At the same time, our survival and future prosperity depend on a functioning and stable Earth system, which is, in fact, our life support system [26]. Therefore, I argue that we need to “design” our

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[5] A fatal accident leads to a death of a person; the number of all accidents was 98 in 2018, which includes minor accidents.

pressure on the planet with the same precaution as we do with our technical artefacts. Our presence on "spaceship Earth" [234] needs to be safe for the planet with high confidence to safeguard livelihood for current and future generations.

To this end, all methods developed in this thesis are built on the precautionary approach, taking into account uncertainties (section 1.5.1.1) through Monte-Carlo simulations (section 1.5.1.2) and results are calculated with a maximum probability of violating Earth system boundaries as environmental sustainability criterion.

1.5.1.1 *Uncertainty modelling*

No parameter can be described with absolute certainty. The distribution of values around the expected value for a parameter can be described and analysed in a probabilistic manner, given that sufficient data points are available. More often than not, insufficient data is available for many parameters in industrial ecology methods to build uncertainty distributions right away from statistical analysis [235, 236]. Alternatively, uncertainty distributions can also be defined by expert judgement or generic factors [237]. For example, the life cycle database ecoinvent applies log-normal distributions to all inventory exchanges by default [238]. The data quality is evaluated as basic and additional uncertainty factors derived from expert judgement and empirical observations [239, 240]. Changing the distribution type of inventory flows does have some effect on the uncertainty distribution of LCA result [237].

Much consideration can be given to choose the "right" probability distribution for each parameter. However such an approach is time consuming for larger models, such as the methods developed in this thesis. In order to exemplify the methods, a simplified approach is taken for choosing uncertainty distributions based on data availability, the existence of upper or lower bounds and literature recommendations. For example, the uncertainty distributions for inventory flows in ecoinvent are modelled as log-normal distributions, as this is the recommended default [238]. This expert judgement is also applied to corresponding inventory flows of Exiobase, which does not provide information on uncertainty.

Five different distributions are used in the methods, see table 1.2. Each parameter is therefore specified with three to four values: minimum, mode, maximum and distribution type (d). If a minimum and a maximum value is known, a uniform distribution for values in between is assumed. When a most likely value (mode) is known in addition, a triangular distribution is formed. Many parameters are known to follow either a normal (symmetric and unbounded) or log-normal distribution (nonsymmetric and only positive values) [219], where the latter is used when negative values are physically impossible. In case where upper and lower bounds exist to a parameter, which is distributed similar to a (log-)normal distribution, a beta-PERT distribution is used. For example, the efficiency cannot be negative or higher than a theoretical maximum (e. g. Carnot efficiency for a thermal engine). Some calculations have dependent variables. For example, the sum of the share of mass flows needs to equal one at all times [236]. For those parameter, a balance procedure is used. The uncertainty for this value results in the balance to the other parameter it depends on. Numerically, this can lead to physically unfeasible values (e. g. negative, or out of a specified range). Such sets of values can then either be discarded and sampled again or the result re-scaled to fit the balance with the balancing parameter equal to zero.

Distribution	**Description**	**min**	**mode**	**max**	**d**
beta-PERT	smooth PDF with absolute min and max	a	c	b	1
triangular	forms a triangle between $(min, p = 0)$, $(mode, p(mode))$, $(max, p = 0)$ with $p(mode)$ so that $\int_{min}^{max} p = 1$	a	c	b	2
normal	Gaußian distribution	–	μ	$\mu + 3\sigma$	3
log-normal	ln-transformed Gaußian distribution	–	e^{μ}	$e^{\mu+3\sigma}$	4
uniform	each value between *min* and *max* has the same probability	min	–	max	5
balance coefficient	is determined as the residue to 1 for columns in a matrix. Only relevant, if the sum of each column in a matrix needs to equal 1	–	–	–	6

Table 1.2: Distributions to calculate random numbers for Monte-Carlo simulations as used in the ATP (chapter 3), ERA (chapter 4) and ERP (section 5.8) methods.

The uncertainty modelling can be improved in the methods developed in this thesis by considering different distribution types (e. g. Weibull) and performing a more refined selection of the distributions and their parameters according to the available data. Furthermore, the uncertainty propagation throughout LCA and EE-IOT calculations can be better represented by using pre-calculated uncertainty distributions of inventory results [241]. It remains a subject to future research on how these refinements influence the results from the presented methods.

1.5.1.2 *Monte-Carlo simulation*

A Monte Carlo (MC) simulation is a calculation procedure to consider the error propagation throughout a calculation. All input parameters are defined as probability distributions. The calculation is then performed n_{runs}-times, sampling input values randomly according to the specified probability distributions. The result is a series of n_{runs} values, representing the probability distribution of the result. A MC simulation converges towards the analytical result with increasing number of simulation runs ($\frac{1}{\sqrt{n_{\text{runs}}}}$), as the likelihood of calculating all possible combinations of parameters increases. For the methods in this thesis, 10^5 simulation runs are used, which give fine results with acceptable computation times of seconds to minutes for the considered problems.

There are different ways to perform a MC. In this thesis, matrix calculations are used, which is illustrated by a basic example here: Consider a set of linear equations (as usual in industrial ecology methods, see section 1.5.3), expressed in matrix form.

$$\vec{y} \quad = \quad \boldsymbol{A} \times \vec{x}$$

Where $\boldsymbol{A}$ is a $n \times m$-matrix of coefficients and $\vec{x}$ is a m-dimensional vector of variables. The result is a n-dimensional vector $\vec{y}$. For the MC, the calculation has to be carried out n_{runs} times and one way to do this, is by forming 3-dimensional matrices with the simulation runs in the third dimension.

$$\begin{bmatrix} y_1 \\ \\ y_n \end{bmatrix}_{\iddots\, n_{\text{runs}}} = \begin{array}{cc} & \begin{array}{ccc} 1 & \dots & m \end{array} \\ \begin{array}{c} 1 \\ \vdots \\ n \end{array} & \begin{bmatrix} A_{11} & & A_{1m} \\ & \ddots & \\ A_{n1} & & A_{nm} \end{bmatrix}_{\iddots\, n_{\text{runs}}} \end{array} \times \begin{bmatrix} x_1 \\ \\ x_m \end{bmatrix}_{\iddots\, n_{\text{runs}}} \tag{1.1}$$

The matrix $\boldsymbol{A}$ contains now a vector for each element in n and m with n_{runs} entries of randomly picked values from the probability distribution specified for this element. And similarly for the vector $\vec{x}$. The results vector $\vec{y}$ contains now n_{runs} values for each element. These elements can be analysed with statistical methods, e. g. to find the 50 % value.

In principle, such an error propagation can also be calculated with analytical methods, i.e. calculating the parameter of the probability distribution for the result of each calculation step [242, 243], or other numerical procedures, e. g. polynomial chaos expansion [244]. The advantages of a MC simulation are that it can be applied to very large (also non-linear) systems, handles different probability distribution types naturally and always converges. It has however the limitations, that the result is only an approximation of the true probability distribution, the convergence is slow and that the calculation time increases with increasing number of simulation runs. So there is a trade off to be considered between accuracy and calculation time.

1.5.2 *Earth System Boundaries*

Planet Earth is a finite entity. This physical reality is ultimately limiting the availability of resources and energy on this planet. In comparison to these physical limits, human demand seems to be negligible in most cases. For example, the energy flux from the sun that hits Earth is in the order of magnitude of 10^{17}W [123, 124, 245], whereas current human demand for energy is 10^{13}W [246, 247]. Therefore, the physical limitations are in most cases not of concern to the human enterprise.

Coming anywhere close to physical limits with human demand, however, entails that nothing is left to nature. In fact, the vast majority of resources (energy and materials) is utilized by different parts of the Earth system already. For example, a large fraction of the incoming solar irradiation is driving the water cycle: evaporating and desalinating seawater, driving atmospheric currents and so on. Diverting this energy flux to human use (e. g. through large scale floating PV systems on ocean surface) will reduce, or possibly even shut down, the previously powered Earth system process.

During the Holocene period, the Earth system had been in a remarkably stable quasi-equilibrium, allowing the rise of human civilizations [77, 248]. The Earth system can change to new stable states after disruptive events that are large enough to push the system over tipping points. These can be either slow processes (e. g. the formation of O_2 by cyanobacteria [2]) or single events (e. g. volcanic eruption).

Humanity is an integral part of the Earth system and as such interlinked in the web of resource flows. Changing and shifting resource use, therefore,

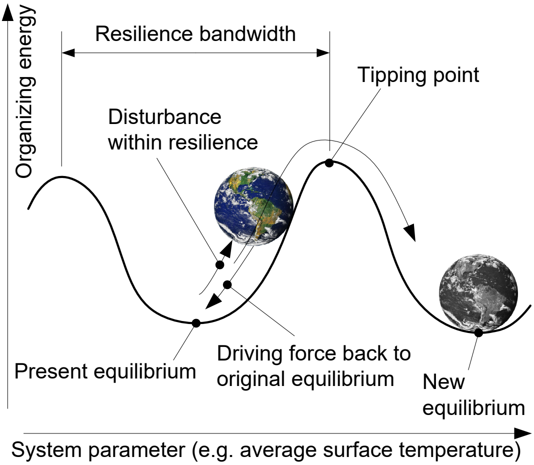

FIGURE 1.3: Conceptual representation of the stability of an Earth system state and its resilience (based on [74, 233, 249, 250]).

has an effect on other Earth system processes. In function of the scale, this effect can be marginal or fundamental (figure 1.3), depending if the change is within or outside the resilience of the current state of the system. Shifting states in Earth's long history did have fundamental consequences for life, e. g. leading to mass extinctions [251]. Human societies have become a driving force in the Earth system, especially over the past century [17, 18], and there is ample evidence that the scale of human activities has the potential to evoke (or is already evoking) such a shift [74]. For a sustainable society that safeguards the basis of existence for future generations [213], it is imperative to keep its pressure within the resilience of the current Earth system state [78, 79], as this is the only one supporting higher civilizations for sure (precautionary principle, see section 1.5.1). Therefore, the resilience of the Holocene state of the Earth system can be seen as the boundaries within which human activities need to take place (i. e. the *safe operating space for humanity* [78]).

The term *Earth system boundaries* (ESB), as it is used throughout this thesis, describes the idea that many of the Earth's systems have boundaries, beyond which there is an increased risk for change in the system's operating mode. Crossing one boundary may then also evoke crossing other boundaries, as the Earth's systems are interlinked. Therefore, ESB are not independent and can be redundant. ESB are lower, in many cases substantially, than physical limits, which result from the finiteness of the planet. Due to incomplete knowledge of the complex Earth system, ESB are likely to be associated with large uncertainties. One possible way to quantify Earth system boundaries is the planetary boundaries framework [77, 79] (see table 1.3). This framework is seen here as a specific set of indicators that is not exhaustive or complete but an approximative quantification of the concept of ESB. The planetary boundaries set limits for nine critical Earth systems below which large scale shifts of the systems' operation is avoided.

Boundary	**Description**
Climate	avoid dangerous climate change [252] based on triggering climate tipping points [16, 231]
Biodiversity	preserving genetic and functional diversity for the resilience of the biosphere
Ozone layer	protect the shield against UV radiation, which is detrimental to living organisms
Ocean acidification	protect marine biota (e. g. coral reefs), which are also acting as a biotic pump for carbon to sediments
Biogeochemical flows	limit disturbance of man-mobilised nutrients in natural ecosystems
Land	prevent irreversible conversion of biomes, maintain carbon storage and resilience of biosphere
Water consumption	water remaining in ecosystems affecting moisture feedback, regional climate and biodiversity
Aerosols	avoid change of precipitation patterns and negative effect on human health
Novel entities	restrict introduction of new substances or engineered organisms with potential detrimental effects on human health and ecosystems

Table 1.3: Earth systems considered in the planetary boundaries [77, 79]

1.5.3 *Industrial ecology methods*

Parts of the methods developed in this thesis use and build on well established methods from the field of industrial ecology. In particular, material flow analysis (MFA) [253], environmentally extended input output tables (EE-IOT) [254, 255] and life cycle assessment (LCA) [191, 192] are used. MFA is widely used in the context of CE to evaluate resource flows in the economy [9, 144] or in particular processes, e. g. waste treatment [118, 256]. In this thesis it is used to model the energy flow through the Earth system to determine the appropriable technical potentials for renewable energy (chapter 3) and to describe the material flow in a product system (chapter 5). Very recently EE-IOT are being used in the field of CE [257], but are widely used for the economy wide analysis of the status quo of environmental performance [258, 259]. They are applied in this thesis to determine the share of safe operating space for resource segments based on the grandfathering approach with historical data (chapter 4). LCA is a well established tool for comparative [260, 261] and lately also absolute assessment [105] of the environmental performance of societal activities, which is used here to estimate the environmental impacts on ESB associated with the extraction, processing and final disposal of primary resources and to compare the results of the resource pressure method (chapter 5) to this well established tool.

In the following, the basic mathematical structure of these methods is presented, because the developed methods build on and use the here presented formulas. All these methods are (potentially large) sets of linear equations. The equations can be solved in the matrix representation, where all linear equations are transformed into one matrix equation. The coefficient matrix $\boldsymbol{A}$ has the dimension of number of system variables $\vec{\boldsymbol{x}}$ (columns) by number of equations (dimension of $\vec{\boldsymbol{b}}$) (rows).

$$\boldsymbol{A} \times \vec{\boldsymbol{x}} = \vec{\boldsymbol{b}} \tag{1.2}$$

The system is determined (i. e. one solution exists), when there are as many equations as system variables (i. e. $\boldsymbol{A}$ is square). Solving this equation requires to build the inverse of the coefficient matrix ($\boldsymbol{A}^{-1}$):

$$\vec{\boldsymbol{x}} = \boldsymbol{A}^{-1} \times \vec{\boldsymbol{b}} \tag{1.3}$$

1.5.3.1 *Material flow analysis*

MFA is used to map the material flow through a system of processes and exchanges [253]. It builds on the mass balance of inputs, outputs and stock changes of a process:

$$\sum_i \dot{m}_{in,i} - \sum_j \dot{m}_{out,j} - \dot{m}_{stock} = 0 \tag{1.4}$$

The system is further defined by transfer equations (model approach), which model the transfer of different input flows to an output flow of a process. We can define transfer coefficients TC_{ij} specifying a share of the flow i going to the output j.

$$TC_{ij} = \frac{\dot{m}_{i\to j}}{\dot{m}_i} \tag{1.5}$$

$$\dot{m}_{out,j} - \sum_i TC_{ij} \cdot \dot{m}_{in,i} = 0 \tag{1.6}$$

For quasi-stationary MFA problems (i. e. $\frac{d\dot{m}}{dt} = 0$), eq. 1.4 and 1.6 are linear equations independent in time, which can be put in the matrix format (eq. 1.2). Each row j in the coefficient matrix $\boldsymbol{A}$ contains the factors to multiply the mass flows i in $\vec{\boldsymbol{x}}$, corresponding to one equation out of all mass balance (like eq. 1.4) and transfer equations (like eq. 1.6) defining the system. Corresponding elements in the vector $\vec{\boldsymbol{b}}$ for these rows are zero (i. e. right side of eq. 1.4 and 1.6). Flows that are known in the system (which are "driving" the system) are specified with separate equations:

$$\dot{m}_i = b_i \tag{1.7}$$

In total, there need to be as many equations (number of rows in $\boldsymbol{A}$) as system variables (columns of $\boldsymbol{A}$), i. e. the system needs to be determined and $\boldsymbol{A}$ invertible. Elements A_{ji} in the coefficient matrix are either $+1$ or -1 for balance equations or $-TC_{ij}$ for transfer equations.

$$\text{flows}\ \underbrace{\overset{1}{\begin{bmatrix}\dot{m}_1\\ \vdots\\ \dot{m}_n\end{bmatrix}}}_{\text{mass flows}} = n\ \text{equations}\ \underbrace{\overset{n\ \text{flows}}{\begin{bmatrix}1 & \cdots & A_{1n}\\ \vdots & \ddots & \vdots\\ A_{n1} & \cdots & 1\end{bmatrix}}^{-1}}_{\text{coefficient matrix}} \times\ \text{equations}\ \underbrace{\overset{1}{\begin{bmatrix}b_1\\ \vdots\\ b_n\end{bmatrix}}}_{\text{"right" side}} \tag{1.8}$$

1.5.3.2 *Environmentally extended input-output tables*

Input-output tables (IOT) are a macro-economic methodology to analyse the relationships of industrial actors within the economy [254, 262]. It is based on the system of national accounts reporting monetary data of the national economies in a uniform format.

With the IOT format it is possible to calculate how much economic activity ($\vec{x}$) is induced in a sector when required to produce a certain final demand ($\vec{y}$). For example, to produce a certain amount of aluminium, also production of steel and supply of electricity are necessary, i. e. inducing demand within the economy. Aluminium is also required for other activities in the economy, therefore, its production x is larger than the final demand for aluminium y. The factors of how much an industry needs as input from another industry are stored in the coefficient matrix $\boldsymbol{A}$

$$\begin{aligned} \vec{x} &= \boldsymbol{A} \times \vec{x} + \vec{y} && (1.9) \\ \vec{x} &= (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{y} && (1.10) \end{aligned}$$

Environmentally extended IOT (EE-IOT, e. g. Exiobase [255, 258]) allow to calculate environmental impacts associated with the economic activity by translating the monetary flows in $\vec{x}$ into environmental flows $\vec{f}$. This translation is done using the environmental extensions (satellite), reporting total environmental flows per industrial sector, and converting it to the flow matrix $\boldsymbol{F}$, containing the emission intensities (i. e. environmental flow of a sector divided by its economic activity).

$$\vec{f} = \boldsymbol{F} \times \vec{x} \tag{1.11}$$

Environmental flows can be translated into environmental impacts $\vec{q}$ using the characterization factors contained in the matrix $\boldsymbol{Q}$.

$$\begin{aligned} \vec{q} &= \boldsymbol{Q} \times \vec{f} && (1.12) \\ &= \boldsymbol{Q} \times \boldsymbol{F} \times (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{y} && (1.13) \end{aligned}$$

$$\text{impacts}\underbrace{\overset{1}{\begin{bmatrix} q \end{bmatrix}}}_{\text{score}} = \text{methods}\underbrace{\overset{\text{env. flows}}{\begin{bmatrix} Q \end{bmatrix}}}_{\text{char.}} \times \text{env. flows}\underbrace{\overset{\text{industries}}{\begin{bmatrix} F \end{bmatrix}}}_{\text{biosphere}} \times \text{industries}\underbrace{\left(\boldsymbol{I} - \overset{\text{industries}}{\begin{bmatrix} A \end{bmatrix}}\right)^{-1}}_{\text{Leontief inverse}} \times \text{industries}\underbrace{\overset{1}{\begin{bmatrix} FD \end{bmatrix}}}_{\text{demand}}$$

1.5.3.3 *Life cycle assessment*

LCA is a tool to analyse and compare the environmental performance of products or processes. The comparison can be either within the life cycle (contribution of different life cycle stages), relative to a reference product/process (relative LCA) [191, 192, 260, 261] or to an absolute environmental benchmark (absolute LCA, e. g. [98–108]). LCA is structured in four standardised steps: goal and scope definition, inventory analysis, impact assessment and interpretation [260, 261].

To perform a LCA, the functional unit (FU) needs to be defined, i. e. the demand for the product that shall be analysed. The technosphere matrix $\boldsymbol{A}$ contains the information, how much of each activity is necessary to provide for the demand. For example, the production of one car (FU) requires a certain amount of steel, electricity and many other inputs, which in turn require inputs from other activities themselves. The activities required to provide FU are calculated by multiplying the inverse of the technosphere matrix with the demand vector $\vec{\boldsymbol{f}}$. Knowing all industrial activities involved for providing FU, the environmental implications can be calculated through a two step procedure. First, the activities are translated into environmental flows by multiplying with the biosphere matrix $\boldsymbol{B}$. Environmental flows are flows of resources or substances relevant for calculating environmental impacts. These are computed in the second step by multiplying with a characterisation matrix $\boldsymbol{Q}$ containing characterisation factors (CF). The characterisation matrix depends on the methods chosen for the impact assessment [192]. The result is a vector of impact scores associated with the provision of FU.

$$\vec{\boldsymbol{h}} = \boldsymbol{Q} \times \boldsymbol{B} \times \boldsymbol{A}^{-1} \times \vec{\boldsymbol{f}} \tag{1.14}$$

$$\underbrace{\begin{array}{cc} & 1 \\ \text{impacts} & \begin{bmatrix} \\ h \\ \\ \end{bmatrix} \end{array}}_{\text{score}} = \underbrace{\begin{array}{cc} & \text{env. flows} \\ \text{methods} & \begin{bmatrix} \\ Q \\ \\ \end{bmatrix} \end{array}}_{\text{characterisation}} \times \underbrace{\begin{array}{cc} & \text{activities} \\ \text{env. flows} & \begin{bmatrix} \\ B \\ \\ \end{bmatrix} \end{array}}_{\text{biosphere}} \times \underbrace{\begin{array}{cc} & \text{activities} \\ \text{products} & \begin{bmatrix} \\ A \\ \\ \end{bmatrix}^{-1} \end{array}}_{\text{technosphere}} \times \underbrace{\begin{array}{cc} & 1 \\ \text{products} & \begin{bmatrix} \\ f \\ \\ \end{bmatrix} \end{array}}_{\text{demand}}$$

2

SUSTAINABLE CIRCULAR ECONOMY FRAMEWORK

> *Our approach to nature is to beat it into submission. We would stand a better change of survival if we accommodated ourselves to this planet and viewed it appreciatively instead of skeptically and dictatorially.*
>
> — E. B. White

BIBLIOGRAPHICAL DATA

Title	A Circular Economy within the planetary boundaries: towards a resource-based, systemic approach
Authors	Harald Desing, Empa Dunia Brunner, University Lausanne Fabian Takacs, University St. Gallen Karolin Frankenberger, University St. Gallen Stéphane Nahrath, University Lausanne Roland Hischier, Empa
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KEY FINDINGS

- A CE has to operate within Earth system boundaries to be environmentally sustainable, which limits the availability of energy and materials to be used in CE.

- A CE has to be regulated by society to ensure inter- und intragenerational equity.

- To ensure an effective resource utilisation, CE needs to aim at minimizing entropy production.

THE AUTHOR'S CONTRIBUTION

The cascading approach to sustainability (fig. 2.1) originated from various discussions I had at the very beginning of the LACE project combined with my previous working experience in development cooperation. Further, the engineering principles (section 2.3.4.2) I developed in the very beginning to get an understanding of circular economy for myself. I initiated this paper with the idea of setting the stage for the project, find a common language and integrate the aforementioned concepts with concepts from the other parts of the project. We did not want to write yet another literature review on circular economy, although it also contains our review on the subject.

During the elaboration of the conceptual framework, we added the precautionary principle, a concept used in both engineering and environmental policy (fig. 2.2) and the restriction of resources utilizable in the economy, to add an absolute bio-physical reference (section 2.3.4.1).

THE CO-AUTHORS' CONTRIBUTION

Dunia contributed the conceptualization (section 2.3.1), normative basis (section2.3.3), environmental policy aspects of the precautionary principle as well as an extensive part of the discussion dedicated to governance and resource management (section 2.4.1 and 2.4.2).
Fabian contributed the business view in the discussion (section 2.4.3) as well as to the development of the definition.
Karolin helped developing the business aspects and reviewed the paper.
Stephane contributed the epistemological status of our work (see. 2.3.2), supported the development of the legal aspects and reviewed the paper.
Roland supported the development of the conceptual framework and the engineering view as well as reviewed the paper.

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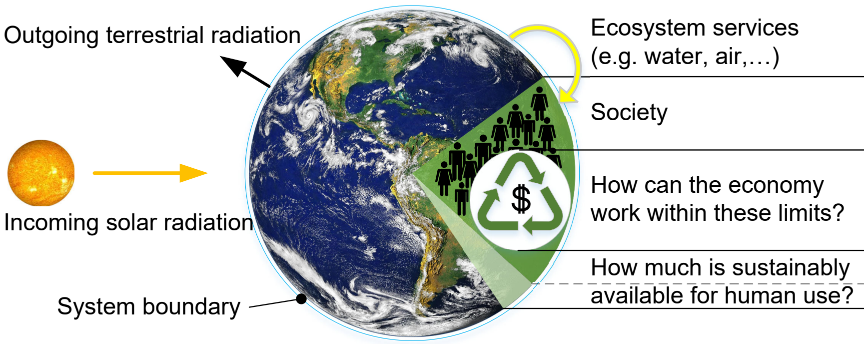
ABSTRACT

Circular Economy (CE) is the buzzword of today, promising an economy able to prosper on limited resources by closing material cycles. However, there is no guarantee that simple strategies of material cycling, as propagated by the various definitions of this concept, will indeed lead to an economy able to manage the world's resources, pollution and societal demand within environmentally sustainable levels. Based on the shortcomings of the present mainstream definitions of CE, this paper proposes an integrative, cascading, resource-based approach aimed at an environmentally sustainable and socially beneficial economy. The international community agrees on the necessity to maintain the current environmental equilibrium to ensure equity for future generations and to allow human well-being and dignity already in the present. Accordingly, physical and environmental limitations are identified, that are to be observed to make CE sustainable. This paper then suggests that a transition towards a sustainable resource-based CE goes hand in hand with a paradigm shift in the way environmental considerations are perceived by individuals, codified in different normative frameworks and dealt with by private companies. It therefore opens the discussion by underlying some challenges that could appear in the view of transitioning to CE.

GRAPHICAL ABSTRACT



2.1 INTRODUCTION

The concept of Circular Economy (CE) has recently gained broad diffusion and popularity, in particular in the policy and business circles in developed nations, promising an economy which can be both profitable and sustainable [35, 42, 263]. The growing amount of peer-reviewed articles on CE and various publications by major consulting firms are reflecting that CE is also becoming an important concept for science and business development [39, 55]. As its name suggests, CE refers to a model of production and consumption that introduces a fundamentally different perspective from the dominant "linear economy" model [264]; it is often presented as an alternative to the current "take-make-dispose" or "extract-produce-consume-trash" industrial model (among many others: [44, 202]). By conceiving end-of-life materials and products as resources rather than waste, it aims at closing the loops of materials, reducing the need for raw materials and waste disposal, following the example of ecosystems [195].

Despite its wide use, there is however no consent on what CE actually means and encompasses, not to speak of an agreed definition [37, 55]. The widespread acceptance of a somewhat not clearly defined concept, often presented as a solution for continuous economic growth and innovation without -– or with minimal -– damaging exploitation of the environment (e. g. [202, 265]), can be explained through the benefits and interests of the actors driving the CE to actively support such a deliberately vague, but therefore uncontroversial approach [42]. The lack of conceptual clarity and an accepted definition represents a challenge for scholars to work on the topic given the abundance of CE conceptualizations, which has been described as "circular economy babble" by Kirchherr et al. [39]; it led Blomsma and Brennan [54] to qualify CE as an "umbrella concept" and Korhonen et al. [38] as an essentially contested concept.

This paper doesn't intend to offer another literature review of existing definitions, as this has already been done by different authors (see for an overview e. g. [37–39, 41, 43–45, 68, 266]). Based on an evaluation of these various reviews in section 2.2, it presents a conceptual framework that allows to integrate multiple CE strategies focusing on individual actors (micro-level) into a global and resourced-based approach. Building on a large consensus that an environment permitting a life of dignity and well-being should be ensured for current and future generations (section 2.3.3), it places environmental realities at the core of the here proposed approach (see section 2.3.4), which leads to the resource-based definition in section 2.3.5. Section 2.4 shortly addresses how the integration of these physical requirements into socio-economic activities represents a paradigm shift for all actors (e. g. consumers, institutions, private companies) and discusses some related challenges, with a particular focus on the legal system – illustrated in the Swiss context – and the economic actors.

2.2 EXISTING DEFINITIONS AND APPROACHES OF CE

As mentioned already above, there is no single definition of what CE means and encompasses. The most often cited and probably best known definition of CE of the Ellen MacArthur Foundation (see supporting information (SI) and [21]), which focuses on regenerative economy and new business models has been adopted and modified many times [39], also by political actors and for institutional positions (e. g. [265, 267, 268], see also SI). Other definitions, mostly stemming from scientific literature, rather focus on material aspects [40] or consolidate various definitions to be found in the recent literature into more comprehensive ones (e. g. [35, 39]).

The mentioned understandings of CE are mostly adopting a bottom-up approach, focusing on individual businesses and economic actors. They encourage them to improve their efficiency, reducing the (per-unit) resource input and minimizing final waste. These approaches are useful and necessary, as they provide tools for single actors to adapt their processes and help operationalizing theoretical principles; hence they certainly play an essential role in the transition towards CE. Such strategies can also be interesting from a pure business perspective, as they make companies less dependent on resource price fluctuations and strengthen customer loyalty thanks to new business models.

Despite its usefulness for direct application, such bottom-up approaches are not per se sufficient to reach sustainability. There is no proof that material-cycling strategies would be environmentally sustainable after all [65–67], as the idea of closing cycles alone does not touch the question on how large and fast such cycles can be [1, 68]. Bottom-up approaches can lead to a confusion between different levels of analysis (micro, meso, macro)[1] and a lack of distinction between relative and absolute efficiency [42, 269, 270]. Indeed, most approaches focusing on production, production sites and techniques are aiming at improving per-unit efficiency but disregard a larger macroeconomic and macro-societal approach, which is necessary

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[1] To add to the confusion, there is no accepted standard in the distinction between the different scales labelled as micro, meso and macro respectively (see e. g. [44]).

to build "authentic" circularity [271, 272]. By neglecting that CE can be conceived and implemented at different scales, they lack a systemic view on the global context of limited environmental resources [35].

CE is often presented as a solution to overcome the tension between unlimited economic growth and finite planetary resources with no further explanation. It is implicitly assumed that improving the efficiency of businesses at the micro level will reduce the global environmental impact of businesses, neglecting the impact of continuous growth. Some authors refer to it as the “myth of decoupling" growth and resource consumption [42]. Grosse [65] argues that in an economy where resource use is growing by more than 1 %, the positive effects of recycling on resource depletion are negligible. CE is seen as an enabler to economic growth [202], but in order to result in an absolute decoupling of resource use from GDP growth [62], the growth would need to be linked to resource efficiency improvements [69]. It is assumed that proposed strategies of material cycling will replace 1:1 primary production, which is a gross oversimplification. On the market, an increase in supply (initial primary production and recycled secondary production) usually leads to a decrease in price and, subsequently, to an increase in consumption [67]. This may in many cases lead to an increase of environmental impacts and create a "rebound effect" [44, 70]. As mentioned, reducing the environmental impact per produced unit will not necessarily reduce the environmental impact of the economy as a whole, if the questions of the numbers of actors and the number of units produced per actor are neglected. The Institutional Resource Regime approach [273, 274], the institutional economics approach of environmental policies [275] or the Institutional Analysis and Development framework [276, 277] have pointed out the theoretical limits and weaknesses of “classical” sectoral emission control-based environmental policy approaches when dealing with the issue of sustainable resource management.

Regarding material flows, it is commonly assumed that engineering materials can be cycled indefinitely in technical applications, disregarding irreversible effects, as well as technological and even physical limitations [35, 45]. It is however inevitable that materials are irretrievably lost during the lifetime of technical products [121, 278]. Thus sustainable raw material extraction [40] and safe disposal in final sinks [121] are necessary parts of a CE, yet they are rarely included in current approaches.

Even if there is no clear evidence of a single origin of the term [45, 279], the paradigm of CE was surely rooted in a reflection around the concepts of environmental science and sustainable development [44, 264].

Approaches like e. g. industrial ecology [48, 49], clean technology [46, 47], cradle-to-cradleTM [20], blue economy [280], performance economy [51] or biomimicry [19] share the idea of the systemic view on "spaceship earth" [234] with limited resources. The development of different strategies to manage the resource flows in an essentially closed system was the result of the awareness that our planet is such a (almost) closed system.

Table 2.1 summarizes the main characteristics of the understandings of CE mentioned earlier, as well as compares them with some related schools of thought.

Appraoch	**Core strategies**	**Focus / aim**
Practitioner's view on CE, e. g. [21]	Renewable energy, no toxic elements, no waste	Economic growth within a resource constrained world
CE with material focus, e. g. [40]	Prolong service life, Reduce resource intensity, Closing resource loops	Keeping products, components and materials at a high value
CE consolidated from literature review, e. g. [39]	Reducing, Reusing, Recycling, Recovering, Addressing different scales (micro, meso, macro)	Sustainable development to achieve environmental quality, economic prosperity and social wellbeing
Cradle-to-cradle^{TM} [20, 41, 172]	Replacing hazardous substances, 100 % recyclable technical or biological nutrients	Creating a wholly beneficial industrial system, Focus on chemical inputs
Industrial ecology [41, 48]	System analysis, Utilize by-products as inputs for other processes (symbiosis)	Designing mature industrial systems inspired by natural ecosystems as a subsystem of the biosphere
Performance economy [51]	Selling performance instead of products (e. g. light as a service)	Economic growth within a resource constrained world

TABLE 2.1: Summary of main approaches to CE and related schools of thought

2.3 CASCADING, RESOURCE-BASED FRAMEWORK AND DEFINITION OF CE

The concept of CE can, to some extent, be described through some of its components or strategies (like e. g. reusing, recycling, eco-design and performance economy), but this is not sufficient to define it, if we aim for a socio-economic system that is sustainable from a resource-based point of view. To be complete, the components have to be seen as parts of the larger system, or “ecosystem" [281]. Then so far, CE has not been systematically thought in a holistic and top-down manner, taking the planetary environmental constraints as the absolute limits of the system [35]. Our intent is therefore to develop a framework based on this understanding. The resulting global and systemic approach is a tribute to various authors and schools of thought (see e. g. table 2.1) that have contributed to the emergence and development of the CE concept. This framework will allow to acknowledge the pragmatic utility of bottom-up and sectorial approaches, while overcoming the identified shortcomings of current definitions, as identified in section 2.2. After presenting the conceptual construction of the framework (section 2.3.1) and its epistemological status (section 2.3.2), we will develop the theoretical basis of the framework by first showing the development and foundations of the normative assumptions on which it is built (section 2.3.3) and then identifying the physical and environmental principles and limitations that have to be taken into account and how they translate to CE (section 2.3.4). This leads to the proposition of a resource-based definition (section 2.3.5).

To illustrate the theoretical concepts, we discuss the application of the findings and derive guidelines for practical consideration on a company or product level, on the example of a washing machine. We will show qualitatively, how the different aspects can be considered in the design of the washing machine (section 2.3.4), its business model (section 2.4.3) and relate to the larger policy and societal frame (section 2.4.2). The example is based on the outputs of various discussions and workshops with a home appliance-company in Switzerland.

2.3.1 *Conceptual construction of the framework*

Our human societies are part of the Earth system; they are organized along normative principles, which can vary depending on cultures, religions and other moral considerations. Nowadays, there is however a global consensus on the fact that human dignity and well-being should be seen as an overall goal of any system developed by humans, while ensuring that the existence conditions of the system are not destroyed. We take this normative consensus as the basis of our CE framework and therefore aim for a CE that acknowledges the need of a sustainable resource management, in order to allow human dignity for current and further generations (see section 2.3.3).

The universe is organized along physical laws, which lead to the unique distribution of energy, and consequently matter, in space and time. These principles limit the possibilities for all natural, but also all technical processes. The Earth system provides vital ecosystem services to humanity, but has a limited resilience against anthropogenic stressors. These boundaries of the planet and the physical limits combined should be considered as the overall frame for human activity, in order not to trigger unintended anthropogenic changes in the Earth system. To design a sustainable CE, two fundamental engineering problems need to be addressed:

1. How to quantify the sustainable resource base and make sure that, despite all uncertainties, the Earth system can sustain the socio-economic metabolism in the long run?
2. How to utilize these limited resources best within the socio-economic system?

Finally, the economy is understood as a constellation of private and public actors and entities providing goods and services to society. The deductive approach implies that economic actors should operate within the environmental constraints, as well as comply to and participate in shaping the normative societal frame. In order to be most profitable, they strive to utilize the available resources most effectively. In summary, our cascading approach for a circular economy (CE) shown in figure 2.1, is deducing a CE from the given environmental realities, which represent the frame for human activities.

2.3.2 *Epistemological status and utility of our framework and definition*

Our contribution relies on an inclusive and integrative approach, allowing to place the useful –– but incomplete –– individual perspectives into a larger frame. We conceived it as an "ideal-type" (see [282] and SI), which represents a clear theoretical ideal version of a concept, a "north star" that helps orientation. In such an ideal–typical perspective, according to Weber, the

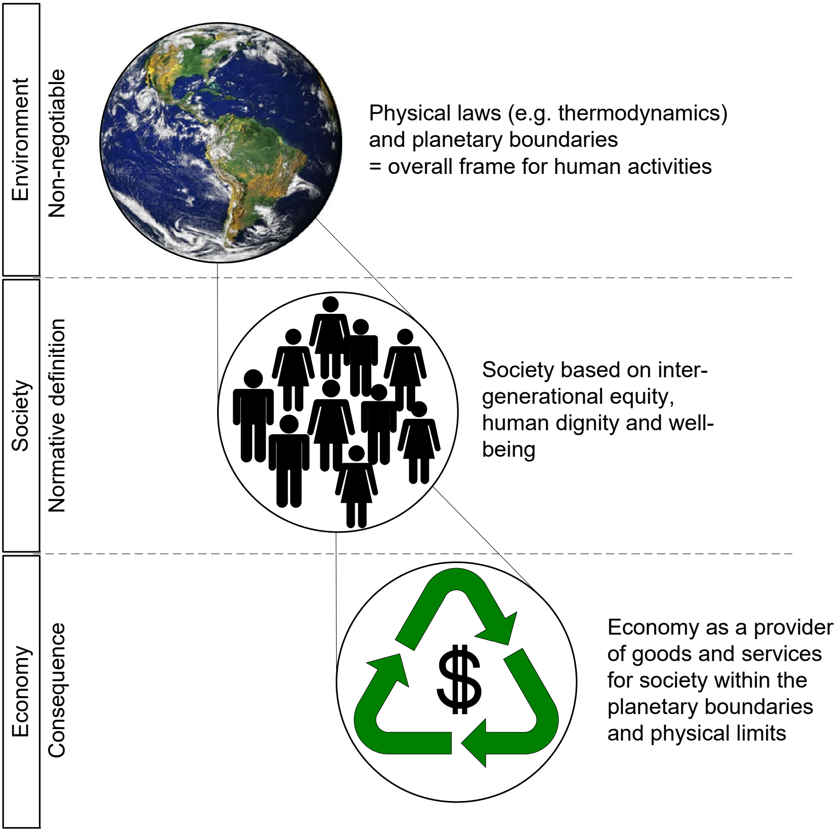

Figure 2.1: Framework for holistic view on "Circular Economy" with a cascading top-down approach in 3 layers: The layer of the environment forms the overall frame for human activities. The latter can be described as the “society”, which is part of the biosphere, as depicted in the second layer. To be sustainable in the long-run, human activities should integrate the nature-given, non-negotiable, physical and environmental restrictions from the first layer. The society is organized along normative definitions. The economy as a third layer is understood as a constellation of actors and entities providing goods and services for the society. The deductive approach implies that economic actors have to operate within the environmental constraints.

conceptual challenge relies on identifying and caricaturing the significant and relevant (system of) features of the (social) phenomenon being studied (see SI). The methodological procedure then consists of confronting and measuring the divergence or, on the contrary, the congruence between the ideal-type or Gedankenbild (i.e. our systemic definition of CE) and the empirical cases studied (i.e. various CE situations or transition processes). Such an analytical construct can act as an ideal reference point for assessing progress and measuring efficiency of initiatives towards CE, allowing to analyze and qualify –– and possibly even quantify — the degree of "circularity". Relevant normative principles for paving the transition process towards CE at different levels (company, sector, region, country, etc.) can be deduced from such an ideal-typical definition, as each of the elements composing it may be used as normative principles for such a transition process. Further research could then develop a more formalized step-by-step proceeding paving the way from linear economy towards the ideal-typical CE (for an example of such a normative use of an ideal typical definition, see e. g. [274]).

Developing a concept of CE that would allow, if completed, to stay within the bio-physical capacity of the planet is of great macro-societal importance. Keeping an eye on the global resource base is useful to ensure that initiatives towards CE do not turn out to be counter-productive from the environmental point of view (e. g. rebound effect) or phagocytosed by the current "linear" paradigm that CE expressly aims to overcome, by confusing the means (e. g. implementation of strategies improving eco-efficiency at the micro level) and the ends (staying within the planet's bio-physical capacity); such considerations can be useful for policy-makers and institutions to design environmentally effective strategies related to CE (top-down approach). On the individual and company level, an ideal-typical definition, and the normative criteria derived from it, can be used by businesses as a benchmark aiming at improving their environmental performance; by consumers to evaluate their choices (bottom-up approach). Moreover, the psychological aspect of presenting an ideal-typical vision should not be overlooked, as ideals and expectations do political work by bringing "futures into being, while presenting pathways through which change is to be achieved" [42].

2.3.3 *Normative basis of the framework: current international consensus*

The willingness to maintain the environmental qualities of today's Earth intact is not an ideal goal pursued for its own sake. It is the result of an anthropogenic and utilitarian view [75], which implicitly assumes that the focus should be on allowing humanity to survive and ideally to thrive further. The relationship between a healthy environment and human dignity and well-being of present generations is acknowledged in international agreements. The Principle I of the 1972 Stockholm Declaration, agreed at the United Nations (UN) Conference on the Human Environment, declared that:

> "Man has the fundamental right to freedom, equality and adequate conditions of life, in an environment of a quality that permits a life of dignity and well-being, and he bears a solemn responsibility to protect and improve the environment for present and future generations.(...)" [283]

Even if it is not a legally binding instrument, its thinking is widely accepted, as shown by various subsequently adopted non-binding declarations (for a list see [284]). Moreover, maintaining the environmental balance in control is necessary to ensure that future generations enjoy the same "playfield" than the present one. The will to ensure both intra and inter-generational equity lies at the core of reflexions on sustainability, as reflected in the famous definition of the notion of Sustainable Development which was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [285, 286]. It stems from the report of the World Commission on Environment and Development (WCED) "Our common future", which is advocating the growth of economies based on policies that do not harm and can even enhance the environment. In 1992, the UN "Earth Summit" in Rio de Janeiro confirmed that environmental questions should be seen as a major global preoccupation of the international community; the global character of problematics of ecosystem degradation and natural resource management was reaffirmed, which largely contributed to the emergence of international environmental law. Building upon a decade of major UN conferences and summits, in 2000, the Millennium Development Goals (MDGs) stated eight development goals for the year 2015 and reaffirmed the willingness to "ensure environmental sustainability"[2]. The Sustainable Development

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[2] See `https://www.un.org/millenniumgoals/bkgd.shtml`

Goals (SDGs), which continue the MDG's and form the core of "Agenda 2030" again confirm the environmental concern and the need to act upon it [287]. CE is particularly relevant in relation to goal 12: "Ensure sustainable consumption and production patterns" and can be seen as a tool to achieve it. As the different SDG's are partly interdependent and CE touches on broad aspects pertaining to reducing environmental harm, it can moreover contribute to achieve others (e. g. direct links with goals 6, 7, 8 and 15 see [288]); actions towards achieving other goals can positively impact the transition towards CE (e. g. reversed links with goals 4, 9, 10, 13, 16, 17 see [288]).

The idea of Earth system limitations to human activities has led to the development of a multitude of approaches to describe the Earth system capacity in ecological terms [75]. Among the most frequently used are the planetary boundaries [77, 79] and the ecological footprint [76]. The basic idea behind such approaches is, that all collective human activities need to be within the bio-physical capacity of our one and only planet in order to ensure its viability for humans in the long run. While the details of the calculation and of the scientific design of the approaches can be largely debated [85, 112, 289–294], the idea of assessing human impact in relation to the critical boundaries and the capacity of the Earth system has found wide international resonance [75][3]. Following this line of thought, we place the physical and environmental limitations of the planet at the core of our CE definition.

2.3.4 *Physical and environmental restrictions on resources*

The physical and environmental constraints that have to be considered towards a transition to CE consist in identifying the sustainable resource base (see section 2.3.4.1) and determining how to best utilize it (see section 2.3.4.2).

2.3.4.1 *Identification of a sustainable resource base*

On a limited planet, the total amount of any resource is limited. Considering the vastness of the planet, human operation may appear insignificant compared with these absolute physical limits. e. g. the Earth system receives a total energy flux from the sun of $\approx 10^{17}$W [245], whereas primary energy

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[3] For Switzerland specifically, see `https://www.bfs.admin.ch/bfs/en/home/statistics/sustainable-development/ecological-footprint.html`; and [87].

demand of humans in 2015 is with $\approx 10^{13}$W [246] four orders of magnitude smaller. However, such an analysis is greatly misleading, as it disregards the resource requirements and emission-absorbing capacity of the Earth system [226]. Thus it is necessary to have a sound understanding of the share of the Earth's physical resources which are sustainably available for human appropriation.

The scientific description of the Earth system is based on modelling, abstraction and empirical calibration, which creates uncertainties. With advances in science and modelling efforts, the uncertainties can be made smaller. Theoretically, the uncertainties will be zero when the models become as complex and complete as reality itself [223]. Models are often used to describe and predicts a system's behavior, where the mean outcome (50 % probability) and the associated uncertainty range are of interest.

For management and design of technical and socio-economic systems, it is however important to make choices and decisions not based on mean values, but on those values which guarantee system functioning with a high confidence[4] (see figure 2.2). This logic is the underlying principle in engineering, i.e. designing systems with a very small probability of failure, despite uncertainties, simplifications and limitations in available models (e. g. [224, 225, 295, 296]).

From a legal point of view, this logic translates into the "precautionary principle"[5], which is a general rule that was developed by international case law in order to avoid potentially dramatic or irreversible hazards. According to this principle, the absence of absolute scientific certainty regarding the effects of an action cannot be used as an excuse to delay the adoption of effective measures for protecting the environment[6]. This principle is implicitly recognized in the Swiss legislation, where the State

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[4] E. g. an aircraft with a probability of arrival of only 50 % (i.e. 50 % probability of crash) would not be considered acceptable. That's why critical aircraft parts and systems are designed in a way that their actual lifetime reaches the expected lifetime with an probability of failure $< 10^{-7} 1/\text{h}$ [227].

[5] The precautionary principle is often distinguished from the prevention principle. The latter applies in the case of recognized hazards and foresees the use of technical measures to reduce or suppress the risk. The prevention principle can be seen as a special case – where the uncertainty is identified and acknowledged – of the more general precautionary principle [218, 297]; in the present article, we include the prevention principle into the precautionary principle.

[6] Principle 15 of the Declaration of Rio (1992 UN Convention on the environment and development); regarding case law see e. g. Southern Bluefin Tuna Cases [New-Zealand – Japan; Australia – Japan], List of cases: Nos. 3 and 4, Provisional measures order of 27 August 1999, § 77 ss; Gabcikovo-Nagymaros Project [Hungary-Slovakia], Judgment, I.C.J. Reports 1997, p. 77-78, in particular § 140. On the principle of prevention and precaution in international environmental law, see Dupuy/Viñuales, Environmental Law, p. 58-64.

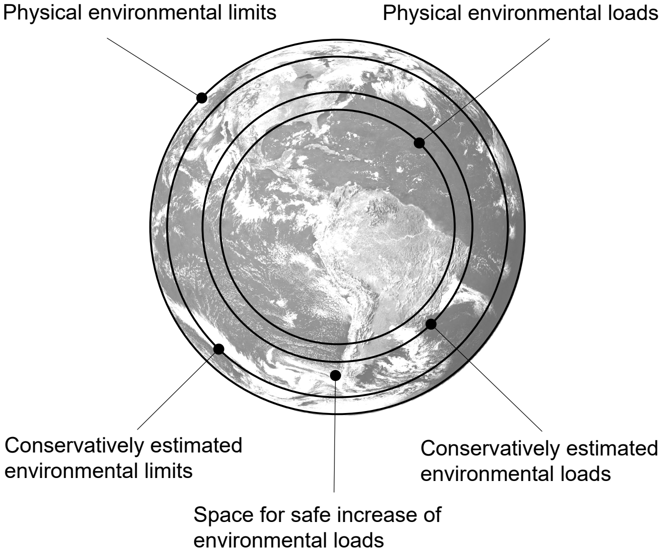

FIGURE 2.2: Precautionary principle for estimating the carrying capacity (or planetary limits) and environmental loads from human activities: the carrying capacity needs to be underestimated and the environmental loads overestimated according to best scientific knowledge, in order not to risk any overshoot.

shall ensure that environmental damage or nuisance is avoided and take early preventive measures in order to limit effects which could become harmful or a nuisance[7]. The application of this principle is leading to determine and adopt a security margin, which is allowing to take the scientific uncertainties into account [218].

Considering the global scale of human operations, the Earth's resources and emission absorbing capacity can no longer be approximated as infinite. On the contrary, it is necessary to apply the precautionary principle when describing the planetary capacity and designing environmental loads. This is to ensure that, despite all uncertainties, there is a high probability that the ecosystem can sustain the socio-economic system for generations to come. Following this logic, planetary capacities need to be determined at the lower

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[7] See art. 74 al. 2 of the Swiss Constitution: Federal Constitution of the Swiss Confederation of 18 April 1999, RS 101, status as of 1 January 2018; as well as art. 1 al. 2 and 11 al. 2 and 3 of the Federal Act on the Protection of the Environment [Environmental Protection Act, EPA]: Federal Act of 7 October 1983 on the Protection of the Environment, RS 814.01, status as of 1 January 2018. On the principle of prevention and precaution in Swiss law, see [218, 298]

end of the uncertainty range, as it is done e. g. in the planetary boundaries framework [77, 79], and environmental loads on the upper end of the uncertainty range, as it is done e. g. in risk assessment of chemicals [299, 300].

The current state of the Earth system is the only one, where we know for certain, that it can support human societies [79]. Ecosystems, however, have a limited resilience against human influence and it is necessary to respect their resilience boundaries in order to maintain their functionality [77]. Bio-physical boundaries have been observed for many variables on a regional (e. g. sustainable forestry [301]) as well as global scale (e. g. biodiversity [302], net primary production [112]). The planetary boundary approach [77, 79] identified 9 boundary categories which are essential to Earth system integrity: Climate change, change of biosphere integrity, stratospheric ozone depletion, ocean acidification, bio-chemical flows, land-system change, freshwater use, atmospheric aerosol loading, and introduction of novel entities, respectively. None of the regional and global boundaries shall be transgressed, thus they are equally important. The actual values and categories can change with progress in Earth system understanding and modelling as well as changes in the Earth system and are thus dynamic boundary conditions [75].

Human activities need to be designed in a way that they do not compromise, ideally even advance the Earth system functioning, also after intentional (e. g. abandoned building) or unintentional (e. g. dispersion [119]) discharge of its material and energy flows. The appropriation and discharge of resources is thus limited by the bio-physical capacity of the Earth system and have to be evaluated regarding the availability upstream and potential harm downstream (see figure 2.3). A CE can be considered sustainable, if it is built exclusively on the sustainably available resources, i.e. products and services utilize the ecologically available material and energy mix and a management system needs to ensure that globally resource needs don't exceed availability.

Let's consider our washing machine example. The outer panels can be made from different materials (e. g. plastics, coated steel sheet, stainless steel. . .). For a sustainable-circular washing machine, the materials would need to be chosen in regard to their global sustainable availability, considering resource utilization parameter like recyclability and lifetime of parts (which includes reuse and remanufacture and repair). Besides the comparison of different material alternatives, the absolute resource availability in relation to current global production indicates how much resource use

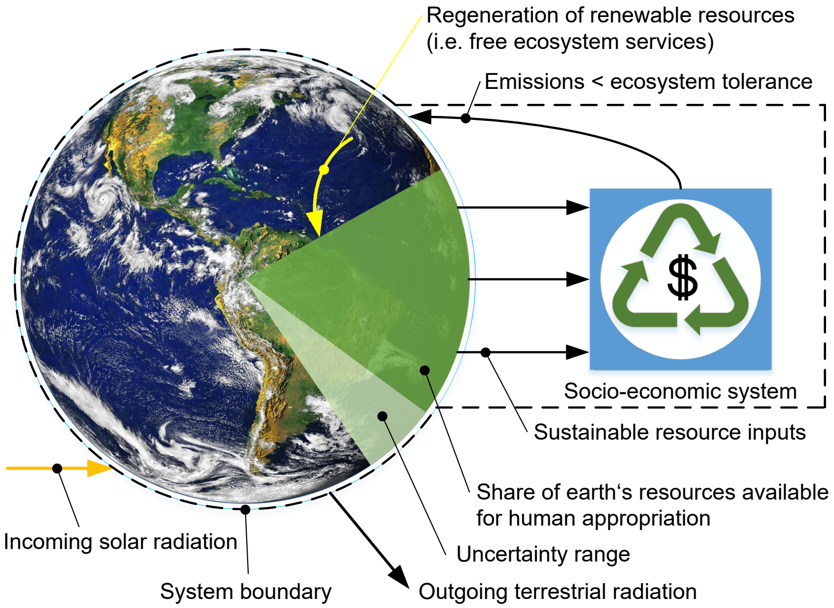

FIGURE 2.3: The dark-green slice schematically represents the sustainably available resources for the socio-economic metabolism. This slice may be in reality a little larger (light-green slice), but the precautionary principle requires that the sustainable share is determined at the lower end of the uncertainty range. The rest of the resources are necessary for Earth system functioning, which includes the absorption and regeneration of emissions, providing free ecosystem services such as fresh water and air.

needs to be reduced (or can be still increased) to become environmentally sustainable. Such targets can be considered in the design of product systems, such as e. g. a washing machine. It provides an indication on how much the resource intensity of the service "washing" would need to be reduced to become sustainable on a global scale, if the demand is assumed to be constant. It can also be used to set targets for industrial sectors and countries to reduce their absolute resource use, as it is attempted for CO2 in the science based targets initiative [303].

2.3.4.2 *Ensure an effective resource utilization*

CE is a system with restricted inputs and outputs. The highest standard of living can be achieved, when the inputs are used most effectively and outputs are reduced. There are, however, physical limitations to the utilization of resources.

Even though energy is conserved, only such energy conversions are possible where the entropy increases. Consequently, there are more or less useful forms of energy and its useful content can be described as exergy [114, 304]. Every conversion process decreases the exergy content, i.e. exergy is destroyed [114, 305]. Entropy correlates to the probability of a system to appear in a particular state [306]. A high state of order, e. g. a crystal structure, is less likely than a low state of order, e. g. random distribution of molecules in gases. Thus the entropy is low, when the order is high and vice versa. It is possible to increase the order in a specific part of the system, such as in the refinement of iron ore to steel. However, this requires useful work (i.e. exergy) and in the overall system the orderliness decreases.

In a production process, raw material with high entropy is refined through the employment of exergy into a product with low entropy (i.e. high order). In the use phase of the product, the entropy increases and, to restore the initial order, it again requires exergy (see figure 2.4). Every change in the entropy level in a product leads to entropy production in the overall system and thus decreases the usefulness of its resources. Consequently, the first fundamental requirement for CE is:

> The circular economy aims at minimizing entropy production.

Small changes in entropy levels are preferable for a CE. The waste hierarchy, as it is often proposed in a CE context (e. g. [307]), can be derived from this requirement. Reuse of parts or products without any changes requires no change in the entropy level of the material, whereas refurbish and recycle result in increasing entropy changes. Production out of raw material and disposal in a landfill (i.e. "linear economy") results, in most cases, in the largest changes of entropy in the material and is thus the least preferable option. However, the principle of minimizing entropy is not limited to end-of-life strategies, but has to be applied to all lifecycle steps, e. g. material selection.

Coming back to the washing machine, every stage of the life cycle consumes exergy and produces entropy. E. g. including the additional functionality of automatic dosing of detergent requires additional equipment but

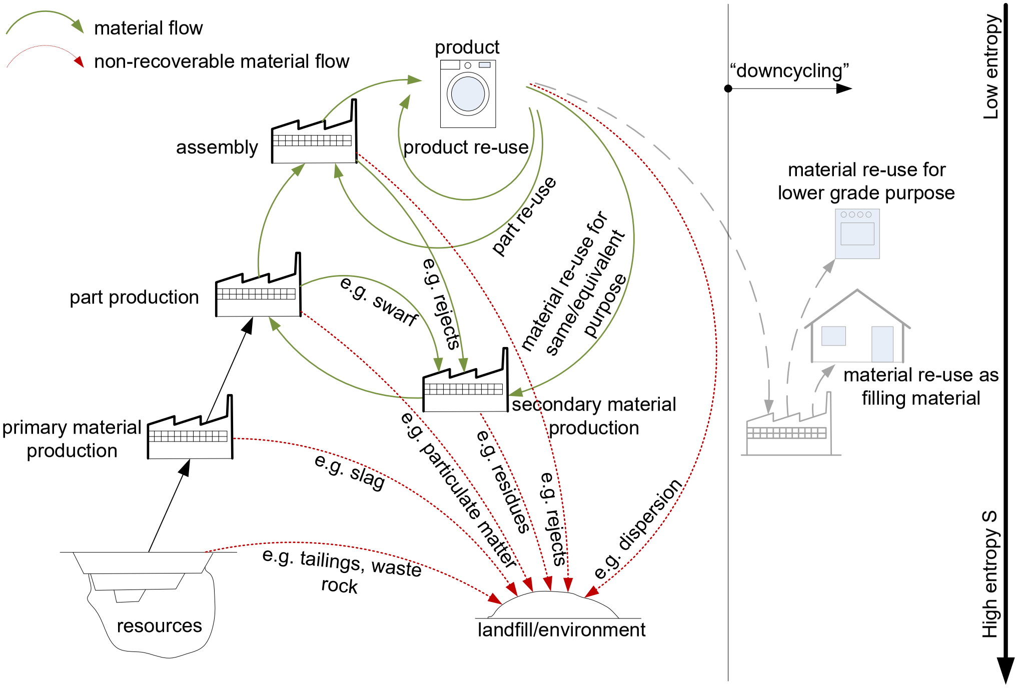

Figure 2.4: Schematic representation of entropy changes in lifecycle steps (entropy axis on the right). Virgin resources (high entropy) are refined to products (low entropy). At the end of life, different strategies lead to different changes in the entropy level, where green arrows indicate recovered materials, and grey denotes downcycling, where the material cannot be used for the same purpose any longer. Every step in the life cycle leads to inevitable losses (red).

potentially reduces detergent consumption. The amount of exergy destruction for the alternatives with and without dosing system can be evaluated and the alternative with the lower value selected. Alternatively, the entropy production can be evaluated through either thermodynamic entropy (e. g. in energy dominated systems, like the heating system in a washing machine) or statistical entropy (e. g. for concentration and dilution activities, like detergent production and waste water treatment, see [205]).

Theoretically, materials can be cycled indefinitely, as long as sufficient exergy is available [5]. Since available exergy is limited, materials need to be kept at a low level of entropy for as long as possible. However, many different mechanisms, such as dispersion, dilution, contamination, degradation and process losses, inevitably transform materials into a state of high entropy, where it is essentially lost for technical use and thus material cycles cannot be fully closed (see figure 2.4 and table 2.2 on page 63 in SM). E. g. material can be dispersed as fine particles in the environment, with no practical means of recovery. Accumulation of impurities is another example for practically limiting factors to recycling [118, 156]. In general, every process step and exposure to ambient conditions, eventually leads to a loss or degradation of the material. To utilize the materials as long as possible, it is essential to build "clean cycles" [121], minimize losses to the environment and design product cycles for longevity [164]. The faster a product needs to be replaced, the more often a cycle is needed to provide the same service again and the more material is lost per functional unit. As a second, general requirement for CE, we can thus derive that:

Durability is key to preserve material value ("slow cycle").

The longer a material can be used for its beneficial and intended purpose, the less material per functional unit is lost. Even though material value is preserved, technological progress might make it beneficial to upgrade or replace the product prematurely due to increased energy efficiency in the use phase [188]. This is however only relevant for technologies in early development stages and products causing high impacts in the use phase in comparison with other life-cycle phases and a technological upgrade may solve the problem [171].

E. g. once produced, the washing machine side panel doesn't cause any environmental impacts during its useful life and it is therefore beneficial to use it as long as possible. The washing machine, at the other hand, requires resources and causes environmental impacts during the use phase. The efficiency of the washing machine declines over time due to calcination, wear and material ageing and a newer model may have increased efficiency, making it environmentally beneficial to replace the old machine at a certain point (i.e. ecologically optimal lifetime [308]). The side panel, as many other parts of the old washing machine, can be still used in its intended function in the new model, which however would require a standardization of these parts and a take back mechanism for old machines. The longer the use of its parts, the smaller the amount of resources required to fulfil the same functionality.

Materials and energy are available in limited quantities, especially those qualities, which can be technically made available for human use [5, 164]. To utilize both materials and energy as long as possible, they need to be applied as effective as possible. Efficiency is the third general requirement for CE:

> Optimizing output per unit input for all resources (i.e. efficiency) utilizes the sustainable resource base best.

For washing machines, energy efficiency had long been in the focus. However, this concept has to also be applied to resource in general, i.e. consumables in all life cycle stages (e. g. detergent, solvents) as well as materials in the machines itself. The efficiency can be increased at the level of processes (i.e. minimize process losses and manufacturing waste) or in the product. e. g. light-weighting, functional integration and washing cycle optimization can reduce resource demand of a washing machine.

The strategies of material cycling of mainstream CE understanding, along with strategies from related schools of thought, are derived as a consequence of optimized resource use in a restricted socio-economic system. To select the optimal solution for a product, initiative or strategy, a thorough assessment against the general requirements and the sustainable resource base needs to be carried out. Again, such an assessment needs to follow the precautionary principle, that is to say, impacts need to be calculated as the upper limit of the uncertainty range.

2.3.5 *Definition*

Building on the findings of the previous sections, taking into account the limitations of current definitions, the idea of a normative status, but also the physical and ecological considerations, we propose to define CE as follows:

> The Circular Economy is a model adopting a resource-based and systemic view, aiming at taking into account all the variables of the system Earth, in order to maintain its viability for

> human beings. It serves the society to achieve well-being within the physical limits and planetary boundaries. It achieves that through technology and business model innovation, which provide the goods and services required by society, leading to long term economic prosperity. These goods and services are powered by renewable energy and rely on materials which are either renewable through biological processes or can be safely kept in the technosphere, requiring minimum raw material extraction and ensuring safe disposal of inevitable waste and dispersion in the environment. CE builds on and manages the sustainably available resources and optimizes their utilization through minimizing entropy production, slow cycles and resource and energy efficiency.

Appropriate strategies within CE can then be e. g. life time extensions, combination of functions, upgrade of old products to new technological standards, repair, reuse functions, reuse parts, recycle materials, etc., which have to be selected, case by case, considering minimum resource requirements and environmental impacts.

2.4 DISCUSSION

Except for the assumed normative position to ensure inter-generational equity and the acknowledged willingness to serve human well-being and prosperity (see section 2.3.2), our abstract and systemic definition of CE intently disregards the content of normative considerations, as they are, per definition, subject to change. From a theoretical perspective, the organization of the society and the contours of – and how we actually define – human well-being and economic prosperity are the result of normative and political choices that therefore do not have to be further defined in the view of an ideal-typical definition as developed above. Different social organization forms and political systems could certainly be fit to stay within this frame and achieve a non-wasteful use of resources, given that they respect a resource based-approach. Moreover, different forms of CE can be imagined and could coexist [270]. In an attempt to nevertheless give hints and avenues for reflection and to embed the natural science and engineering considerations developed in section 2.3.4 into a larger context, we suggest that following general considerations may be discussed, if the goal is to implement a CE concept that is systemic and resource-based by definition. In section 2.4.1 we raise some important governance questions and show in section 2.4.2 possible pathways towards an integration of Earth system capacity into resource governance. Section 2.4.3 discusses the role of business in this approach and will highlight some possible challenges and consequences deriving and whenever useful, applied to the example of a sustainable-circular washing machine.

2.4.1 *Resource management and governance questions*

A resource-based approach implies to quantify the resources available and then to agree on repartition mechanisms. A big task ahead will consist in developing mechanisms to ensure the allocation of the available resource base, as different allocation principles can be imagined (e. g. egalitarian, based on economic throughput or capacity, using historical approaches like the grandfathering principle, etc. [303]). In this regard, some of the questions which need to be addressed in a political discourse – and more importantly agreed on and implemented – are:

- How to globally agree on a method or standard to quantify the available resource base, as different methods can be challenged and all integrate necessary approximations and assumptions?
- How to divide and allocate this available resource base then among nations, regions, economic sectors, companies and individuals? By whom should the allocation be calculated and by using which criteria?
- How to ensure that the planetary limits are respected everywhere and at all times? What kind of (world-wide) monitoring system could help achieve such a goal?
- What are the more efficient and politically acceptable policy instruments? Should we favour top-down regulations, with quotas, legal interdictions, obligations and penalties over “political incentives” and self-regulation (“budgeting” and/or “targeting”)?
- Under what conditions could we rely on existing market-based mechanisms for a sustainable resource allocation? In other words, could the weight of negative externalities be integrated into and reflected by price mechanisms?
- How to achieve coherence in the governance of natural resources, especially with regard to the current spatial mismatch between sovereign institutional territories and global resource flows?

2.4.2 *Towards a systematic socio-economic integration of Earth capacity*

Ehrenfeld [49], building on intuitionalist models of organized social behaviour, describes "the dominant social paradigm" (DSP) as the paradigmatic foundation in which dominant beliefs and social norms are contained: specific forms of social structures result from the diffusion of "the culturally foundational notions into more explicit organizational (or paradigmatic) forms – government, church, family, corporate, etc. – and the shape of missions, tools, and authoritative relationships that characterize them". The author states that the natural world has been disconnected from social thinking and action in the paradigmatic base of western modernity; therefore implementing our ideal-typical CE within the current DSP represents an (impossible) challenge. Indeed, most of our current institutional structures are being rooted in a "linear" world view and the transition towards a more "systemic" one imply deep changes. Environmental law for example, as credibly shown by DeLucia [22], historically, is infused with particular epistemological assumptions and cultural values, which reflect a worldview developed "under the influence of the prevailing Cartesian legal ontology". The current position of environmental law internationally is therefore really delicate, as its role is to address multiple ecological crises, while "structurally and conceptually being rooted in a broader legal tradition thoroughly implicated in the domination and 'othering' of nature", hand in hand with science ("the scientific-legal complex") [22].

With regard to a systemic and resource based CE, it appears that the integration of the natural world and the Earth capacity into socio-economic thinking requires a shift in the paradigmatic base, as it implies a change in the way all social actors, be it individuals, businesses or governments consume and produce, and more generally, on how they see the world. It may require to question and adapt our world-views on different subjects (e. g. relationship between humans and nature, patterns of politics, methods of scientific inquiry) [49, 309]. As stated by the World Business Council for Sustainable Development [310], "transitioning to the circular economy will catalyse the most transformational economic, social and environmental changes since the First Industrial Revolution". As an illustration, in the following lines, some institutional consequences of a model being deeply rooted in a linear world view and how systemic thinking might affect them, are briefly discussed.

2.4.2.1 *From compartmentalization towards integration*

According to a strong compartmentalization logic, environmental considerations are treated as separate and distinct from social and economic considerations. For example, "environmental sustainability" was only one out of 8 MDGs and the environment is considered in only 3 out of 17 SDGs. A similar logic is often present in national regulations, where environmental law is approached as a specific domain instead of being embedded into other regulatory fields. The interests of the environment are weighted as separate parameters to be balanced with other considerations, implicitly occulting the link between the economic and social impacts of the environmental and resource crisis. This reductionist understanding is particularly visible in the weak understanding of sustainable development[8], which is aiming at balancing environmental, economic and social considerations, while accepting that a decrease of environmental capital can be compensated by the increase of economic or social capital. The original conception of sustainability, as presented in the Brundtland report [285], imposed to preserve natural systems and resources in order to maintain the global integrity of the Earth system, is more in line with a systems perspective; there was no possible trade that would allow to compensate irreversible environmental losses through an increase in economic or social capital [311]. For approaching our ideal-typical definition of CE, the physical limits and environmental boundaries, derived according to the precautionary principle, can be seen as the frame within all activities need to take place. Hence, to reach a socio-economic system that is sustainable in the long run – at least from an environmental perspective – it should be ensured that the principles of CE, as defined in section 2.3.5, are respected on a global scale and every socio-economic activity takes place within these boundaries. As a consequence, when it comes to regulating the social organisation (and the economy, which is part of the society), decisions that are not allowing to stay within the safe operating space for humanity [313, 314] should be dismissed. Considerations about the sustainably available resource base are therefore to be integrated into every sector and activity. An example of this understanding is the "wedding cake" representation of the SDG's developed by the Stockholm Resilience Centre, which acknowledges that economies and societies are embedded in the biosphere and that different

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[8] For the distinction between strong and weak sustainability and different understandings of the notion, see e. g. [311, 312].

SDG's directly or indirectly rely on a sound resource base and food system[9]. Also, the idea of integration has already found its way into the policies of the EU: making sure that environmental concerns are fully considered in the decisions and activities of other sectors is a requirement under the EC Treaty since 1997[10]. To put this requirement into practice, the European Council launched the "Cardiff process" in 1998, which was designed to introduce a horizontal approach to environment policy by incorporating it into all Community policies[11]. The importance of environmental integration was reaffirmed in the 6th Environment Action Programme[12].

2.4.2.2 *From short-sighted and free market coordination towards prioritization of long-term sound management of resource base*

Given the combination between the free market as the primary coordination institution [49] and a short time-horizon for decision making and profit earning, environmental regulations are generally perceived as barriers to the exercise of individual and economic freedom[13]. The subsidiary importance of environmental protection acts and its potential opposition with individual and economic freedom can be observed in the international context[14]. Environmental law is sometimes presented as a "mitigating"

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[9] See `https://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html`, consulted on June 17, 2019.

[10] Article 6 of the Treaty establishing the European Community (Consolidated version 2002), OJ C 325, 24.12.2002, p. 33–184 (ES, DA, DE, EL, EN, FR, IT, NL, PT, FI, SV), Document 12002E/TXT, `http://data.europa.eu/eli/treaty/tec_2002/oj`: "environmental protection requirements must be integrated into the definition and implementation of the Community policies [.] in particular with a view to promoting sustainable development".

[11] More information related to the Cardiff Process see `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l28075` and Communication from the Commission to the European Council – Partnership for integration – A strategy for Integrating Environment into EU Policies – Cardiff – June 1998 /* COM/98/0333 final */ (`https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:51998DC0333&from=EN`)

[12] Pertaining to art. 1 al. 1 of Decision No 1600/2002/EC of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme, "[t]he Programme should promote the integration of environmental concerns in all Community policies (...)" (`https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32002D1600&from=EN`).

[13] For an example: the main argument for rejecting the interdiction of single-use plastic bags in Switzerland was that it could be considered as a disproportionate limitation of economic freedom, see [315]

[14] See e. g. in the field of biodiversity protection art. 2 al. 3 of the Convention on Wetlands of Importance especially as Waterfowl Habitat (or Ramsar Convention): "the inclusion of a wetland in the List does not prejudice the exclusive sovereign rights of the Contracting Party in whose territory the wetland is situated", `https://www.ramsar.org/sites/default/`

or "containment" instrument aiming at reducing the ecological problems created by economic and industrial activities "to the extent possible" [22]. The same phenomenon is to be found at the national level: in Switzerland for example, some dispositions of the Environmental Protection Act (EPA)[15] are weakened by typical reservations expressed as "wherever possible" (e. g. art. 30 al. 1 et 2 EPA) or "provided that this is economically acceptable" (e. g. art. 30d al. a EPA, see also art. 11 al. 2 EPA). Swiss case law also explicitly addresses the relationship between environmental protection and economy as a "tension field" (ATF 131 II 431 ss, ground 4.1)[16]. According to art. 36 of the Swiss Constitution (Cst.)[17] restrictions to fundamental rights can be admitted, if the restrictions are necessary and proportionated to guarantee a higher public interest (health, political stability, etc.). In some cases, restrictions to economic freedom (which is a fundamental right, see art. 27 Cst.) were justified by the protection of the environment (ATF 140 I 218 ss, ground 8.8; Supreme Court 2C_136/2018, September 24, 2018, ground 6.1). From a systems perspective this makes a lot of sense, a stable environment is a precondition for the economy and society to function. As already identified by the Commission of the European communities in 1998, *"the current pattern of economic development too often entails conflicts between development and environment; this cannot be permitted to continue. Policies that result in environmental degradation and depletion of natural resources are unlikely to be a sound basis for sustainable economic development"* (COM/98/0333)[18]. Regulations, their application – and therefore mentalities – need to adapt in order to overcome this constructed and unsystematic tension field that lies in the way of a transition towards a CE. With a change of perspective, environmental regulations and restrictions could even be perceived as a positive enabler to allow well-being (including economic wealth) and long-term survival (and profit), rather than a barrier to the exercise of their

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`files/documents/library/scan_certified_e.pdf`; RS 0.451.45 or art. 22 of the Convention on biological diversity (CBD) "The provisions of this Convention shall not affect the rights and obligations of any Contracting Party deriving from any existing international agreement, except where the exercise of those rights and obligations would cause a serious damage or threat to biological diversity", `https://www.cbd.int/convention/text/.`; RS 0.451.43.

[15] Federal Act of 7 October 1983 on the Protection of the Environment, Systematic Register for Swiss Federal Legislation ("SR") 814.01, status as of 1 January 2018; it is among other intending at preserving "the natural foundations of life sustainably" (see art. 1 al. 1 EPA).

[16] ATF stands for "arrêt du Tribunal federal", which means Decision of the Swiss Federal Supreme Court; on this question see Felix Uhlmann, Grundprinzipien der schweizerischen Umweltverfassung aus der Sicht des Wirtschaftrechts, in URP 2007 p. 706.

[17] Federal Constitution of 18 April 1999 of the Swiss Confederation, SR 101.

[18] see footnote 11

rights and freedom[19]; hence, instead of thriving to balance supposedly conflicting interests, measures towards a sound resource management would be prioritized in order to ensure other interest (like economic and individual freedom).

2.4.2.3 *From end-of-life towards life-cycle thinking*

The evolution of environmental law shows that often, major regulations were adopted after main environmental catastrophes, namely to mitigate contaminations, when they became a visible nuisance (see e. g. [317]). Waste law is being rooted in an end-of-life approach, where the goal is to better manage waste and the contamination of the environment. It is focusing on improving collection and recycling. A lot of progress has been made over the years (from landfill to incineration, better recovery rates and recycling techniques, etc.). However, such an end of pipe approach, focusing on reducing the symptoms and trying to mitigate the negative impacts of production and consumption, rather than examining the global picture, does not cover all aspects of a CE and is therefore insufficient. A conceptual shift towards life-cycle thinking which could be recognized as a formal environmental principle [318] would be beneficial. It reflects a perception of environmental problems that puts the product at the centre, through its entire life phases and associated impacts [319]. Product design and the policy framework impacting design "assume a central role, guiding the flows of materials in and out of the environment, and, at the same time, reflecting their social, economic importance. Looking at products, rather than processes, shifts the policy-maker's focus from the end of the process pipe to the center stage of the market and the market's social importance as a means to satisfy the collective demands of a policy" [49]. Legislation doesn't expressly address or define life-cycle thinking yet, but the EU environmental policies, namely in the light of the CE Package[20] and the Green Paper on Integrated Product Policy[21] consider it as an important "policy principle" [318]. The cascading waste hierarchy, which establishes a priority

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[19] Regarding frameworks aiming to elaborate an ecological philosophy of law, see [316]

[20] More information on the Final CE Package for Circular Economy see `http://ec.europa.eu/environment/circular-economy/index_en.htm`; regarding the adoption of an Action Plan towards CE, see COM/2015/0614 final: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Closing the loop – An EU action plan for the Circular Economy, 2.12.2015: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614`.

[21] COM/2001/68 ; see also Commission Communication on Integrated Product Policy Building on Environmental Life-Cycle Thinking, COM/2003/302 final, p. 10.

order from prevention, preparation for reuse, recycling and energy recovery through to final disposal, such as landfilling, is a principle that aims to encourage the options that deliver the best overall environmental outcome (see COM/2015/0614 final cited in footnote 20; in Switzerland, see art. 30 EPA), which is also reflecting a step in direction of life-cycle thinking approach. Going a step further could consist in recognizing the existence of "(EU) materials law" [318] or to shift from waste to product law [60]. In relation to the illustrating example of the circular washing-machine, the integration principle could lead to take into account a sound allocation of resource scarcity and budgets in public policies or legislation: that could for example be formalized through importation taxes or directives regarding the choice of materials and product design (e. g. prohibition to use scarce materials if an alternative is available); prioritizing environmental impact rather than free market as a coordination mechanism could for example lead in extended interdictions of toxic substances and materials, changes in accounting rules and standards, taxing "entropy production" rather than "value creation", which should all be designed in a way to make a circular washing-machine more attractive over its life-cycle. Finally, shifting to a life-cycle approach could, for example, be reflected with further implementation of the Extended Producer Responsibility, extension of guarantees, obligations to provide spare parts, higher taxes on primary resources and lower taxes on labour, which are all possible actions that incentivize a better conception of the product with a long-term perspective in mind and an extended usage, through maintenance, repair and refurbishment.

2.4.3 *Business as a driving force of the transition?*

Implementing sustainable CE imposes new boundary conditions for the economic system and also requires a paradigm shift in corporate understanding. As argued in section 2.3.4.1, resources are available in finite quantities. Hence, either there will be regulations that oblige companies to internalize their resource budgets or companies will voluntarily internalize it. In the second case, companies will benefit from the saleable first mover advantage, reduced dependence on resource price fluctuations and positive benefits of social welfare. Either way, this inclusion of resource finiteness would be the starting point for companies to change the current inside-out perspective in the business-as-usual paradigm and shift the perspective to outside-in. Analogous to the considerations of Dyllick and Muff [320] thoughts to "Truly Sustainable Business", this means that companies need to integrate environmental and social factors into their business management strategies and in their business models. The typological increase (Business Sustainability 1.0, 2.0 and 3.0) used by Dyllick and Muff [320] starts with companies that pay attention to sustainability due to external pressure or market factors without changing the current business premises up to companies that convert sustainability challenges into business opportunities and give business sense to social or environmental issues. The voluntary inclusion of such resource budgets as a self-restricting instrument raises companies in this typology high upwards.

The pragmatic application of this outside-in approach can be found in the innovation from traditional to more sustainable (e. g. [321–323]) or in our case cycle-oriented business models (e. g. [324]). The change of perspective through the outside-in approach can also lead to more integral and sustainable management practice as called for e. g. by Stead and Stead [325]. Especially the voluntary restriction to sustainable resource budgets and optimizing its use through company management may stimulate activity in the market economy as well as in social and political structures and provide important impulses for the introduction of state-coordinated regulations towards sustainable resource allocations. The paradigm shift lies in the fact that the inclusion of a finite availability of resources becomes a key factor in strategic decisions and thus actively flows into the corporate calculation.

The paradigm shift can also be seen in a further pragmatic step as the effort of companies to innovate their business models as a result of the (exogenous) resource budget constraints. This is due to the fact that innovative business models (e. g. "light as a service" [326]) can drastically reduce the resource requirement and thus can be of significant competitive advantage. And business models determine the profound purpose and activities of a company as well as the logic of how value is delivered to the consumer as a holistic description [327–330]. The growing business model literature deals with the in-depth redesign of business models and demands an easier integration of sustainability into the business of companies [322, 324, 331–334]. In this context, various authors speak of "circular business models" [165, 335, 336]. It is important to note that the idea of “one” business model on its own can achieve CE seems rather illusory – in view of all the business activities that have to be undertaken to create a CE. The "circular" says more about the "cycle applicability" than about a self-contained circular business model. It is therefore helpful to place the innovation of "circular" business models in the larger context and to see it as a bundle of business models along the closed-loop supply chain which enable for CE [337–

339]. It is important, consequently, that the considerations of the boundary conditions are carried out over the entire closed-loop supply chain.

The practical example of the washing machine from section 2.3 with the changes in design, selection of materials and the adapted possibilities of usage show how challenging the design of new, cycle-oriented business models can be. A critical and complicating issue, which is typical for the linear economy, is the fact that products are classically sold to the consumers. The resulting loss of customer relationship and control over the product itself while it is used - due to the change in ownership - makes lifetime-extending repairs, maintenance or concrete refurbishment measures difficult [58, 340, 341]. In order to increase the profitability of such circular changes, incentives can be internalized via new revenue models, which no longer require a change of ownership and expand the corporate customer relationship [324, 340]. For practical illustration, two suitable revenue models – as an important part of a cycle-oriented business model – are presented in more detail: Performance-based contracting or pay-per-use [21, 58, 342]. The first one enables companies to deliver a comprehensive service promise (which includes maintenance, upgrading etc.) to their customers which aims to provide a desired outcome (e. g. clean garments) instead of the purchase of the washing machine. Due to the new contractual situation, the company generates income during the entire lifetime of the washing machine, and no longer only by selling it once. Also with the second revenue model the washing machine remains in the ownership of the manufacturer and the customer pays simply per wash, i.e. pay-per-wash. In addition, this increases the incentive for consumers to limit their consumption to what is necessary and to price it more precisely. Studies in the corporate context show that the implementation of cycle-oriented business models or patterns is complex and subject to a wide variety of interlinked dimensions of politics, market, society and technology [39, 343, 344]. All these studies show barriers towards the implementation of CE and demonstrate at the same time the key role of companies in the centre of all these interconnections and interdependencies as effective implementing bodies of CE. The analysis of the barriers identified (often divided into cultural, technical, market and regulatory barriers) indirectly reveal the enormous inherent potential that can be found in solutions to overcome them. Kirchherr et al. [39] show how the different barriers are connected and that the interrelatedness of these can lead to chain reactions towards the implementation failure or success of CE. In this way, market-relevant factors can prevent political and thus legal changes, which in turn prevent market efforts towards new and innovative cycle-oriented business model innovations and in the end hinder change in consumer behaviour. For example, a lack of demand for resource-saving and cycle-oriented products can lead to a restrained supply of such products on the market and limited funding related business models, which in turn reduces the signal for politicians to elaborate incentive systems for companies who want to produce cycle-oriented products. The described interdependence does not only move in one direction but can also be seen as one with reciprocal potential.

This is a clear statement for the voluntary participation of companies in the integration of the above-mentioned resource budgets and thus taking up the role as exemplary signal carriers in the market. Companies can therefore not only benefit from the predicted financial long-term potential of CE and innovative cycle-oriented business models [61, 345], but also redefine its corporate sense of purpose. They can directly or indirectly as a by-product of their traditional corporate activities play this important role in the transition towards CE. The corporate opportunities resulting from new cycle- oriented business models can thus be transferred on the one hand to secure corporate prosperity and long-term survival and on the other hand, trigger important impulses beyond the actual corporate sphere of activity. In order to bring CE forward, there is a need to critically evaluate the risk that either companies or governments use CE as pure symbolic signalling effect [346, 347]. Otherwise, CE as a concept becomes meaningless and degenerates into a simple marketing medium.

2.5 CONCLUSIONS

This paper presents a systematic top-down approach to CE, which describes an ideal, or reference, and aims at connecting global sustainability criteria with initiatives at company level. The normative assumption behind this ideal is based on the global consensus that humanity thrives for well-being and survival for present and further generations. In order to connect environmental boundary conditions with individual decision making, we identified a need to translate ecosystem boundaries into resource budgets. These serve two purposes: the comparison of material alternatives to aid the selection of materials based on easy-to-handle environmental criteria, as well as the quantification of the absolute resource intensity reduction required to reach environmental sustainability on a global scale. A CE strives to utilize these limited resource most effectively and we have identified three general engineering guidelines to achieve this:

- Minimize entropy production: selecting circular strategies (e. g. reuse, refurbishment,. . .) according to the entropy production over the whole life-cycle.
- Slow cycles: prolonging the service life of parts (e. g. to be used in refurbished products) or the whole product (e. g. reuse).
- Resource efficiency: reducing process losses (e. g. off-cuts) and material demand for functional equivalence (e. g. light-weighting).

The implementation of a CE could be eased by the adoption of punctual new regulations and incentives, such as for example interdiction of mixed-materials, higher tax on raw material and lower tax on labor, etc. More importantly, transitioning towards a sustainable CE is tightly linked with a shift in the way we look at the world, which in turn impacts how we conceive, systematize and apply our regulatory and institutional systems. Namely, from a policy perspective, we suggest that a CE could benefit from and lead towards higher integration of environmental concerns into every other field, a clear prioritization of maintaining a sustainable resource-base over other short-term interests – in order to safeguard these interests in the long-run –, and finally a life-cycle-thinking approach. At the company level, this raises the question of how business models can be innovated along closed-loop supply chains in such a way that they can jointly satisfy customer needs within the resource budgets. This involves the shaping of customer relationships, entrepreneurial cooperation in value networks along the closed-loop supply chain and the shaping of suitable revenue models as well as product take-back procedures.

To support business model and technical innovations, guidelines and indicators need to be developed to enable and ensure an effective implementation of CE. These guidelines can influence the design of a product system starting with the conception phase, when the environmental impacts are essentially determined. Before a product enters the market, a life cycle assessment (LCA) [191, 192] study can show how effective the design process had implemented the sustainability requirements of CE. Further, material flow analysis (MFA) [253] on sector, country and global scales need to keep track of the material flows and monitor the actual utilization of the sustainable resource base and its associated environmental impacts of socio-economic activities. The business motive will drive innovation to utilize the restricted resources best. This will, we believe, trigger research and development of truly "circular" products, following the general guidelines outlined in this paper.

As a next step, there is a need to develop possible pathways to initiate a transition process towards such a CE. It is necessary to develop a methodology to estimate and calculate global sustainable resource budgets. Based on this, concrete product design guidelines can be formulated and tested in case studies together with companies. Business model innovation goes hand in hand with the product design, in order to achieve the resource intensity reductions in the product or service required to reach environmental sustainability globally. From an implementation perspective, the allocation of resource budgets requires the creation of new institutional structures or a political agreement within the current ones; however, voluntary bottom-up initiatives from companies, sectors, countries, can lead to self-orientation towards the respect of planetary boundaries.

Supplementary Material

QUOTATIONS OF KEY CONTEXT DEFINITIONS AND TEXTS TO SECTION 2.2

Definition of CE by the Ellen-MacArthur-Foundation:

> “The Circular Economy is an industrial system that is restorative or regenerative by intention and de-sign. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” [21].

Definition of CE by Kirchherr et al.:

> "A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." [39]

CE understanding by the European Commission:

> According to the scoping study of the European commission to identify potential circular economy actions, priority sectors, material flows and value chains (August 2014), “in contrast to today’s largely linear, ‘take-make-use-dispose’ economy, a circular economy represents a development strategy that enables economic growth while aiming to optimise the chain of consumption of biological and technical materials. A deep transformation of production chains and consumption patterns is envisaged to keep materials circulating in the economy for longer, re-designing industrial systems and encouraging cascading use of materials and waste. Although there are some

> elements of circularity such as recycling and composting in the linear economy [. . .] where progress needs to be maintained, a circular economy goes beyond the pursuit of waste prevention and waste reduction to inspire technological, organisational and social innovation across and within value chains." [265]

United Nations Environment Program's understanding of CE:

> The United Nations Environment Programme (UNEP) presents CE as "an economy which balances economic development with environmental and resources protection. It puts emphasis on the most efficient use of and recycling of its resources and environmental protection. (. . .) features low consumption of energy, low emission of pollutants and high efficiency. It involves applying Cleaner Production in companies, eco-industrial park development and integrated resource-based planning for development in industry, agriculture and urban areas". [268]

ON THE IDEAL TYPE AND 'GEDANKENBILD' (SECTION 2.3.2)

> According to Max Weber, "an ideal-type is formed by the one-sided accentuation of one or more points of view and by the synthesis of a great many diffuse, discrete, more or less present and occasionally absent concrete individual phenomena, which are arranged according to those one-sidedly emphasized viewpoints into a unified analytical construct ('Gedankenbild'). In its conceptual purity, this mental construct cannot be found empirically anywhere in reality. It is a utopia. Historical research faces the task of determining, in each individual case, the extent to which this ideal-construct approximates to or diverges from reality". [282]

TO SECTION 2.3.4.2

Mechanism	Description
Dispersion	Low concentration, fine distributed material, without or with chemical change (e. g. corrosion)
Dilution	Low concentration in application; e. g. coatings, composites, alloying elements, . . . [160]
Contamination	Material composition can change over time through contamination with foreign elements, e. g. through diffusion. In subsequent recycling loops, such contamination can increase in concentration, requiring dilution with primary material [118].
Degradation	Materials degrade under the influence of high-energy radiation, such as UV light or γ-radiation. [160]
Process losses	During any material processing a fraction of the feedstock cannot be turned into the final product. This is due to losses at the atomic level, incomplete chemical reactions, chemical side reactions, residues, mechanical machining, off cuts, . . .

TABLE 2.2: Mechanisms of irreversible loss of materials in a CE.

3

RENEWABLE ENERGY POTENTIALS TO POWER A CIRCULAR ECONOMY

> *Stone age didn't end because we ran out of stones ...*
> — William McDonough

BIBLIOGRAPHICAL DATA

Title	Powering a Sustainable and Circular Economy – An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries
Authors	Harald Desing, Empa
	Rolf Widmer, Empa
	Didier Beloin-Saint-Pierre, Empa
	Roland Hischier, Empa
	Patrick Wäger, Empa
Journal	Energies, MDPI
Date	submitted: 30 October 2019; published 11 December 2019

KEY FINDINGS

- Earth system boundaries and human demand for chemical energy limit the appropriable technical potential of renewable energy resources.

- Solar energy harvested on the already built environment and in parts of the world's deserts dominates this potential. All other renewable energy resources are of minor importance globally.

- It is possible to power a 2000 W-society with solar on the built environment alone, however, reaching the energy demand of a Swiss citizen in 2016 globally requires to develop solar in deserts.

THE AUTHOR'S CONTRIBUTION

I have developed the concept and method of ATP, wrote the calculation procedure in Matlab, gathered and analysed the data and wrote the original draft of the paper, including visualisations.

THE CO-AUTHORS' CONTRIBUTION

Rolf supported me with the development of the concept and method, validated the calculations and contributed to the analysis.
Didier validated the calculation and data.
Roland supported the development of the method.
Patrick supported the development of the method.
All co-authors contributed to and edited the manuscript.

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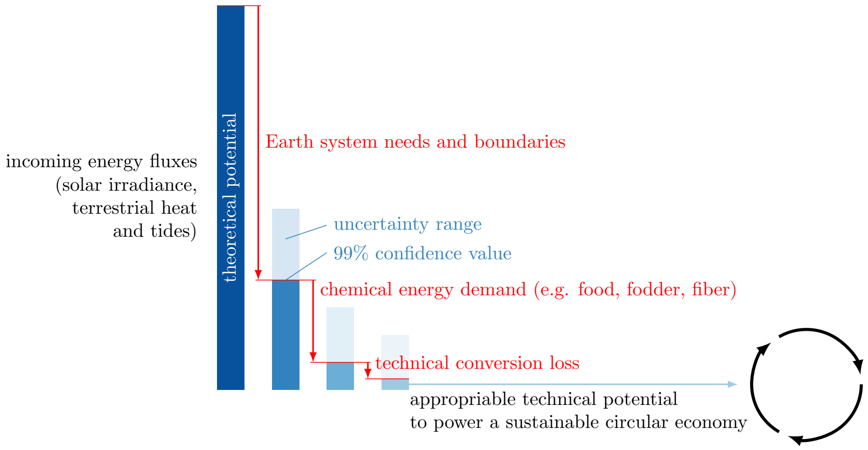
ABSTRACT

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.

GRAPHICAL ABSTRACT



3.1 INTRODUCTION

A circular economy (CE) aims at decoupling economic growth from natural resource depletion and environmental degradation, acknowledging the finite nature of the planet [21, 56]. 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 [5]. Moreover, the effort to recover materials (i. e. required exergy) increases nonlinearly with improved recycling yield [348, 349], 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 [246]), 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 [258], for example triggering a climate crisis [15, 77, 79, 350]. 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 [127]. 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" [285]. 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 [123, 124, 245, 351]. 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 [352]. 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) [246]. 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, ...) [126, 129, 353–355]; (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. [356, 357]); or (C) considering, in addition, political and economic feasibility in the assessment (e. g. [135, 136, 358–360]). 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 [56]. 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?

3.2 METHOD DEVELOPMENT

The method developed in this paper follows incoming global RE fluxes to the level of ATPs only (see figure 3.1). 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 3.1 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.

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 [77, 79]. However, crossing these thresholds runs the increasingly higher risk of triggering fast and irreversible environmental change towards new and likely less hospitable states [74]. 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 3.2.2.2), i. e. subtracting Earth system needs from the theoretical potential.

The appropriable potential satisfies the human demand for chemical energy (section 3.2.2.1) – 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.

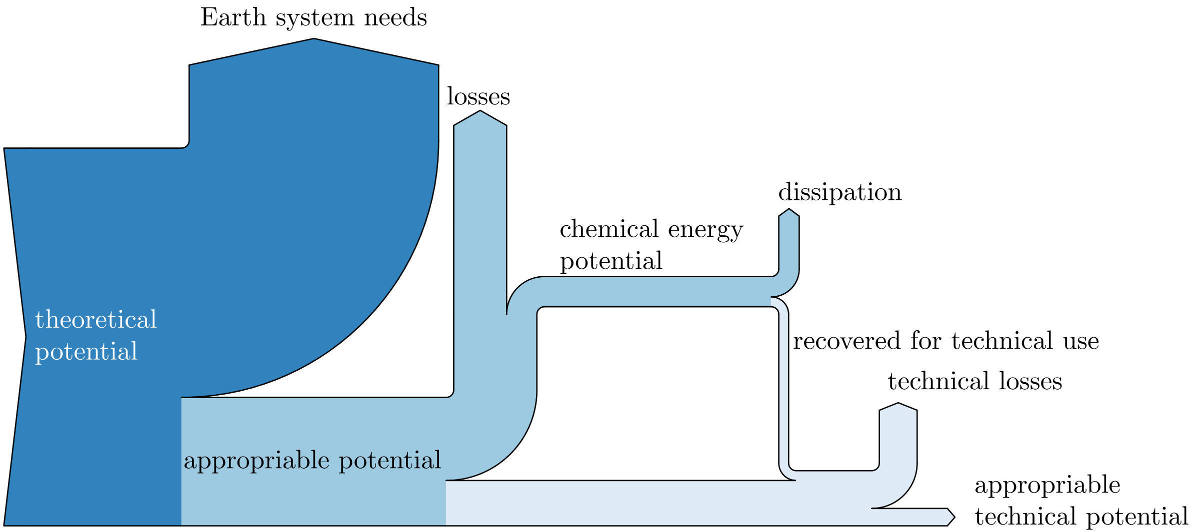


FIGURE 3.1: Schematic representation of the concepts of theoretical potential (i. e. incoming energy flux), appropriable potential (i. e. minus Earth system energy needs), and appropriable technical potential (ATP) (i. e. minus what is needed to provide appropriable chemical potential plus what can be recovered for technical use after chemical use and minus the technical conversion losses to electric energy). Fluxes are not to scale.

Conversion losses deducted, the remaining potential is defined here as *appropriable technical potential*.

3.2.1 *Core Modelling Principles*

The method is based on a common unit of comparison (section 3.2.1.1), a simplified system model (section 3.2.1.2) and explicitly deals with uncertainty to allow an assessment in line with the precautionary principle (section 3.2.1.3).

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 3.2.1.2), and therefore, energy fluxes are reported as annual average power and ATPs as annual average electric power output in units of watt[1]. The electrification of the energy system is often seen as key for a post-fossil society [361], 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.

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[1] Not to be confused with installed capacity; $1\,\mathrm{W} = 1\,\mathrm{J/s}$; conversion $1\,\mathrm{EJ/a} = 3.17 \times 10^{10}\,\mathrm{W}$

3.2.1.2 *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, $TSI_{p=0.997} = (1360.9 \pm 6.1)\,\mathrm{W/m^2}$ [245, 352, 362] [2]); (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 3.2.1.3). 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.

3.2.1.3 *Precautionary Approach, Uncertainty, and Assumptions*

Models are, by definition, abstractions from reality, inevitably leading to uncertainties [223]. 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 3.8 for more details). Despite the often large uncertain-

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[2] 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.

ties, 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 [56]. 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 °C [350] and $p = 0.5$ for 1.5 °C [15]) and lower than in many engineering fields (e. g. for aviation, ships, power plants, etc. $p > 0.999$ [227, 296, 363]). Furthermore, this approach is also in line with the concept of planetary boundaries (PB) [77, 79], 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 [353, 364]). 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.

3.2.2 *Limits to the Appropriation of RE*

According to figure 3.1, the appropriation of RE fluxes is limited by available technologies (see section 3.9 in Supplementary Materials), the human demand for chemical energy (section 3.2.2.1), and the environmental sustainability criteria (section 3.2.2.2). Detailed descriptions of values and calculations can be found in the calculation worksheet and accompanying code provided online (see Supplementary Materials).

3.2.2.1 *Human Need for Chemical Energy*

Plants are the first trophic level that convert solar irradiance into chemical energy, mostly as glucose and other sugars [123, 365], 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 [112]. Human appropriation of NPP (HANPP) has become a major factor in biological systems [11, 23, 366]. HANPP should be limited by ecosystem requirements, interference with water and biogeochemical cycles, biosphere integrity, and land transformation [10, 112, 367]. The latter three are already beyond safe limits [77, 79, 368], and water use trespasses safe limits in some regions [12, 369]. The appropriability of NPP is further lowered due to ecosystem degradation (e. g. soil loss) [34, 370] and will be exacerbated by the climate crisis [371].

Currently, HANPP is dominated by food production [11]. As the world's population is expected to grow and stabilize at $N_{p=0.95} = (10.87^{+1.79}_{-1.45}) \times 10^9$ in 2100 [372], the production of sufficient and healthy food is a key challenge for sustainable development [24, 370, 373], necessitating a more efficient use of the resources *land* [131] and *nutrients* [374]. 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 [24, 375–381]. Willett and colleagues [24] 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 [246]). 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 [216]. 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 [15, 370]; however, this could result in a significant increase of HANPP, which is already beyond safe limits [11, 111, 382]. Transforming food into an energy crop production area, as suggested in some scenarios [370], 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 [126, 132, 370]. We thus exclude all biomass of agricultural origin from being an appropriable energy resource.

3.2.2.2 *Environmental Sustainability Criteria*

Various attempts have been made to describe Earth system boundaries with key parameters that are representative and measurable [75]. For our proposed method, we use relevant limit values from the PB framework [77, 79], which are specified for nine key Earth system processes[3]. 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 3.2.2.1), these boundaries are not discussed here. Since there is no land transformation in the model (section 3.2.1.2), 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.

LAND SYSTEM CHANGE The Earth surface of 5.1×10^{14} m^2 is divided between 28% of land and the rest for ocean surface [383–385]. Without human disturbance, the land would mainly be covered with climax vegetation, which is classified into various biomes, such as tropical forest or savanna [383]. Removing the climax vegetation has an effect on the climate system [384] as well as on biodiversity [30]. The PB for *land system change* [79]

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[3] Climate change, change of biosphere integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows, land system change, freshwater use, atmospheric aerosol loading, and novel entities

is based on simulating its effect on climate system only [384]. It specifies the maximum sustainable removal of forest biomes, as deforestation is the most pressing driver for land system change [79]. 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 [384]; (2) appropriating much of the nonforest biomes would severely reduce their biodiversity, which would violate the biosphere integrity boundary [10, 29].

In order to maintain the functional diversity, Dinerstein and colleagues argue that at least half of each terrestrial biome needs to be intact [33]. We use this estimate and combine it with the original PB (see table 3.1). 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.

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 [216, 368, 370, 386–392]. 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 [368, 386–391]; (2) *reduce pasture:* The area of built environment and cropland is kept at the level of 2010 and pasture scaled to fit the PB [378], and in deserts, the 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 [372]. The scenarios are described in detail in section 3.8 in the Supplementary Materials.

FRESHWATER WITHDRAWAL The annual global river runoff is $\dot{V}_{\text{global},p=0.68} = (1.46 \pm 0.14) \times 10^6\ \mathrm{m^3/s}$ [385]. Annual variation is significant ($\frac{\dot{V}_{\text{monthly}}}{\dot{V}_{\text{global}}} = [0.31, 1.85]$ [81]); however, there are on average as many low as high flow months [81]. The PB specify the maximum monthly river withdrawal as:

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

	Appropriable Share of Land Area Biome			**Appropriable Land Area**
Biome	**According to [33]**	**According to [79]**	**Combined**	$A_{\mathrm{appr},p=0.98} / 10^{12}\,\mathrm{m}^2$
tropical forest	0.5	$[0.15, 0.4]$	$[0.15, 0.5]$	6.22 ± 2.77
temporal forest	0.5	$[0.5, 0.8]$	$[0.5, 0.8]$	11.1 ± 2.51
boreal forest	0.5	$[0.15, 0.4]$	$[0.15, 0.5]$	4.31 ± 1.92
others (excl. polar and RoL)	0.5	?	0.5	36.6 ± 0.18
sum			$[0.35, 0.48]$	60.1 ± 9.24

TABLE 3.1: Combination of planetary boundaries (PB) [79] and biodiversity conservation targets [33] to form a boundary for land system change across all biomes. Intervals are expressed in this paper in their mathematical form, i. e. $x = [x_{\mathrm{min}}, x_{\mathrm{max}})$ meaning $x_{\mathrm{min}} \leq x < x_{\mathrm{max}}$. This notation implies a level of confidence of the interval of $p = 1$.

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 $[1.26, 1.90] \times 10^5\,\mathrm{m^3/s}$ 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 $\frac{\dot{V}_{\text{withdrawal,temporary}}}{\dot{V}_{\text{global}}} = [0.13, 0.75]$.

3.2.3 *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.

$$\tilde{\tau}_i = \frac{P_{\text{required},i}}{ATP_i} \tag{3.1}$$

The required power needs to be converted to electric energy equivalents by applying average energy conversion efficiencies between fuel and electric energy (see table 3.4 on page 95 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_{el} (see Supplementary Materials). An $REF = 1$ indicates a purely RE mix, whereas $REF = 0$ corresponds with a purely non-RE mix.

$$REF = \frac{\sum_{i=1}^{n_{\text{RE}}} E_{\text{el},i}}{CED_{\text{el}}} \tag{3.2}$$

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.

$$REI = REF \cdot \left| \frac{\sum_{i=1}^{n_{\mathrm{RE}}} (\alpha_i - \overline{\alpha})(\beta_i - \overline{\beta})}{\sqrt{\sum_{i=1}^{n_{\mathrm{RE}}} (\alpha_i - \overline{\alpha})^2 \sum_{i=1}^{n_{\mathrm{RE}}} (\beta_i - \overline{\beta})^2}} \right| \in (0,1] \qquad (3.3)$$

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

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*).

3.3 RESULTS

We tested the introduced method with data from the literature. In figure 3.2, 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 (1.7×10^{17} W, i. e. 100%), an ATP of 7.1×10^{13} W (or 0.04%) can be harvested without violating land system change or water withdrawal boundaries with a confidence of 99% (see table 3.3). 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.

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.

3.4 DISCUSSION AND CONCLUSION

3.4.1 *Comparison to Current Energy Demand*

The total RE potential is about an order of magnitude larger than the current energy demand $P_{\mathrm{el},2016} = 6.72 \times 10^{12}\,\mathrm{W}$ (data from [246] 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 [372]) 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 [393] without appropriating deserts. However, raising the

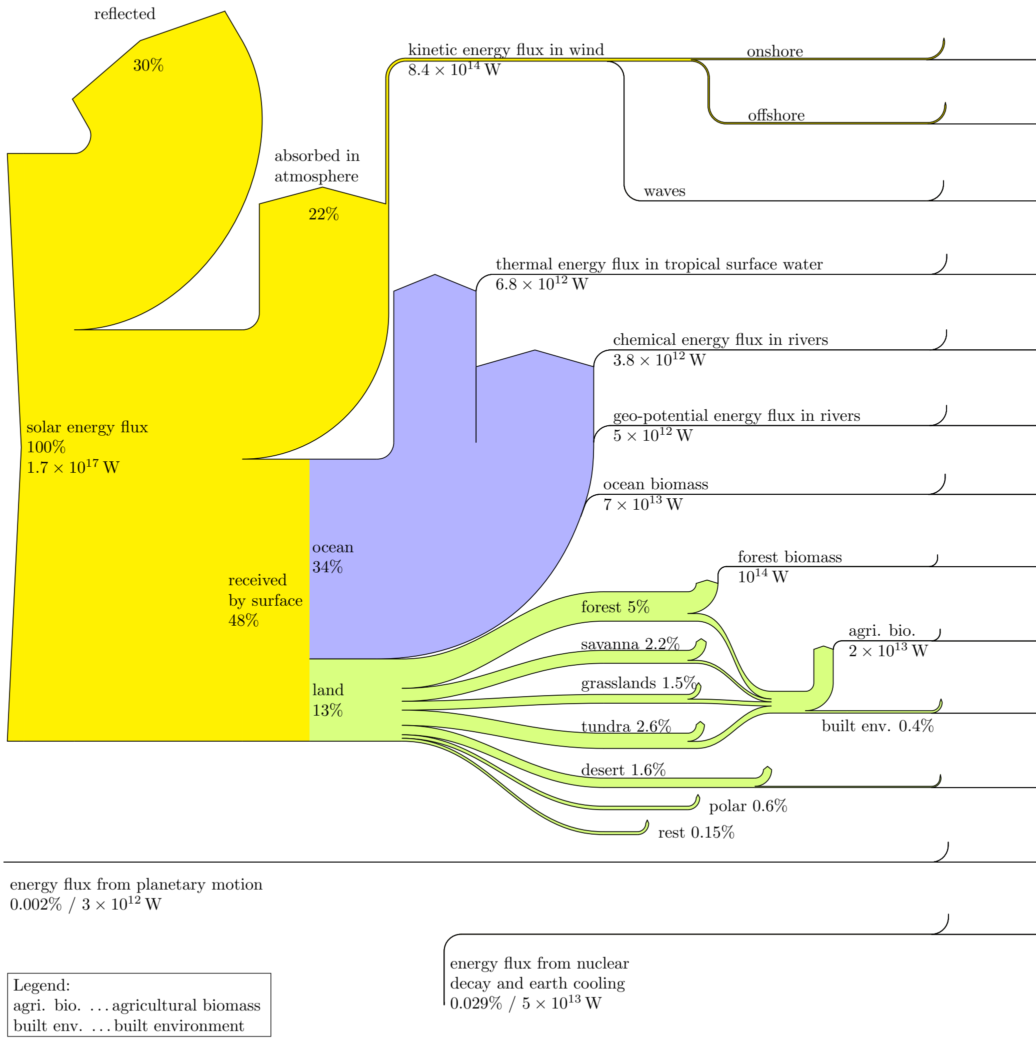

FIGURE 3.2: Sankey diagram of renewable energy (RE) flows from incoming energy flux to appropriable technical potential (ATP) with the limits (1% quantile) for the three land use scenarios (see section 3.2.2.2).

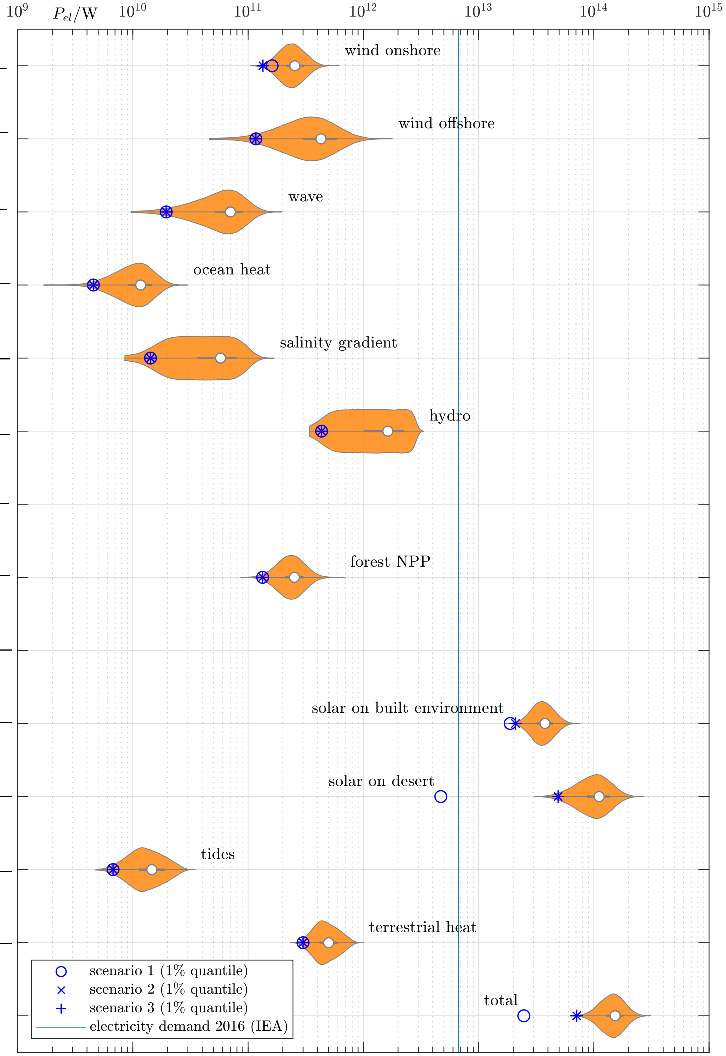

FIGURE 3.2 continued.

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.%

Table 3.2: 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 3.2. Resources marked with * are based on prospective technologies.

energy demand worldwide to, e. g. the Swiss average of 5000 W per capita in 2016 [393] 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 3.3), biomass use is already beyond the ecologically safe limit ($\tilde{\tau}_{\text{biomass}} = 4$, see section 3.2.3). This is explainable through the wide usage of charcoal and wood for cooking and low temperature heat production [126, 246]. 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.

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 [246], whereas the potential mix is dominated by solar.

3.4.2 *Comparison with Other Studies*

In figure 3.3, we compare the ATPs calculated with our method to values from ten studies that mostly report on technical potentials [126, 127, 129, 132, 246, 353, 354, 382, 394, 395]. 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 [127]. 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 [394], which specifically

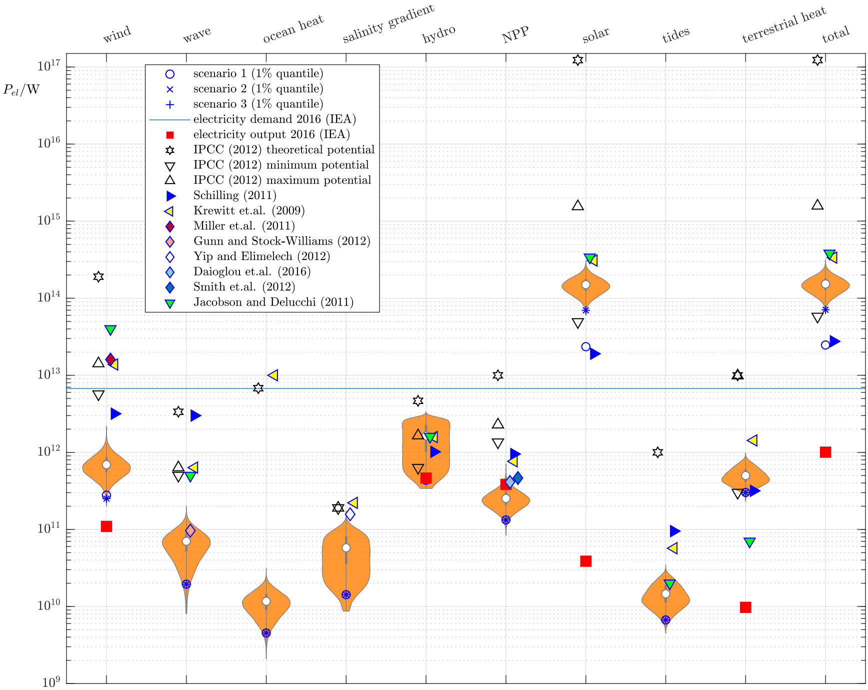

FIGURE 3.3: Comparison of ATP to other estimates: IEA [246], IPCC [126], Schilling [353], Krewitt et.al. [129], Miller et.al. [354], Gunn and Stock-Williams [394], Yip and Elimelech [395], Daioglou et.al. [132], Smith et.al. [382], and Jacobson and Delucchi [127].

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 [132] and another one that is constrained by biological reproduction rates [382]. 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.

3.4.3 *Limitations and Further Developments*

The results presented in section 3.3 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 [396].

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 [133, 397]. Likewise, our method assesses neither societal nor economic costs for building and operating the necessary infrastructure.

3.4.4 *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?"

Supplementary Material

3.5 ENERGY FLUXES AND CLASSIFICATION OF RE RESOURCES

The Earth system is powered by three energy potentials emanating from inaccessible resources: solar irradiance fed from solar fusion processes, geothermal heat flux fed from residual heat, fission, and crystallization processes, as well as tides fed from rotational inertia of the gravitationally coupled earth–moon–sun system. In this text, these incoming energy fluxes (synonymous to flows) are considered constant over long time spans and inexhaustible. In the Earth system, they are balanced exclusively by terrestrial albedo and excitance, that is, with two radiant fluxes of non-overlapping spectra: reflected short wave (i. e. solar 5760 K) and emitted long wave (i. e. terrestrial 255 K).

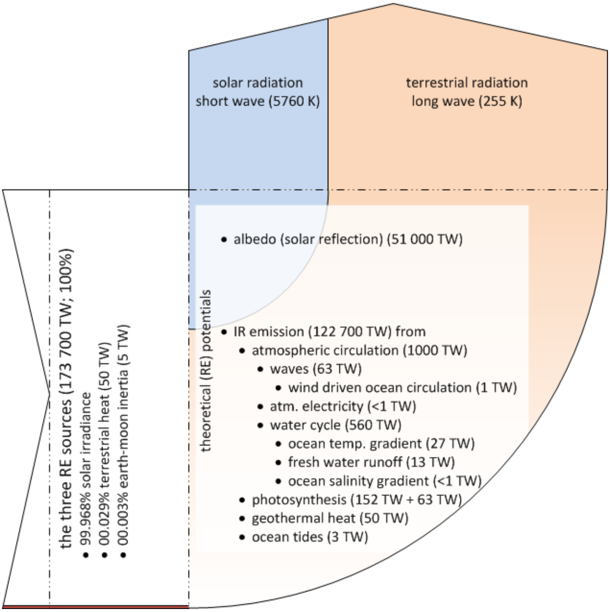

FIGURE 3.4: Schematic overview of the energy fluxes in the undisturbed Earth system (data from [123] and NASA `https://earthobservatory.nasa.gov/features/EnergyBalance`.

In this context, we adhere to the SI terms and units of radiometry (wikipedia) and use joule for energy in general, watt for energy fluxes

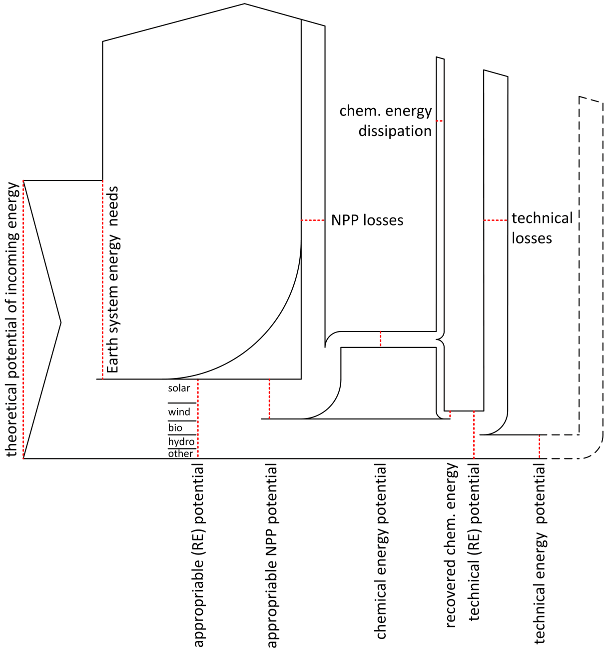

FIGURE 3.5: Schematic overview of the energy fluxes in the Earth system with the human appropriation of chemical and technical energy.

($1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}}$), and watt divided by square meter for flux densities ($1\,\mathrm{W\,m^{-2}} = 1\,\mathrm{J\,s^{-1}\,m^{-2}}$). In this text, e. g. an annual energy demand in tonnes of oil equivalent (toe) is referred to as an energy flux expressed in watts; the quantity *toe* is converted to SI with $toe/\mathrm{GJ} = 41.868$ and with $\mathrm{a\,s^{-1}} = 3.156 \times 10^7$ (seconds in one year) to a flux $41.868\,\mathrm{GJ\,a^{-1}} = 41.868\,\mathrm{GW\,s\,a^{-1}} = 41.868/(3.156 \times 10^7)\,\mathrm{GW} = 1.33\,\mathrm{kW}$. Or, e. g. the annual insolation, the solar irradiance cumulated over one year, is a radiant exposure and is expressed in joules per square meter $1\,\mathrm{J\,m^{-2}} = 1\,\mathrm{W\,s\,m^{-2}} = 1/(3.156 \times 10^7)\,\mathrm{W\,a\,m^{-2}}$.

Following the cascading conversion chain of an incoming energy flux, the occurring RE resources are classified according to the pathway through the Earth system. Other possibilities are to classify the energy resources according to conversion technologies (e. g. heat engine) or energy form (e. g. kinetic energy).

All RE potentials, except terrestrial heat and tides, originate from solar irradiance. An almost constant energy flux of $1.7 \times 10^{17}\,\mathrm{W}$ reaches Earth at the top of the atmosphere (TOA), out of which approximately 30 % is reflected without much interaction with the Earth system. Approximately 21 % is absorbed in the atmosphere. Approximately 2/3 of the solar irradiance reaches the surface on ocean and the rest on land. The spatially and temporally varying irradiation is absorbed by and unevenly heats the different surfaces resulting in (a) long wave IR emission and (b) important temperature gradients leading to convective and conductive heat transfer in the atmosphere. Due to the greenhouse effect by greenhouse gases (GHG), vast amounts of long wave IR radiation (almost twice the solar irradiance) are exchanged between the troposphere and the surface. Air currents which tend to equalise the atmospheric temperature gradients [123, 245, 351, 352, 398, 399] are an available energy potential (mainly horizontal winds) and can be appropriated and converted to technical energy via *wind power* technologies.

Plants convert solar irradiance to chemical energy in biomass (net primary production, NPP). This primary biomass is the sole energy input to the trophic chain, supporting all other life forms. The available energy potential of surface irradiance as well as NPP can be appropriated and converted into technical energy.

Energy absorbed in the surface layer of water bodies leads to a vertical temperature gradients which *ocean thermal energy conversion* devices can convert to technical energy. Dried continental air moving over the warmed water surface enables continuous evaporation, which desalinates sea water and feeds the global water cycle [385]. Water vapor is transported by winds and precipitates partly over land. The water runoff from land driven by the potential energy of the elevated water carries sediments and nutrients back to the ocean. The available part of this potential can be appropriated and converted into technical energy via *hydro power* plants.

When the freshwater runoff mixes with salty ocean waters, the chemical potential between fresh and salt water is dissipated as low temperature heat. The available part of this potential can be appropriated and converted to technical energy via *forward osmosis* devices, which utilize osmotic pressure differences.

The shearing forces on water surface exerted by wind cause the formation of waves and currents. The available energy potential of water waves can be appropriated/harvested via *wave power* plants.

Additional to solar energy, a comparatively small terrestrial heat flux from residual heat, crystallization, and nuclear fission in Earth's core and mantel of about 3.1×10^{13} W [351] reaches via conduction and convection as low temperature heat Earth's surface. Due to geological anomalies in certain places and in deep boreholes, the temperature differences to the surface are high enough to appropriate and technically convert in *geothermal power* plants.

Last but not least, an even smaller energy flux of about 3×10^{12} W fed from rotational inertia of the gravitationally coupled earth–moon–sun system enters the Earth system [351, 400]. Tidal forces mainly from the orbiting moon combined with the Earth's rotation lead to a periodic lift of ocean water. The available energy potential in tides can be appropriated and converted to technical energy in *tide power* plants.

Each conversion process in the cascaded Earth system (e. g. solar irradiance $\rightarrow$ evaporation $\rightarrow$ precipitation $\rightarrow$ surface runoff) has a limited thermodynamic efficiency and reduces the appropriable potential of the resulting RE resources significantly [123]. The fewer conversion steps, the more of the initial energy is available for technical conversion, and thus, the higher the possible yield.

3.6 UNCERTAINTY MODELING

Each parameter is modeled as an uncertainty distribution (see tab. 1.2 on page 17). The error propagation throughout the calculation is considered with Monte Carlo simulations, i. e. calculations are run 100 000 times with randomly picked values as specified by the parameter's uncertainty distributions.

Since no uncertainties regarding the climax vegetation are indicated in the original publication [383], they are estimated here as normally distributed within the range of $3\,\sigma = \pm 1\,\%$. The resulting limits to appropriate land from the different biomes are given as minimum and maximum values without information about the distribution [79]. Therefore, a rectangular distribution is assumed.

3.7 ELECTRIC ENERGY CONVERSION EFFICIENCY

In energy statistics of the international energy agency (IEA), primary energy use is reported on the level of caloric energy content of fuels for some energy carriers (e. g. oil) and electricity for others (e. g. solar) [246]. The same applies to the life cycle inventory database ecoinvent [401] and other databases. In order to convert these energy flows to the common form of electric energy, average conversion factors are applied (see table 3.4) [402].

RE resource	**technology**	**theoretical potential** P_{th} / TW	**appropriable potential** P_{app} / TW	**final RE potential** P_{el} / TW
wind onshore	wind turbine	243	12	0.134
wind offshore	wind turbine	611	2	0.12
wave	WEC	56.7	0.18	0.02
ocean temperature gradient	OTEC	3.42	0.034	0.0045
salinity gradient	forward osmosis	3.02	0.016	0.014
freshwater runoff	hydro turbine	4.9	0.47	0.43
ocean NPP	combustion	69.6	0	0
forest NPP	combustion	101	0.63	0.143
agricultural NPP	combustion	16.5	0	0
solar on infrastructure	PV	20036	559	20.9
solar on desert	PV / CSP	2334	924	49
tides	hydro turbine	2.85	0.029	0.0067
terrestrial heat	geothermal power	29.45	8.4	0.3
total		172947	1507	71

TABLE 3.3: Comparison of theoretical and appropriable technical potentials (ATPs) used in this study. The theoretical potential is indicated here as the value corresponding to each renewable energy (RE) resource; conversion in the Earth system is not accounted for. Consequently, the individual entries in this column do not add up to the total theoretical potential.

For specific RE technologies, the conversion efficiency is described in the respective section in this Supplementary Material.

Conversion of energy carrier into electric energy	**conversion efficiency** [402]
Biomass	0.25
Natural gas	0.4
Oil	0.37
Coal	0.34
Uranium	0.33

TABLE 3.4: Average conversion efficiency of different energy carriers into electric energy [402].

3.8 APPLIED LAND USE SCENARIOS

The land system change boundary specifies the maximum land area appropriable for human use. It is segmented in three land use types: cropland, pasture, and built environment. Cropland, including forest plantations (e. g. oil palms), is required to feed humanity and nongrazing livestock but also needs to satisfy nonfood agricultural demand (e. g. fibers, timber, agrofuels). Pasture is used for the grazing of domestic animals. Built environment includes all other surfaces changed by humans (e. g. buildings, roads, mines). The following three exemplary segmentation scenarios (see also figure 3.6) are investigated in this study:

1. *Proportional*: The land use mix is divided according to actual data on biome resolution in the year 2000 [368, 386–391]. For each biome, the appropriable land is allocated according to its relative share in 2000. Infrastructure data are available as the global average only, which is applied evenly over all biomes. In some biomes (e. g. tropical forest), land use exceeds safe limits in 2000 and is therefore reduced accordingly. In other biomes (e. g. temperate forest), the opposite is the case. Overall, this scenario yields global areas for each land use type lying between the aggregated values for the years 2000 and 2010 [216, 392];

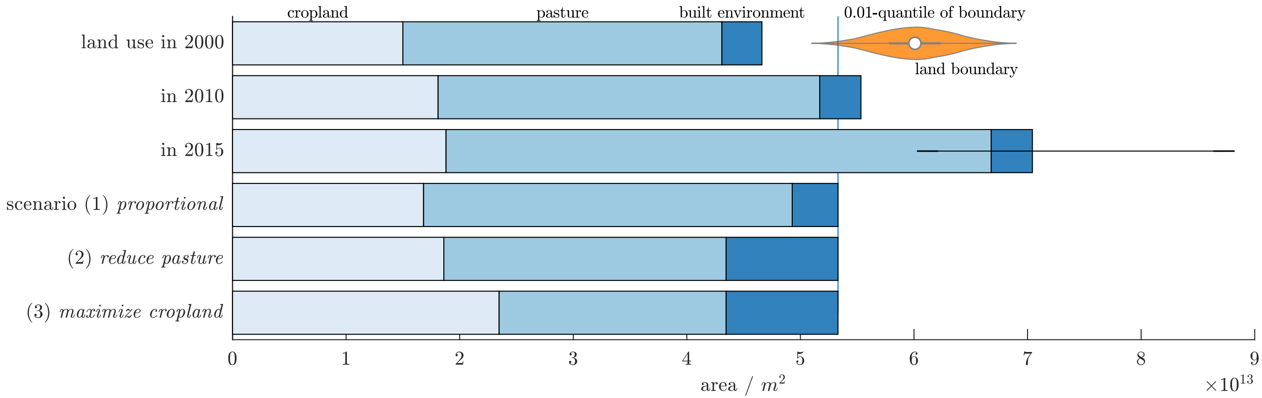

FIGURE 3.6: Different land use scenarios (1–3) and historic land use data (2000 [368, 389, 390, 403], 2010 [216, 392], 2015 including uncertainty (min, max) [370, 390]), divided into cropland, pasture, and built environment, in comparison with the land system change boundary [33, 79].

2. *Reduce pasture*: Pasture is seen as an additional source of food and not essential for human survival [378]. Therefore, the area of cropland and infrastructure is kept at the level of 2010 and pasture is rescaled to fit the PB. It is assumed that the increase in cropland (+20 %) and infrastructure (+3 %) from 2000 to 2010 was shared equally across all biomes. In the *tropical forest*, the cropland area exceeds the appropriable area; therefore, its fraction is limited to 90 %. In deserts, we assume that pasture and cropland remain constant at 2010 level as NPP is low, leaving the rest for infrastructure. The reference for the calculation is the 1 %-quantile of the distribution of appropriable land (see figure 3.6);

3. *Maximize cropland*: To increase the food supply for a growing population [372], the cropland area is increased in this scenario [378]. The built environment is kept as in scenario 2, while pasture area is reduced. It is assumed that cropland areas can be increased on areas where the climax vegetation would be forest by 50 % and on areas which would be savannas, grasslands/steppe and shrub land/tundra biomes by 25 % relative to scenario 2. As cropland on tropical forest areas has already surpassed the appropriable limit, it is kept at 90 %. Further, cropland and pasture in deserts remain as in scenario 2.

These land use scenarios define the area available for technical energy conversion. Therefore, each land use type can be used for multiple purposes simultaneously, e. g. pasture for grazing and wind energy conversion or built environment for housing and solar energy conversion. However, as argued in the main text, whenever technical energy conversion competes with chemical energy demand, the latter is given priority (e. g. solar energy conversion on cropland is not permitted).

3.9 DATA AND ASSUMPTIONS USED TO CALCULATE ATP

3.9.1 *Solar*

The highest overall efficiency can be obtained by converting solar irradiance into electric energy [124]. Two main conversion technologies (photovoltaic (PV) and concentrated solar power (CSP)) are currently available. The decisive limiting factor for direct solar energy conversion is the appropriable surface area. According to the PB, appropriation of surface is limited to about $2/5$ of the total land area (see main text). Water surface is not restricted in the PB; however, the effects of large scale coverage of ocean and lake surfaces on weather systems, marine life, and fisheries are currently unknown. In addition to that, technical solutions are currently unavailable. Consequently, water surfaces are not appropriable in this assessment. Most of the appropriable land surface is necessary to satisfy human demand for chemical energy, such as food, feed or fiber (see section 3.8). Built environment surfaces and low NPP land such as deserts are therefore the only appropriable surfaces for direct solar energy conversion. The built environment subdivides into buildings, roads, parking, rail networks, gardens, green belts, and others. On buildings, the entire envelope, i. e. roof and facade areas exposed to direct and diffuse irradiance is potentially usable for harvesting solar potential. This area approximately matches the area of the covered surface. However, not all building envelopes are suitable for PV systems: They might be shaded by taller buildings, mountains or trees or are historically important and cannot be changed. Globally, approximately 18 % of the built environment is covered by buildings in 2000 and 21 % in 2015 [370, 389, 390, 403, 404]. As the density of buildings in built environments is increasing, we assume an interval for the building fraction of $[0.21, 0.25]$. In Switzerland, about 60 % of roof area is estimated to be suitable for PV systems [135]. In the US, this value is between 70 % to 80 % [357]. Additionally, facades can be utilized, and for Switzerland, it is estimated that the suitable facade area corresponds to about 40 % of covered surface area (= roof area), though with roughly 1/3 of the energy yield of a roof PV system. For locations closer to the equator with a higher solar altitude, this value is smaller and vice versa. In this study, we estimated the globally available energy potential of buildings to between 70 % and 80 % of the PV potential of the covered surface.

Roads, open parking spaces, rail tracks, and similar uses seal 18 % to 20 % of the built environment [370, 389, 390, 403, 404]. This area can potentially be used for solar power conversion, though to a lesser extent and with added technical difficulties. We estimate that globally, 20 % to 50 % of this area is available for PV conversion. All other covered surfaces are excluded. In total, we therefore estimate that 18 % to 30 % of the projected surface area of the built environment can convert solar irradiance to electric energy with PV technologies.

The desert area is largely unsuitable for agriculture or animal husbandry [405]; therefore, large surfaces could be available for infrastructures. The effect of covering large desert areas with solar technology on weather patterns, albedo, and wildlife is currently unknown and would need to be assessed in detail. Further, the built environment in deserts may have multiple competing usages, such as mining or roads. Therefore, not the entire built environment in deserts is available for solar power conversion. We estimate the appropriable area suitable for solar technologies to be in the range of 20 % (similar to other built environments) to 80 % (limited by geometry, e. g. of access paths).

The yield of a solar energy system depends, among other factors, on the location on the Earth's surface. Locations closer to the equator have a higher irradiance and potentially higher yields. This dependence is modeled with a simple geometric relationship between the slice of the cross-section of a sphere and its corresponding surface (equation 3.4). For the different biomes, the irradiance is divided according to the latitude range of the biome (taken from [384]). A simple geometrical relationship between the cross-section, which receives a constant irradiance, and the surface ring of the sphere is made.

$$\begin{aligned} f_{\text{irr}}(\phi_1, \phi_2) &= \frac{\int_{\phi_1}^{\phi_2} dA_{\text{cross section}}}{\int_{\phi_1}^{\phi_2} dA_{\text{surface}}} = \frac{\int_{\phi_1}^{\phi_2} 2r^2 \cos^2 \phi d\phi}{\int_{\phi_1}^{\phi_2} 2\pi r^2 \cos \phi d\phi} \\ &= \frac{\phi_2 - \phi_1 + \sin\phi_2 \cos\phi_2 - \sin\phi_1 \cos\phi_1}{2\pi(\sin\phi_2 - \sin\phi_1)} \end{aligned} \quad (3.4)$$

For the entire sphere, this factor is $f_{\text{irr}}(-90\,°, 90\,°) = 0.25$ (circle area to sphere surface with same radius); for areas closer to the equator, the factor is higher, while for areas closer to the poles smaller. The solar irradiance, which is received by the Earth's surface, is mapped on the different biome types accounting for the geometric differences on their location on Earth.

Other factors are local weather patterns or ambient temperature. A comparison to other studies [135, 356, 357, 406, 407], which model solar yields for specific locations and regions using GIS data on irradiance and local conditions (e. g. roof topography), shows that local factors other than position are of minor importance when integrating over large areas. The error is $< \pm 4\,\%$ for regions like the entire United States [357] or Switzerland [135]. Thus, these are of minor influence for a global assessment and therefore not considered. For smaller regions with specific conditions (e. g. Arizona in the US with low precipitation [357]), deviation increases significantly up to 25 %. A spatially explicit global assessment could be integrated to refine the results in the future.

Photovoltaic systems (PV) convert direct and diffuse irradiance into electric power without moving parts (solid state). Depending on location and module orientation, some of the irradiance is lost due to reflection ($\gamma_{\text{refl.}} = [0.025, 0.06]$ [406]). The module efficiency ranges between $\eta_{\text{PV,module}} = [0.17, 0.4]$ [135, 357, 406, 408, 409] under standard test conditions (STC: $1000\,\text{W}/\text{m}^2, 25\,°\text{C}$ [409]). Losses may occur by deviating STC (temperature and irradiance $\gamma_{\text{temp.}} = [0.02, 0.11]$ [406]), and some electrical system losses (e. g. in inverters and cables) in the range of $\gamma_{\text{el},p=1} = 0.14^{+0.06}_{-0.04}$ [406] are inevitable.

Concentrated solar power (CSP) systems convert irradiance first into high temperature heat and, in a second step, into electric power via heat engines. Individual CSP systems require large areas and are not easily integrated into buildings. Therefore, this technology is currently only viable in deserts. Current annual average efficiencies are in the range of $\eta_{\text{CSP}} = [0.1, 0.3]$ and thus lower than PV systems [409]. Therefore, it is assumed that only large scale CSP systems will be installed, once they reach a higher efficiency.

Appropriable solar potential on desert surfaces is estimated with PV system performance. The losses due to reflection as well as temperature and low irradiance are slightly smaller in desert areas than on average [406]; therefore, the overall efficiency of PV systems is modeled as slightly higher (see Excel calculation sheet for more details).

3.9.2 *Hydro Power and Power from Forward Osmosis*

The global water cycle transports water vapor from ocean to land surfaces, where precipitations result in a runoff of surface freshwater back to the oceans of $1.46 \times 10^6\,\text{m}^3/\text{s}$ [385]. This runoff has a geodetic potential of $5 \times 10^{12}\,\text{W}$ [351, 353] and a mixing free energy of freshwater with seawater of $2.9 \times 10^6\,\text{J}/\text{m}^3$ [395], a total potential for the salinity gradient of $4.24 \times 10^{12}\,\text{W}$.

In 2011, non-energy sectors required $2.3 \times 10^4\,\text{m}^3/\text{s}$ of the run-off [255]. Assuming this demand is constant, the remainder to the PB (see main text) can be appropriated for electric power generation, which is in the case of an all-renewable scenario hydro and forward osmosis (FO) [4]. The appropriable limit is therefore $[0.11, 0.74] \times \dot{V}_{\text{global}}$. It is assumed that $[0.90, 0.95]$ of the appropriable potential is converted by hydro power plants, and the rest by FO.

Biodiversity impacts can be technically minimized through fish ladders and specific hydraulic design in state-of-the-art technology [410]; however, they are technology-specific and therefore not considered in this study. Conversion efficiency in hydro power plants is reduced by losses in ducts

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[4] The reversal of the process (reverse osmosis, RO) is used for desalination.

($\eta_{\text{ducts}} = [0.9, 0.98]$ [353, 409]), turbines ($\eta_{\text{turbine}} = [0.85, 0.96]$ [353, 364]) and electrical installations ($\eta_{\text{el}} = [0.95, 0.98]$ [353]).

When freshwater meets the ocean, the mixing free energy is dissipated as low temperature heat. FO with a conversion efficiency of $\eta_{\text{FO}} = [0.4, 0.48]$ can be applied to utilize this energy potential [395]. River deltas are fragile ecosystems, and the water flow is often spread out over huge areas, posing a logistical challenge in capturing this resource's potential. It remains to be estimated how FO impacts biodiversity both up and downstream.

3.9.3 *Wind and Wave*

Wind is largely created by temperature differences in the atmosphere with an energy potential of approximately 9×10^{14} W globally [123, 353, 354]. About half of this potential is dissipated in the $\delta = [900, 1000]$ m thick atmospheric boundary layer [354] between surface and free atmosphere [399]. In the boundary layer, the horizontal velocity v_x increases logarithmically with altitude z [399]:

$$v_x(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \tag{3.5}$$

with surface tension velocity $u_* = \sqrt{\frac{\tau_w}{\rho}}$ [411], the Kármán constant $\kappa = 0.4$, and the surface roughness height z_0, depending on the surface type [399]. The wind power is a function of area perpendicular to wind direction x, density of air ρ, and wind velocity v_x:

$$dP(z) = \frac{\rho}{2} \cdot dy \cdot dz \cdot v_x^3(z) \tag{3.6}$$

$$P_{\text{boundary}} = \frac{\rho u_*^3}{2\kappa^3} \cdot l_y \int_0^{\delta} \left(\ln \frac{z}{z_0} \right)^3 dz \tag{3.7}$$

Wind turbines have technological restrictions in size, with a hub-height of $H = [80, 170]$ m [353, 355, 358] and a diameter of $D = [80, 250]$ m [353, 358]. Generally, offshore turbines are slightly larger than onshore [353]; therefore, the respective intervals for offshore turbines are assumed to start with $H = D = 100$ m. The range reflects the current technological average up to future potential [358]. The wind turbine parameters determine the fraction of the boundary layer volume, where technical energy conversion is possible.

Wind power extraction is only possible in the range of the rotor from $z_l = H - \frac{D}{2}$ to $z_u = H + \frac{D}{2}$, and thus, the fraction of wind power that can be extracted from the boundary layer is:

$$f_{\mathrm{WT/BL}} = \frac{\int_{z_l}^{z_u} \left(\ln \frac{z}{z_0}\right)^3 dz}{\int_0^{\delta} \left(\ln \frac{z}{z_0}\right)^3 dz} \tag{3.8}$$

This fraction is a function of surface roughness only. For offshore areas, the surface roughness is $z_0 = [0.001, 0.02]$ m [399] and for onshore, it is assumed that wind parks would preferably be installed on pastures, cropland, and other similarly smooth areas, which results in $z_0 = [0.01, 0.2]$ m [399].

Wind parks can be installed on land as well as offshore. Offshore wind parks need to be close to the shoreline, due to maintenance access, increased sea roughness, cable length, link to sea floor, and other reasons. On average, wind parks can be installed within $l_{p=1} = 43.3^{+57}_{-33}$ km from shore [412]. Furthermore, it is assumed that between 30 % and 80 % of this area can be populated with wind parks, leaving enough surface for shipping routes, access to ports, coastal fisheries, etc. [413]. Onshore, the occupation of land is marginal (i. e. the tower cross-section); however, it creates obstacles for farming, visual obstruction, and noise. Therefore, it is assumed that a maximum of 20 % to 40 % of cropland and pastures can be used for wind farms, with the exception of former forest biomes. Because of the surrounding forest, the wind speeds close to the surface are low, which in turn makes it technically unsuitable, and the wind turbine fraction is set to zero. The built environment surfaces are unsuitable due to high surface roughness [399] and noise. The impacts on biodiversity (collision of birds with blades, noise, impact on food web [413]) are not considered in this study.

Wind turbines can harvest a theoretical maximum of 59 % of the kinetic power in the wind, which is known as the Betz' limit [353, 354]. Achievable aerodynamic efficiency is somewhat lower between 40 % and 50 %, and additional losses in the mechanical and electrical system amount to 5 % to 15 % [353].

Waves are mainly caused by shearing forces between wind and the ocean surface. The wave energy potential amounts to approximately 7 % of wind energy or 6.3×10^{13} W [123]. Practically possible wave parks are restricted to coastal ocean surfaces with enough wind, which is estimated to have an appropriable potential along suitable coast lines of 2.11×10^{12} W [394]. Wave energy conversion (WEC) devices have to be sufficiently spaced due to operational requirements, which limits the technical potential to 0.046 of the coastal potential [394]. It is assumed that WEC parks can be installed at $[0.3, 0.5]$ of the total coast line, due to access to ports, coastal fisheries, recreational areas, and protected areas (e. g. coral reefs). A typical efficiency for WEC devices ranges $\eta_{\mathrm{WEC}} = [0.2, 0.5]$, depending on the technology [414, 415].

3.9.4 *Terrestrial heat*

Net heat flux from the Earth's interior to the surface is 3×10^{13} W [351, 362, 416] Its origins are radioactive decay, crystallization, and residual heat. Areas with a heat gradient larger than 0.1 K/m are suitable for geothermal power conversion [362], which is mainly the case in geological anomalies [416]. It is assumed that the heat flux is evenly distributed on the planet but that geothermal power cannot be harvested on ocean floors, restricting the accessible potential to land only. It is estimated that $[0.1, 0.3]$ of the theoretical heat flux can be appropriated. Typical upper $T_{\mathrm{max}} = [443, 543]$ K and lower process temperatures $T_{\mathrm{min}} = [303, 313]$ K [362] result in a Carnot efficiency:

$$\eta_{\mathrm{C}} = 1 - \frac{T_{\mathrm{min}}}{T_{\mathrm{max}}} \tag{3.9}$$

Depending on the technology used, practically achievable efficiencies are $[0.8, 0.9]$ of the Carnot efficiency [409].

3.9.5 *Biomass Production*

3.9.5.1 *Agriculture*

The main purpose of agriculture is to produce food. As outlined in the main text, food production systems face the challenge of feeding a growing human population and are already breaching Earth system boundaries. Therefore, dedicated agrofuel production is not considered.

Other potential resources of agricultural origin are food waste and harvest residues. Food waste should be reduced as much as possible [24, 375, 381], leaving the option to harvest residues [132]. To estimate whether residues from agriculture could potentially be important as a technical energy resource, we considered the total useful harvest of NPP for food (1.3×10^{12} W in the year 2000 [11]) and fodder (4×10^{12} W) in relation to the direct HANPP. A bit more than 1/3 of the direct HANPP is not utilized as food or fodder and is left as, e. g. harvest residues or feces [11]. Considering that 50 % of the chemical energy potential can be converted to electric energy with an efficiency of 30 %, a technical potential of 3×10^{11} W would become available. Daioglou and colleagues [132] arrive at a similar value by considering agricultural residues without the fraction considered necessary to maintain soil quality, animal feed, and traditional fuel. However, the authors emphasize that the mechanisms to maintain soil quality are largely unclear and therefore uncertain [132]. Moreover, the study does not consider Earth system boundaries, and it remains unquestioned if a change in agricultural practice, in order to respect Earth system boundaries, would not change the availability of residues in return. In our view, an evaluation of agricultural residues would require evaluating agricultural practice against Earth system boundaries and future food demand. Only then will it be possible to evaluate whether or not the agricultural sector can provide technical energy in addition to fulfilling the chemical energy demand.

3.9.5.2 *Forestry*

In forest areas, wood for material and energetic use can be harvested given sustainable forest management is in place [216, 417]. Parts of the forest area are not accessible for appropriation, due to protected habitats or geographical remoteness (e. g. mountain regions). Today, (13 % of forests is protected [216] and 36 % is still primary forest and probably worth protecting [216]. A total of 50 % is argued to need protection to maintain biodiversity [33]) and the regeneration of the forest ecosystem [216].

The sustainable harvest rate of the net annual increment $NAI = [1.9, 3.5] \times 10^{-4}\ \mathrm{m^3/m^2{\cdot}a}$ is between 60 % and 80 % on the accessible and nonprotected forest area [216].

The harvested wood is assumed to enter a cascaded use where, finally, all chemical energy is used for conversion to electric energy (e. g. via a conventional combustion process and Rankine cycle or pyrolysis and combustion in a internal combustion engine or gas turbine). We assume a conversion efficiency of $\eta_{p=1} = 0.35^{+0.05}_{-0.15}$ [126, 409].

3.9.5.3 *Marine biomass production*

Algae and phytoplankton are the basis of the trophic chain in the oceans [23]. The ocean's food web is already under great pressure [10] to provide for current food supply (i. e. aquaculture and wild catch). The consequences of appropriating additional ocean biomass for technical energy supply are largely unclear [10, 126] and in competition with food production. Therefore, this RE potential is excluded from the assessment.

3.9.6 *Tides*

The gravitationally coupled motion of the earth–moon–sun system accelerates ocean waters by tidal forces, which excites the water to slosh periodically in the ocean basins producing sea level changes known as tides. The energy dissipated in ocean tides is estimated at 3×10^{12} W [351, 400]. Most of this energy is dissipated at the rising sea floor between open ocean and shore [400]. Tidal power can be harvested using the sea level difference or tidal currents in channels. Technically feasible power conversion, however, requires coastal areas with sufficiently high sea level differences and suitable geography (i. e. channels, bays, . . .), which are estimated to be $[0.01, 0.05]$ of the total coast line. Furthermore, it is estimated that $[0.2, 0.3]$ of the total energy is dissipated at the shoreline, whereas the rest is dissipated as friction at the rising ocean floor and in the water itself [400]. The energy can be converted with conventional hydro turbines (see section 3.9.2).

3.9.7 *Ocean thermal energy conversion*

The ocean surface water in the tropics has a temperature between $[25, 30]\,°\mathrm{C}$, which is sufficiently higher than temperatures in 1000 m depth of about $[4, 7]\,°\mathrm{C}$ in order to drive a heat engine and convert the energy flux into electric energy. The theoretical potential is estimated as approximately 6.85×10^{12} W [126, 129]. The Carnot efficiency (equation 3.9) is, however, low due to the small temperature difference [362]. Increasing the temperature in deep water reduces the solubility of CO_2. Therefore mixing heat of surface to deep water eventually releases CO_2 into the atmosphere. Additionally, the accessible area can only be accessed partly, due to geometric parameter, such as distance to shore, access to ports, area required for local fisheries, etc. We therefore assume that $[0.01, 0.05]$ of the area with suitable temperature differences can actually be covered with heat exchange devices. A more rigorous assessment would need to quantify the impact of CO_2 release on the climate boundary.

4

ECOLOGICAL RESOURCE AVAILABILITY

> *There is sufficiency in the world for man's need but not for man's greed.*
>
> — Mohandas K. Gandhi

BIBLIOGRAPHICAL DATA

Title	Ecological Resource Availability – A Method to estimate resource budgets for a sustainable economy
Authors	Harald Desing, Empa
	Gregor Braun, Empa
	Roland Hischier, Empa
Journal	Global Sustainability, Cambridge
Date	submitted: 29 January 2020; published 6 October 2020

KEY FINDINGS

- To reach environmental sustainability, resource use needs to be limited by environmental boundary conditions.
- Rescaling the current economy to fit within Earth system boundaries (i. e. grandfathering allocation), requires to reduce all anthropogenic activities by a factor of 40.
- The method allows to evaluate different allocation principles and scenarios on future resource needs on the effectiveness of increasing the ecological resource availability within Earth system boundaries.

THE AUTHOR'S CONTRIBUTION

I have developed the concept and method, wrote the Matlab code for the calculation, gathered and analysed the data for the case study as well as wrote the original draft of the paper.

THE CO-AUTHORS' CONTRIBUTION

Gregor was active in refining the method and performed the case study. He contributed to and edited the manuscript.
Roland supported the development of the concept and method, assisted with the data from *ecoinvent* as well as contributed to and edited the manuscript.

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NON-TECHNICAL SUMMARY

Resources are the basis of our economy and their provision causes major shares of the global environmental burdens, many of which are beyond safe limits today. In order to be sustainable, our economy needs to be able to operate within those boundaries. As resources are the physical "currency" of our economy, we present a method that allows translating Earth system boundaries into resource budgets. This ecological resource availability determines the global annual production of a resource that can be considered absolutely sustainable. The budgets can be managed like financial budgets, bringing absolute environmental limits one step closer to decision makers.

TECHNICAL SUMMARY

In this paper, we propose a new method translating Earth system boundaries into resource budgets. These Earth system boundaries are represented by 10 variables from the planetary boundaries framework and one additional boundary for renewable energy potentials. This follows the idea that in a sustainable economy, resources are not limited by their physical and/or geopolitical availability, but rather by the environmental impacts caused due to their utilization. The method is designed to estimate how much of a specific resource can be provided to the society within Earth system boundaries, taking into account impacts caused by primary production and end-of-life treatment. For the calculation, it is necessary to specify how global boundaries are allocated to the various resources and the acceptable risk of boundary violation. The method considers multiple boundary dimensions and can therefore effectively avoid burden shifting. We calculate the ecological resource availability (ERA) for major metals. We find, that in the current way of production (state-of-the-art processes), the current share of production (i. e. resource mix) and when allocating the global boundaries according to the same share of impacts caused by these resources today (grandfathering principle), the ERA budgets are 40 times smaller than production volumes in 2016.

SOCIAL MEDIA SUMMARY

Resource budgets in accordance with the Earth system boundaries enable the management of our planetary household.

4.1 INTRODUCTION

Natural resources are at the basis of all products and services in the economy [168, 169] and have enabled the progress of mankind over the past centuries. However, not only have they caused economic progress but their extraction is also responsible for major shares of today's environmental burdens [122]. The pressure of our society on the Earth system has already crossed safe limits for many vital Earth system processes [77, 79]. One increasingly popular concept among academia, policymakers and businesses to reduce those burdens is to create a circular economy (CE), where materials do not become waste at the end of the product's life, but instead are recovered to be used as an input for new products [56]. Nevertheless, materials cannot be cycled indefinitely [5], due to irreversible losses (such as corrosion, abrasion, and degradation), necessitating primary material input [40, 113] and safe final sinks [121].

Locking at physical availability, major resources remain abundant in the Earth's crust, albeit at lower and decreasing concentrations than the deposits mined today [141, 349, 418, 419]. In view of the global environmental crisis, the concern to society may not be that we run out of resources, but rather that the environmental impacts associated with the production and final disposal of these resources irreversibly damages Earth's life support system. For example, burning up all fossil fuels contained in the Earth's crust will certainly destabilize the climate system beyond safe limits [15, 252, 350]. As a counteraction, the international community has decided to restrict the use of fossil fuels, i. e. reduced their availability to society based on an environmental boundary condition. Sustainable production rates for other resources have been proposed by Henckens *et al.* [141] based on minimum required depletion time of known deposits. This approach, however, does not ensure that Earth system boundaries are respected. Generalizing the idea of environmental restrictions to resource production rates, it can be formulated as a hypothesis: The primary material input into a sustainable economy is not limited by the physical availability of resources, but by the environmental pressure arising from extraction, processing and disposal.

In this paper, we follow this hypothesis and propose a new method that allows to quantify the annual production of primary resources compatible with a stabilised Earth system. The idea of Earth system boundaries has been proposed decades ago [14, 234, 420] and several attempts to quantify them exist [75]. While some approaches focus on single indicators (e. g. remaining carbon budget [15]), others take multiple dimensions into account to better reflect the complexity of the Earth system (e. g. ecological footprint [76], planetary boundaries [77, 79]). To ensure that Earth system boundaries are respected, governments, companies and individuals have to integrate them into their decision making [421–423]. In fact, governments and companies have shown strong interest in using Earth system boundaries as a decision support tool for production or consumption activities [87, 88, 421, 424]. To facilitate this, the method described in this paper translates global environmental limits, expressed as ecosystem parameters, into annual resource budgets, expressed in units of mass, which we define here as *Ecological Resource Availability* (ERA). In contrast to existing absolute sustainability assessment tools that focus on comparing societal activities to absolute benchmarks (e. g. [91, 98, 99, 104, 105, 109, 422]), our method aims at exploring the magnitude of sustainable resource consumption. It is a modelling tool for testing the effect of technological and societal options on the sustainable resource base. Furthermore, the resource budgets can be used for decision support when designing new products or resource governance strategies.

In section 4.2, the ERA method and its five consecutive steps are introduced. We then show the application of the method with the example for major metals, which are produced with current technology and with the same relative importance in the economy than today (see section 4.3). In section 4.4 we discuss possible applications and further developments. Further details on methods, data and calculation code can be found in the supplementary materials (SM) online.

4.2 THE ERA METHOD

The ERA method aims to quantify global resource budgets, i. e. the amount of primary resources that can be made available annually while respecting Earth system boundaries (ESB) in the long run. Over time, all resource inputs into the socio-economic system are turned into final waste or emissions (mass conservation). Therefore, the ERA method includes environmental impacts associated with primary extraction, processing as well as final disposal back to the environment (see figure 4.1). ERA represents the level of resource consumption the Earth system can sustain continuously, i. e. once such a sustainable situation has been reached. It is the aim of the method, to explore the solution space for a sustainable resource consumption. The definition of resource budgets for the time during the transition remains a subject for future research.

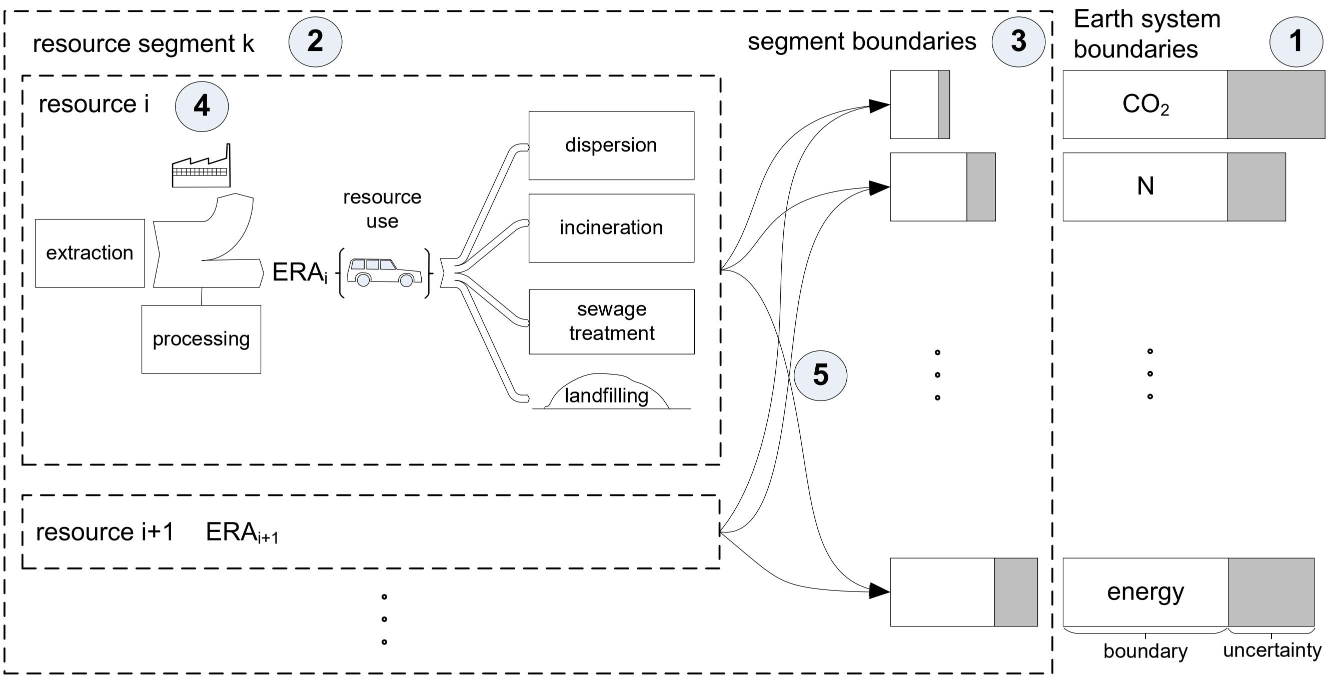

FIGURE 4.1: Schematic representation of the ERA method, consisting of five steps: (1) selection of Earth system boundaries; (2) resource segment definition; (3) allocation of safe operating space (e. g. by using EE-IOT); (4) environmental impacts of resource production (e. g. by using LCA); (5) upscaling of resource production until the impacts “hit” the allocated segment boundaries to determine ERA.

In details, the ERA method is composed of the following five steps (figure 4.1):

1. Selection of environmental sustainability objective, relevant Earth system boundaries and a required level of confidence in the results.
2. Choice of the resource or resource segment to be investigated. Selecting a resource segment requires the determination of the share of production of different resources within the segment.
3. Allocation of a share of the global boundaries to the segment.
4. Calculation of the environmental impacts per unit of resource production and end-of-life (EoL) treatment (i. e. life cycle impacts excluding use phase).
5. Scale-up of the combined resource production of the segment, until a first segment boundary is violated with the chosen probability of violation P_v.

With these steps, the ERA is calculated as annual resource budgets for each resource within the segment. Each of the five steps is described in detail in the following subsections.

4.2.1 *Selection of Earth system boundaries*

The first step in the ERA method is to select an environmental sustainability objective and a set of suitable boundaries describing the objective. The boundaries can be global or regional, interdependent or independent, and be either driver, pressure, state or impact in the DPSIR framework[1] [425, 426]. The condition for selecting a boundary is that it needs to be measurable with the methods chosen to allocate the safe operating space (step 3) and quantify the impacts (step 4). In general, each boundary demarcates the maximum value for an indicator that can be tolerated by the Earth system before it collapses or changes irreversibly [427, 428]. The uncertainty range of the boundary can reflect the parameter uncertainty and/or increased risk to society associated with the transgression of the boundary value [79].

The ERA method is based on the precautionary principle, which means that despite the often large uncertainties in both boundary values and impact measurements, the resulting ERA budgets needs to be viable with

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[1] Driver, Pressure, State, Impact, Response

high confidence [56, 226]. Therefore, an acceptable probability of violating the defined boundaries P_v is required as an input parameter. This value is a normative choice, reflecting the acceptance of risk in society.

For the ERA calculations, the boundary values are stored in a three dimensional matrix ($n_{ESB} \times 1 \times n_{\text{runs}}$), with the third dimension containing random values for each element in the other two dimensions according to the probability distribution of the respective boundary.

$$ESB \quad = \quad \begin{array}{cc} \text{boundaries}\downarrow & 1 \\ \begin{array}{c} 1 \\ \vdots \\ n_{ESB} \end{array} & \left[\begin{array}{c} \\ ESB_i \\ \\ \end{array} \right]_{\cdot^{\cdot^{\cdot}}\, n_{\text{runs}}} \end{array} \tag{4.1}$$

4.2.2 *Resource segment definition*

The second step in the ERA method is to select the resource segment k to be investigated. Such a segment comprises one or several resources (e. g. metals). This choice may be limited depending on the data source used for allocation. For example, the *Exiobase* database [255, 429] provides information on aggregated industry level (e. g. casting of metals). In this case, the resource segment needs to comprise at least all (bulk) metals. When a resource segment comprises more than one resource, the relative share of production (SoP) of each resource needs to be specified. The SoP expresses the fraction that a single resource contributes to the total mass flow of the segment. The SoP data is stored in a vector ($n_{\text{resources}} \times 1$).

$$SoP \quad = \quad \begin{array}{cc} \text{resources}\downarrow & 1 \\ \begin{array}{c} A \\ \vdots \\ X \end{array} & \left[\begin{array}{c} \\ \frac{m_j}{\sum_{i=A}^{X} m_i} \\ \\ \end{array} \right] \end{array} \tag{4.2}$$

4.2.3 *Allocation of safe operating space*

The ESB define a *safe operating space* (SOS) [78], within which collective human activities can be considered environmentally sustainable. This space needs to be allocated to specific activities in order to set boundaries for those activities. In the ERA method, the ESB is allocated to the resource segment under investigation, resulting in segment boundaries SB_k. This allocation is performed by assigning a *share of safe operating space* (SoSOS) [105] to the segment k for each boundary i. There are many different possibilities to define SoSOS [89] (e. g. economic value of a resource [105, 107], grandfathering approach [430] or future emission scenarios [303]). In general, any allocation principle can be applied in the ERA method.

The allocated segment boundary (SB_k), which is the absolute share of the total boundary available for the respective resource segment, is calculated by multiplying the diagonal of SoSOS with ESB for each MC simulation run (third dimension). It has the same matrix dimension as ESB.

$$SB_k = diag(SoSOS_k) \times ESB \tag{4.3}$$

4.2.4 *Environmental impacts of resource production*

After specifying the segment boundaries, the impacts on these boundaries need to be determined for one unit of resource provision. Impacts not only arise from extraction and primary material production, but also from EoL treatment. Every material introduced to the socio-economic system eventually finds its way back to the environment, be it through unintentional dispersion (e. g. abrasion) or intentional discharge (e. g. landfill) [56]. Following the responsibility principle[2], environmental impacts for final disposal have to be added to primary production. Impacts associated with the use of the material, such as product manufacturing, product use and cycling strategies, are not considered in the ERA method, as these are covered in the respective sectors in the economy. Impacts resulting from the input of energy and materials in the use phase of the material are considered in the respective ERA budgets. Direct use impacts are to be considered in the relevant segments. Similarly, secondary material production can be considered as a separate segment with its own boundary, and thus it is assumed not to affect the ERA of primary materials. Cycling strategies do increase the resource base available to the economy, but only delay and not prevent materials from entering final sinks.

Four principal disposal options can be distinguished: *open dump (= dispersion)*, *landfilling*, *incineration* and *sewage sludge*. If the disposal routes are known (e. g. for plastics in Switzerland see [431]), an overall waste process can be created as a combination of the four options. Otherwise, impacts can

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[2] The responsibility principle means that the actor introducing primary materials is responsible for all environmental impacts caused by it, even if they are spatially and temporally separated [213].

be modeled with an uncertainty range spanning over the best and worst option.

The application of the precautionary approach necessitates modelling of uncertainties for unit impacts. For example, uncertainties in LCA stem from the inventory uncertainties (e. g. measurement errors, spatial and temporal variability) [238, 240] and different impact assessment methods (LCIA) (e. g. different time horizons for global warming potentials). Data for unit impacts (UI) is stored in a three dimensional matrix ($n_{\text{resources}} \times n_{ESB} \times n_{\text{runs}}$):

$$UI \quad = \quad \begin{array}{cc} \text{resources}\downarrow & \begin{array}{ccc} 1 & \dots & n_{ESB} \end{array} \\ \begin{array}{c} A \\ \vdots \\ X \end{array} & \left[\begin{array}{ccc} \frac{m_{CO_2}}{m_A} & & \\ & & \\ & & \frac{E_{\text{el}}}{m_X} \end{array} \right]_{\cdot^{\cdot^{\cdot}} n_{\text{runs}}} \end{array} \tag{4.4}$$

In consequence of the global scope of the ERA method, the processes modeled to calculate the unit impacts have to be representative for the global average for primary production (e. g. global datasets in *ecoinvent*). Attention has to be paid that secondary materials are not included in these global averages.

4.2.5 *Upscaling of resource production*

The last step of the ERA method increases the production of a resource (and thus its environmental impacts) until the probability density functions (PDF) of both the boundaries and environmental impacts overlap. As long as all possible impacts are smaller than all possible boundary thresholds, the system can be considered fully sustainable. However, as soon as some possible impacts are larger then some possible boundaries (i. e. when two PDF start to overlap), there is an increasing probability that the system will violate the environmental sustainability criterion and thus be not sustainable (see figure 4.2). If all impacts are larger than their respective boundaries, then the system is certainly not sustainable.

The UI of the individual resources within one segment are combined to an overall unit impact for the segment UI_k, i. e. the impact caused by the production of one unit of the resource mix as specified by SoP (see sec. 4.2.2).

$$UI_k = SoP^T \times UI \tag{4.5}$$

The production volume of the resource mix in the segment ERA_k is then increased step-wise, until one segment boundary SB is violated with the

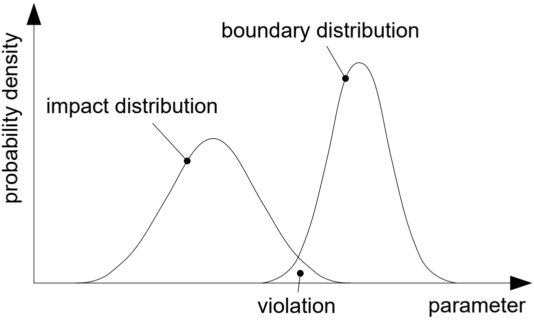

FIGURE 4.2: Schematic representation of the concept of probability of boundary violation, which results from the overlap from the probability distribution of the environmental impacts with the distribution of the respective boundary.

chosen probability of violation P_v. As the calculation of $P_{v,i}$ in each step depends on the shape of the distributions of both impacts and boundaries, a numerical approach is taken. The initial $ERA_{k,i}$ is calculated as the $1 - \frac{P_v}{2}$-quantile of the UI_k PDF and the $\frac{P_v}{2}$-quantile of the SB_k PDF. In an iteration loop the P_v is calculated and the $ERA_{k,i+1}$ increased or decreased until $P_{v,i}$ equals the required value P_v.

$$ERA_{k,i} = \frac{quantile\left(SB_k \left| \frac{P_v}{2}\right.\right)}{quantile\left(UI_k \left| 1 - \frac{P_v}{2}\right.\right)} \tag{4.6}$$

$$ERA_{k,i+1} = \begin{cases} ERA_{k,i} \cdot (1 - 5 \cdot P_v(1 + P_{v,i})) & P_{v,i} > P_v \\ ERA_{k,i} \cdot (1 + P_v - P_{v,i}) & P_{v,i} < P_v \end{cases} \tag{4.7}$$

The resource budget ERA_k is calculated for each boundary separately. As all SB need to be respected, the smallest ERA_k is defining the budget for the resource segment. For each resource in the resource segment k, the resource budget is calculated through multiplying the smallest ERA_k with the SoP. ERA is a vector ($n_{\text{resources}} \times 1$) and contains the ERA budget for each of the resources in the segment with the chosen confidence $1 - P_v$.

$$ERA = SoP \cdot min(ERA_k) \tag{4.8}$$

4.3 CASE STUDY: METALS

In the following subsections we demonstrate the application of the ERA method for the resource segment *metals*, using a grandfathering allocation approach.

4.3.1 *Selection of Earth system boundaries: adaption of planetary boundaries*

As the sustainability objective, we chose the protection of the Holocene like state of the Earth system and use the planetary boundaries framework as a set of ESB [77, 79]. The adaption of the boundaries is based on literature and for the purpose to demonstrate the ERA method. Furthermore, the probability of violating the boundaries is set to $P_v = 0.01$ [226] to illustrate the method. This is in between the probability of failure tolerated for critical technical systems (usually < 0.001, see table 4.3 on page 133) and deemed acceptable in current Earth system governance (e. g. $P_v = 0.33$ for reaching 2 °C target [350]; $P_v = 0.5$ for 1.5 °C target [15], despite potentially catastrophic effects [231]).

The PB define boundary values for nine crucial Earth system processes[3]. When crossing the boundary values, fast and irreversible environmental change is expected to happen – leading to a new Earth system state being less hospitable for human civilizations and most other forms of life [74]. Respecting the PB can be seen as necessary for reaching, however not sufficient to ensure environmental sustainability [102]. The PB framework can be refined with more detailed control variable definitions (e. g. for biodiversity [86, 302]) or extended to other variables (e. g. net primary production [93, 112]). To show this, we add a boundary on renewable energy potentials [226], representing the amount of energy that can be appropriated by society without transgressing other critical PB (e. g. land-system change) or compromising food supply. The global appropriable technical potential (ATP) for renewable energy is estimated to be $ATP_{el,p=0.98} = (1.52^{+1.24}_{-0.81}) \times 10^{14}$ W [226]. This added boundary is a global boundary for a driver of environmental pressure and particularly relevant for a circular economy, as for increasingly closed material cycles energy may become limiting [5].

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[3] I. e.: climate change, biodiversity integrity, landsystem change, freshwater use, biogeochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion, novel entities. Several boundary categories have more than one control variable specifying the boundary.

The PB themselves need translation in order to be compatible with the measurement of impacts with units commonly used in LCA and EE-IOT. This has been addressed by various authors using different approaches (e. g. impact reduction targets in LCA [109], deriving measurable boundaries [87, 422, 432], boundary characterisation factors [105], per-capita impact allowance [104, 433], combining footprints with PB [91]). For the purpose of illustrating the method, we do not consolidate the various different approaches, which is a topic for further research. Meanwhile, we derive measurable boundaries and uncertainty ranges by using a combination of approaches in literature (figure 4.5 on page 134 and section 4.7), except for the three boundaries described in the following. We adopt the biodiversity boundary from [104], however, highlight the need to refine this boundary in the future. For example, up-to-date and UNEP-SETAC recommended methods to assess the global fraction of species loss exist [434] and can be converted into extinction rates [86]. The land appropriation boundary in Ryberg *et al.* [105] only considers forest area, which cannot be measured easily with LCA and EE-IOT, whereas in Doka [104] all biomes other than forest can be appropriated, endangering biodiversity in these biomes. Bjorn and Hauschild [433] define the land boundary based on minimum biodiversity conservation targets, however, do not consider the forest boundary set with climate considerations of the original PB. We therefore adopt the land boundary setting in our earlier work [226], which combines the remaining forest area boundary from Steffen *et al.* [79] with the "nature needs half" proposal [33] for all other biomes.

For the CO_2 boundary we propose a different approach to be in line with the ERA method's scope of maintaining a sustainable state of the Earth system over time. The atmospheric CO_2 concentration needs to be constant at or below the PB. Without human influence, the CO_2 concentration in the atmosphere had been decreasing [435]. Continuous CO_2 emissions are possible to the extent of continuous removal by natural processes. CO_2 removal by sedimentation and weathering are relatively constant over the last 20 Ma [350, 436], when atmospheric CO_2 concentration had been below 450 ppm [350] and therewith within or below the PB, and overcompensate the natural CO_2 release (e. g. volcanism). The condition to keep the concentration constant, allows continuous (but small) emissions of anthropogenic CO_2 of $\dot{m}_{CO_2} < [8.25, 22] \times 10^{11}\,\mathrm{kg/a}$. This boundary translation is in contrast to other studies, where the CO_2 emission boundary is set with a specific time horizon (e. g. 300 a [105], or for negative emissions required between 2050 and 2080 to reach the 350 ppm target before 2100 [422]).

Boundary category	**Control variable**	**Original boundary**
climate change	atmospheric CO_2 concentration	$[350, 450]\text{ppm}$
	energy imbalance at top of the atmosphere	$[1, 1.5]\text{W}/\text{m}^2$
biosphere integrity	extinction rate	$[10, 100]\text{extinctions}/10^6\text{species}\cdot\text{a}$
	biodiversity intactness index	$BII > [0.9, 0.3]$
stratospheric O_3 depletion	stratospheric O_3 concentration loss	$[14.5, 29]\text{DU}$
biogeochemical flows	P to oceans	$\dot{m}_{\text{P,ocean}} < [11, 100]\text{Tg}/\text{a}$
	P to soil	$\dot{m}_{\text{P,soil}} < [6.2, 11.2]\text{Tg}/\text{a}$
	industrial and intentional biological N fixation	$\dot{m}_{\text{N}} < [62, 82]\text{Tg}/\text{a}$
land system change	remaining fraction of original forest area (global average)	$\frac{\text{area of forest}}{\text{area of original forest}} > [0.75, 0.54]$
	fraction of ice free land appropriable for cropland	$< [0.15, 0.2]$
freshwater use	blue water consumption	$\dot{m}_{\text{w,global}} < [4000, 6000]\text{km}^3/\text{a}$
	blue water withdrawal	$\frac{\text{monthly withdrawal}}{\text{mean monthly river flow}} < [0.25, 0.85]$
atmospheric aerosol loading	aerosol optical depth (South Asia only)	$AOD < [0.25, 0.5]$
ocean acidification	surface saturation state of aragonite	$\Omega_{\text{arag}} \geq [0.8, 0.7]$
novel entities	no control variable defined	–
energy	–	–

TABLE 4.1: Translation of Earth system boundaries considered in this study (10 variables from the planetary boundaries framework [77, 79] and complemented by the appropriable technical potential for renewable energy [226]) to annual flows compatible with EE-IOT and LCA units.

Translated control variable	Translated boundary
direct fossil CO_2 emissions to air	$\dot{m}_{CO_2} < [8.25, 22] \times 10^{11}$ kg/a
global warming potential	$\dot{m}_{CO_{2,eq}} < [2.83, 16.4] \times 10^{12}$ kg/a
not considered	–
potentially disappeared species (reversible)	$[1.95, 13.7] \times 10^5$
emission of O_3 depleting substances (ODS)	$\dot{m}_{CFC-11.eq} < [4.24, 36.9] \times 10^8$ kg/a
no change	$\dot{m}_{P,ocean} < [11, 100] \times 10^9$ kg/a
no change	$\dot{m}_{P,soil} < [6.2, 11.2] \times 10^9$ kg/a
reactive N emissions	$\dot{m}_N < [62, 82] \times 10^9$ kg/a
appropriable land area (all biomes)	$A_{appr,p=0.98} = (6.01 \pm 0.92) \times 10^{13}\,\mathrm{m}^2$
appropriable land area for cropland	$A_{crop} = [1.94, 2.61] \times 10^{13}\,\mathrm{m}^2$
no change	$\dot{m}_{w,global} < [4, 6] \times 10^{12}$ m³/a
not considered	–
not considered	–
not considered, as respected if CO_2 is respected	–
not considered	–
appropriable technical potential (ATP) for renewable energy resources (in electricity equivalents)	$ATP_{el,p=0.98} = (1.52^{+1.24}_{-0.81}) \times 10^{14}\,\mathrm{W}$

TABLE 4.1 continued: 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 $p = 1$. Uncertainty of values is reported for a specified level of confidence of the interval p, the 50 % value and the lower and upper deviation that confine the interval.

4.3.2 *Resource segment definition: metals*

The resource segment *metals* includes all 14 metals given in the *Exiobase* database: Aluminum, copper, steel, cast iron, zinc, lead, tin, nickel, gold, silver, platinum, titanium, chromium, and stainless steel. Other metals (e. g. rare earth metals) are not included in this segment. The production share (mass fraction) of all materials within the segment (SoP) needs to be defined. We use production data from USGS [437] and for cast iron from Ashby [169], as this material is not reported in the first source. In order to calculate the SoP as the final output of resource segments to the rest of economy without double counting the production that is necessary to produce other materials, the production data needs to be corrected into production output with the oversize factor $\omega = \frac{\dot{m}_{\text{overall production}}}{\dot{m}_{\text{production output}}}$ [259, 438] (see table 4.2 and SM section 4.8.4).

4.3.3 *Allocation of safe operating space: grandfathering approach*

The allocation principle has an important influence on the results [75, 99, 107]. To illustrate the ERA method, a grandfathering allocation approach [75] is applied in this case study, where each resource receives a SoSOS equal to its historic impact share. For example, if the production of steel is responsible for nine percent of the global CO_2 emissions today, steel receives the same share of the CO_2 boundary. This approach reflects the question: What if we re-scale today's socio-economic system to fit within ESB? As today's world economy already transgresses six boundaries (see figure 4.3), resource production as well as final demand would have to be down-scaled significantly, leaving large parts of the global society without access to basic services. This scenario is therefore to be seen as indicative only.

The calculation of the relative historic impact of each resource segment is conducted with a top down approach, using the *Exiobase* database v3.4 [255, 429][4]. In *Exiobase*, the emissions for each industry are reported, which are directly produced in the industry's activity itself. Industries concerned with the production or EoL treatment of materials are grouped in nine resource segments and the remaining industries aggregated to *rest of economy*. Impacts associated with consumption in households are contained in the final demand category. We use the approach from Cabernard *et al.* [439] to

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[4] Available online: `https://www.exiobase.eu/index.php/data-download/exiobase3mon`

calculate the cumulative impacts for nine resource segments without double counting the impacts already included in the supply chain of another segment (e. g. metals necessary to produce plastics). A detailed description of the calculation, the impact characterization methods used and the uncertainty modelling can be found in the SM. The results of the SoSOS calculations are shown in panel A of figure 4.3. The SoSOS is determined by the 50 % value of the uncertainty distribution resulting from the Monte Carlo simulation. This set of values is chosen in order that the total relative impacts add up to one and the full SOS can be utilized. The SoSOS has been determined with data from the year 2011 (the difference to the same procedure with data from 1995 is small, Person co-variance $r = 0.9954$). The overall impact for the year 2011 on the global boundaries as calculated with *Exiobase*, is qualitatively consistent with Steffen *et al.* [79], except for the two climate boundaries. In Steffen *et al.* [79], the impact on these boundaries is within the uncertainty range, whereas in our assessment they exceed the boundaries by far (see panel B of figure 4.3). This is due to the translation of state variables (CO_2 concentration; irradiation imbalance) into pressure variables ($\dot{m}_{CO_2}$; $\dot{m}_{CO_2,eq}$; see sec. 4.3.1).

4.3.4 *Environmental impacts of metals production*

The impacts on the selected boundaries, caused by the production and EoL treatment of one unit of material, is calculated with a bottom-up approach using LCA and *ecoinvent* v3.5 [401]. This database is chosen, because it aims at offering global coverage of the supply chains of materials in necessary detail. Hence, for each material, at least a global average dataset is available as required in the ERA method for calculating global resource budgets. The unit impacts are constructed from two processes: (1) primary material production (e. g. aluminum, primary, ingot) and (2) EoL treatment, which can consist of several processes (e. g. incineration, landfill). From *ecoinvent*, the cut-off (or recycled-content) system model is chosen, as in this model the primary material production chains show the entire impacts of the production steps; no parts of these impacts are already allocated to secondary material cycles or to EoL treatment processes. At the same time, the EoL processes contain only the impacts related to the respective treatment processes. An overview of all processes considered, as well as the impact characterization methods and uncertainty considerations for this analysis are provided in the SM.

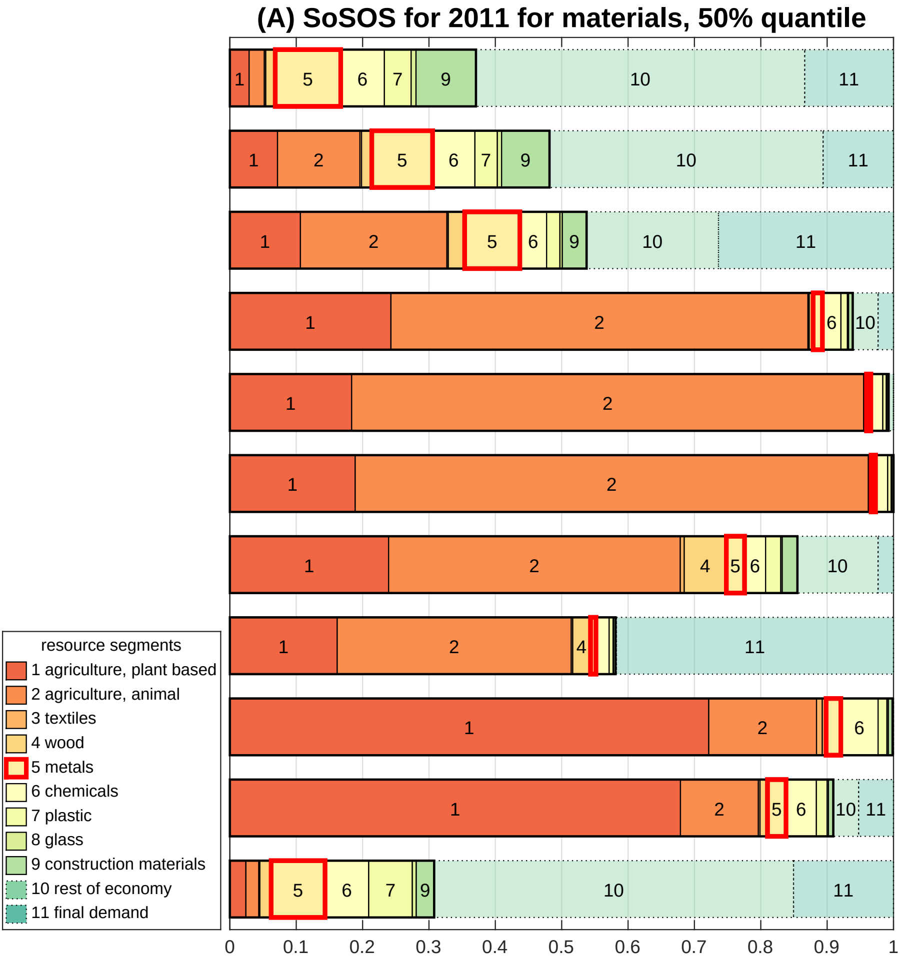

Figure 4.3: Panel A shows the relative impact contribution for nine resource segments (including supply chain impacts), which defines the SoSOS in the grandfathering approach. The contributions of the resource segment *metals* (5) is highlighted with red boxes. The *rest of economy* (10) holds all activities that are not part of the resource production chain (e. g. manufacturing of end-user devices), while *final demand* (11) comprises the purchase and use of goods and services by the end-consumer.

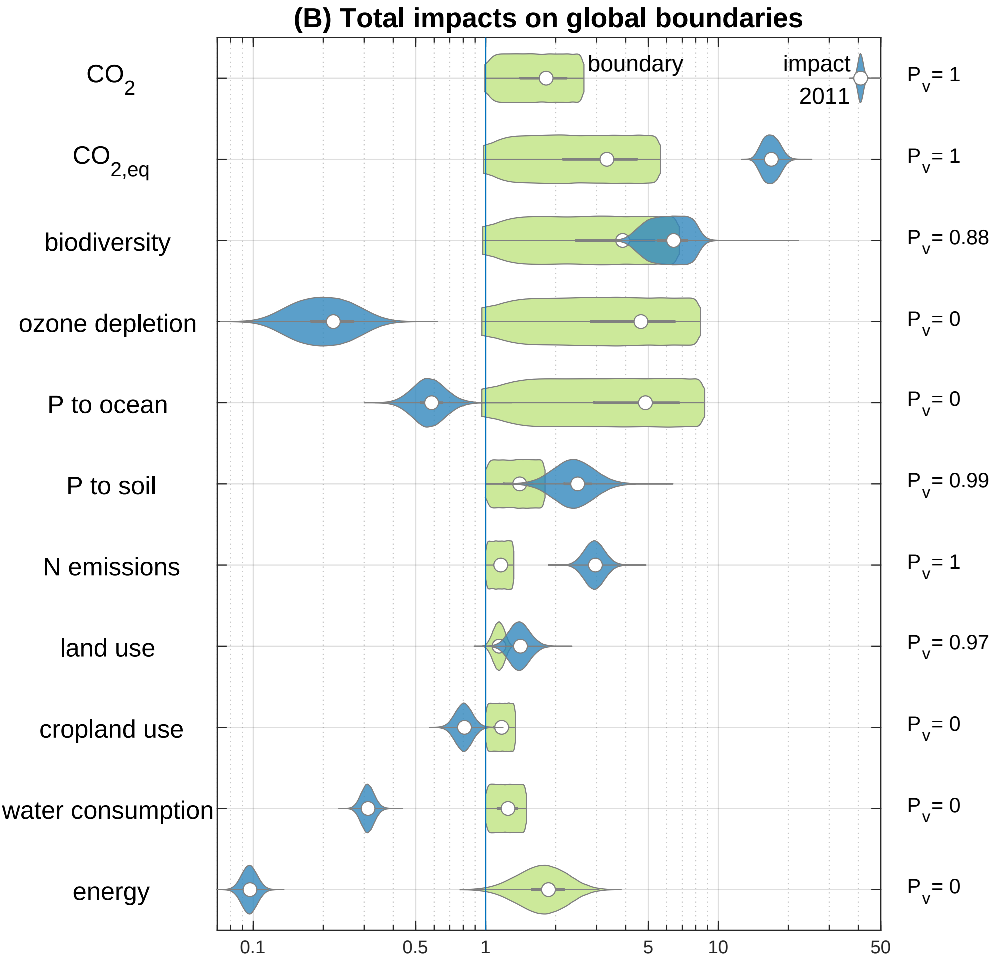

FIGURE 4.3 continued: In panel B, the total global environmental impacts of the socio-economic system in the years 2011 is compared to the global boundaries. Six out of the 11 boundaries are crossed with a probability greater than 1 %. All values are scaled relative to the 0.5-percentile of the respective boundary distribution ($1 \hat{=} ESB_{p=0.005}$).

4.3.5 *Upscaling of resource production: ERA determination*

Following the calculation steps (sec. 4.2.5) and using $n_{\text{runs}} = 10^5$ simulation runs, leads to the results as depicted in figure 4.4. The limiting SB for metals is CO_2 due to the large overshoot of global impacts on this boundary. The production in 2016 [437], ω, SoP, and ERA budgets are given in table 4.2 for the metal segment. The ERA for the whole segment is 3.05×10^{10} kg/a and thus 40 times smaller than production output in the year 2016. In other words, the primary resource production must be reduced by a factor of 40 to be within the selected ESB in the grandfathering approach. The CO_2 boundary is limiting the production of metals (see figure 4.4) as

Metal	$\dot{m}_{\text{production,2016}}$ / kg/a	ω	SoP	ERA / kg/a
Aluminum	5.89×10^{10}	1.4	0.035	1.06×10^{9}
Copper	2.30×10^{10}	1.36	0.014	4.26×10^{8}
Steel	1.63×10^{12}	1.49	0.9	2.75×10^{10}
Cast iron	2.30×10^{9}	1.49	0.0013	3.89×10^{7}
Zinc	1.35×10^{10}	1.6	0.007	2.12×10^{8}
Lead	4.95×10^{9}	1.6	0.0026	7.79×10^{7}
Tin	2.89×10^{8}	1.6	0.00015	4.55×10^{6}
Nickel	2.28×10^{9}	1.91	0.00099	3.01×10^{7}
Gold	3.10×10^{6}	1.91	0.0000013	4.09×10^{4}
Silver	2.51×10^{7}	1.91	0.000011	3.31×10^{5}
Platinum	1.89×10^{5}	1.91	0.0000001	2.49×10^{3}
Titanium	1.60×10^{8}	1.91	0.00007	2.11×10^{6}
Chromium	3.04×10^{10}	1.91	0.013	4.01×10^{8}
Stainless steel	4.20×10^{10}	1.49	0.023	7.10×10^{8}
Resource segment	1.81×10^{12}	1.49	1	3.05×10^{10}

TABLE 4.2: Golabl production in 2016 $\dot{m}_{\text{production,2016}}$ [437], oversize factor ω, share of production (SoP) and ecological resource availability (ERA) for the investigated metals.

it is the boundary crossed the most on the global scale (see figure 4.3). Within the segment, steel is dominating the impact shares due to its large production share ($SoP_{\text{steel}} = 0.9$). The depletion time of extractable global resources [141, 437] at the rate of ERA is for all investigated metals $\gg 1500\,\text{a}$ (except $920\,\text{a}$ for gold). This confirms the hypothesis that the depletion of physical resources is not the pressing constraint for a sustainable economy but rather the environmental impacts caused.

4.4 DISCUSSION

Based on our settings above, we show that ERA budgets for metals are 40 times smaller than production rates in 2016, assuming state-of-the-art-technology, today's resource demand pattern (grandfathering allocation) and current production shares in the metal sector. The CO_2 boundary is thereby limiting the ERA budget due to today's carbon intensive production technology. The climate crisis is to our findings the most pressing environmental concern, followed by biodiversity loss (see panel B in figure 4.3). This confirms the current societal and political focus on CO_2. However, a shift in production technology (e. g. fossil-free) and towards less-carbon intensive materials (e. g. biomass) may lead to increased pressure on other boundaries.

The here proposed method is capable of avoiding *hidden burden shifting* among the included boundary categories and additional categories can be included in the method to avoid negative effects on processes currently not considered (e. g. soil quality [102], imperishable waste [422]). Furthermore, the flexible design of the ERA method allows to consider different technologies for resource production, allocation principles or sustainability objectives and thus can serve as a scenario tool for modelers. The method can be also used to evaluate, for example, a fossil-free scenario, where resource production processes do not run on fossil fuels, but on renewable energy exclusively. In this way, the ERA method can be used as a quantitative tool to evaluate the effect of different scenarios on the sustainable consumption scale of resources for the future. Such scenarios can form the basis for sustainable resource governance and the design of effective policies. For example, the ERA method can be used to evaluate different policy options (e. g. allocation principles, technology promotion) on their effect on the availability of resources to society. Resource budgets can serve governments and international organisations as a strategic prioritisation tool for resource governance. Furthermore, the ERA budgets can be used

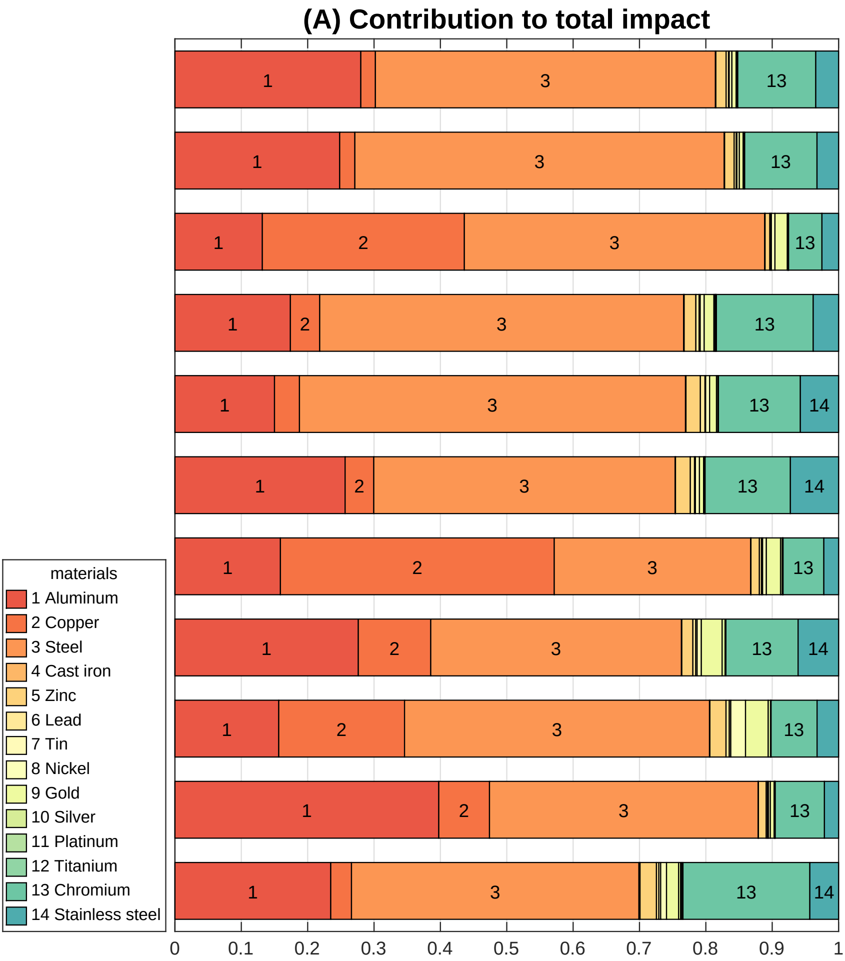

Figure 4.4: Panel A shows the relative contribution of each metal to the total environmental impacts of the resource segment *metals*.

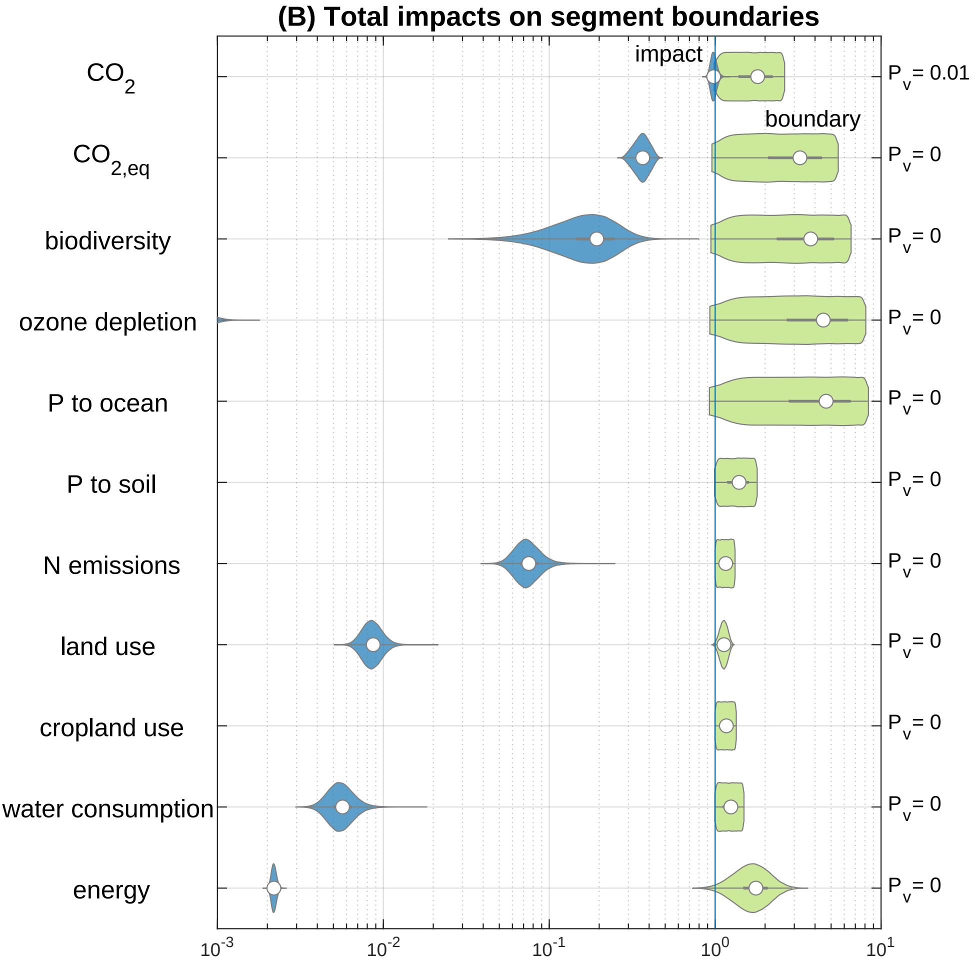

FIGURE 4.4 continued: On panel B, the cumulative impacts of metals (blue) is compared relative to the 0.5 percentile of the allocated boundary for the metal segment (green) ($1 \hat{=} SB_{p=0.005}$). CO$_2$ is limiting the metal segment ($P_{v,CO_2} = 0.01$).

for decision support, such as material selection for product design or assessment of products' and companies' resource footprints [440]. The concept of a resource budget allows to include ESB into decision making similar to today's consideration of financial budgets.

For the moment, the ERA method is designed to calculate global budgets only. However, environmental circumstances on a regional level can be different compared to the global average (e. g. biodiversity [32], land use [215], water scarcity [83, 84, 369]) and therefore require regionalisation. In principle, integrating regionalized boundaries is possible in the ERA method, however, requires both the setting of regional boundaries as well as regionalized impact assessment.

Another limitation is the allocation process of the boundary to resource segments. In this paper, we applied a grandfathering allocation approach to divide the SOS based on historic emission shares for the purpose of demonstration. While informative, we do not consider it a realistic allocation principle, as scaling the whole economy equally will result in an economy unable to provide a decent living standard [441] for a growing world population [372]. For example, food production will be down-scaled by the same order of magnitude as metals, which may lead to starvation. Therefore, it is essential to define allocation principles that allow a decent life for a prospective world population of $N_{p=0.95} = (10.87^{+1.79}_{-1.45}) \times 10^9$ in 2100 [372]. For example, an allocation approach that assigns very small shares to fossil resources (coal, oil, gas) would free-up operating space for other resources and increase their budgets. Even more interesting for the transformation towards a sustainable economy would be to develop an allocation principle that increases the final services provided for society, e. g. based on Science Based Targets [303], which try to define ambitious but realistic emission reduction scenarios for different industries in a participatory approach. For the proof of concept of the ERA method in this paper, this is not considered but a potential area for further research. For the application of the ERA method, it must always be made clear which allocation and assumptions have been chosen.

4.5 CONCLUSION AND OUTLOOK

In this paper, we presented a novel method – the ERA method – to calculate the maximum production of primary materials that respects Earth system boundaries. The ERA method effectively translates Earth system boundaries into annual primary material production budgets and thus brings absolute environmental limits one step closer to decision makers. Materials bring benefits to society, therefore they are at the core of decision making on different levels (e. g. product design, resource governance) – in contrast to environmental impacts.

We have shown in the exemplary application of the ERA method for metals that current production rates deplete the sustainably available budgets on January 9^{th} (in analogy to the Earth overshoot day[5]), if we continue to produce them with current technology, today's economic structure, and current production shares in the metal sector. This confirms our hypothesis that environmental impacts are presently the most limiting factor for sustainable metals production. But how can we avoid running out of sustainably produced metals? The ERA method can help to evaluate the effectiveness of various measures on pushing the date, such as for example:

- Reducing the primary resource intensity of the economy through resource efficiency and increased material cycling
- Shifting technology to low-carbon intensity (e. g. renewable energy [226, 247, 303] or direct hydrogen reduced steel [442])
- Optimizing the share of production by using more resources with low unit impacts. This is, however, only possible to a certain extent, as every resource has specific properties required in applications (e. g. electrical conductivity of copper).

Applying the ERA method allows to evaluate how effective these options are in increasing the resource budgets for society and thus provides companies and governments with "consistent and accurate feedback about whether the magnitude of their impacts mitigation efforts is sufficient to halt large scale planetary change" [75].

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[5] `https://www.overshootday.org/`

Supplementary Material

The supplementary material contain details on uncertainty modeling, translation of the planetary boundaries framework for the ERA method, the quantification of impacts from industrial sectors and their supply chains using *Exiobase* [255], the quantification of environmental impacts from processes using *ecoinvent* [401], a list of abbreviations and a glossary. The calculation code in Matlab (R2018) and necessary Excel-files are available online at `https://doi.org/10.5281/zenodo.3629366`.

4.6 UNCERTAINTY MODELING

No parameter is known with absolute certainty, due to inherent uncertainties of the system, such as e. g. statistical nature of real life chaotic problems, measurement errors, influence of observation on the system, and limitations of current scientific understanding and spatial and temporal variability. The latter group of uncertainties can be reduced through improved modeling (i. e. regionalization and dynamic modeling) and advances in scientific knowledge.

Each parameter in the Ecological Resource Availability (ERA) method is specified with an uncertainty range and assigned a probability density function (PDF) [240, 242]. A Monte-Carlo simulation (MC) is performed with $n_{\text{runs}} = 10^5$ simulation runs to consider the uncertainty of the parameters and the uncertainty propagation throughout the calculations. The calculation and simulation is performed in Matlab R2018. The advantage of a MC simulation over analytical calculations is, that different PDF and empirical data sets can be considered also in complex linear and non-linear systems. Each parameter is therefore picked randomly for each simulation run n_{runs} according to the PDF specified with the input parameters in table 1.2 on page 17.

The probability of violation is the area of overlap between the segment boundary (SB) and upscaled UI distributions. It is numerically calculated through counting the number of occurrences, that a load is greater than the strength and divided by the total number of runs.

$$P_{\text{v}} = \frac{1}{n_{\text{runs}}} \sum_{i=1}^{n_{\text{runs}}} \begin{cases} 1 & \mathit{load} \geq \mathit{strength} \\ 0 & \mathit{load} < \mathit{strength} \end{cases} \tag{4.9}$$

In the paper we set the acceptable risk of violation for the Earth System Boundaries (ESB) to $P_v = 0.01$. In current Earth system governance, this value is usually much higher (e. g. the climate change targets and trajectories limiting global warming to $< 2\,^{\circ}\mathrm{C}$ are set with a confidence of 2/3 [232], i. e. there is a 1/3 chance that the climate targets are not met even when the emission reduction targets are fulfilled); whereas for technical systems (see table 4.3), the probability for system failure is much lower.

Engineering field	p_f / 1/h	t_L / h	P_f	**Description**
Automotive structure [225]	10^{-5}	10^{3}	10^{-2}	Failure of structural components lead to a serious accident
Aircraft engine, critical system [227]	10^{-7}	10^{4}	10^{-3}	Hazardous engine defects could potentially lead to a crash
Ship hull [296]	10^{-8}	10^{5}	10^{-3}	Cracking of the hull due to wave loads will lead to sinking of the ship
Nuclear power plant [363]	10^{-10}	10^{5}	10^{-5}	Melting of the core can have major and long lasting effects on the environment and society

TABLE 4.3: Typical probabilities of failure used in engineering. Probability density per operating time of failure p_f; service lifetime t_L; probability of failure over service life P_f.

4.7 PLANETARY BOUNDARIES TRANSLATION, IMPACT CHARACTERIZATION AND UNCERTAINTY

In this section, the boundary translation used in the case study is described in detail. The translation is based on and compared to multiple methods (figure 4.5) [89, 103–105, 422, 432, 433]. The translated boundaries have to be measurable in the EE-IOT *Exiobase* v.3 [255, 258, 429] and LCA database *ecoinvent* v.3.5 [401].

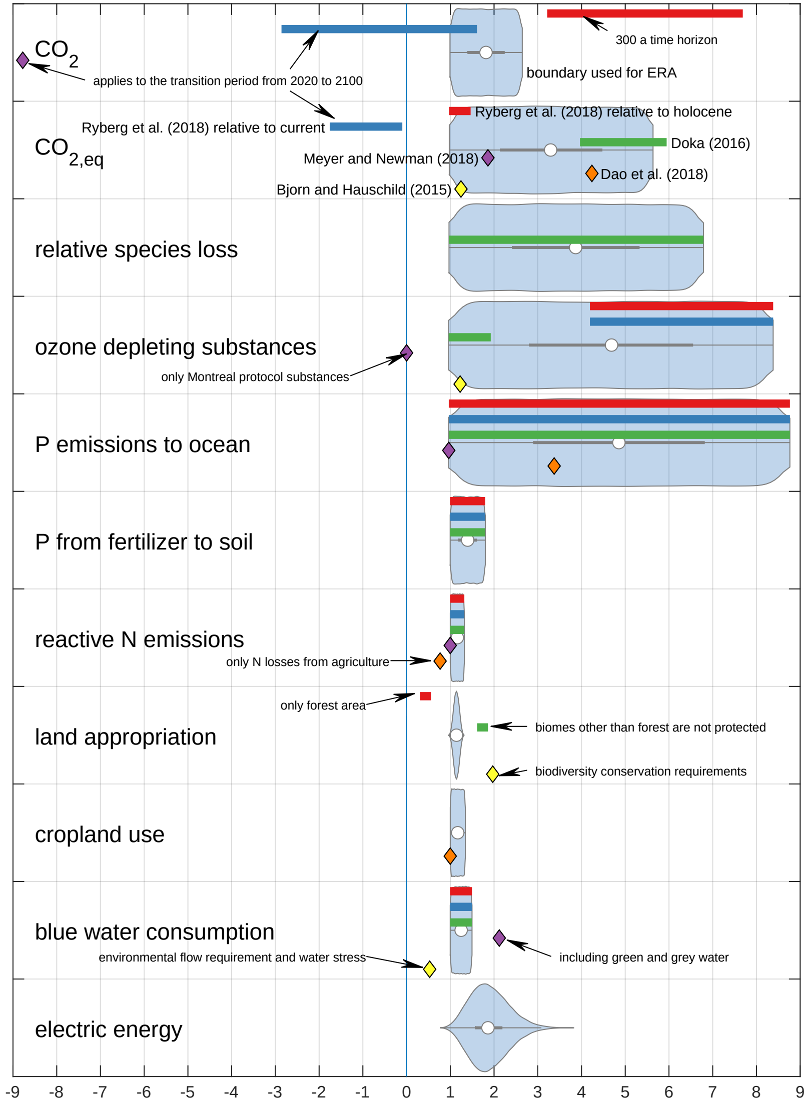

FIGURE 4.5: Comparison of ESB used in this case study (blue violins) to the translation using characterisation factors from Ryberg *et al.* [105] relative to the holocene state of the Earth system (red bars) and relative to the current state (blue bars), translations done by Doka [104] (green bars) and single boundary values from Meyer and Newman [422] (violet diamond), Dao *et al.* [87] (orange diamond) and Bjorn and Hauschild [433] (yellow diamond). All values are normalized to the 0.5 % value of the boundary's uncertainty distribution as considered in the case study (=1).

4.7.1 *Climate change*

4.7.1.1 *Atmospheric* CO_2 *concentration*

The first control variable defines the atmospheric concentration of $c_{CO_2} < [350, 450]$ ppm [79]. CO_2 emissions are well reported in LCA and EE-IOT, however in units of mass, not concentration change. Ryberg *et al.* [105] propose to translate CO_2 emissions into CO_2 concentration change with a characterisation factor based on a 300 a time horizon. This factor can be used to calculate the annual emission allowance in starting from a reference concentration. Taking the pre-industrial concentration of 278 ppm, translates to annual emissions of $\dot{m}_{CO_2} = [2.68, 6.39]$Pg/a; whereas taking the current concentration (414 ppm)[6] as a reference, allowed annual emissions are $\dot{m}_{CO_2} = [-2.38, 1.43]$Pg/a. Meyer and Newman [422] set the boundary based on a transition pathway scenario, where the target concentration of 350 ppm is reached in 2100. As a boundary, they take the negative emissions required in this pathway between 2050 and 2080: $\dot{m}_{CO_2} = -7.3$Pg/a (no uncertainty specified). All other authors do not translate this boundary.

Because the boundary settings from Ryberg *et al.* [105] and Meyer and Newman [422] are set with limited and specific time horizons, they do not correspond well with the scope of the ERA method. Therefore, we propose an alternative translation. The ERA method quantifies resource use at the level where the Holocene-like state of the Earth system can be maintained over time. This requires, that the atmospheric CO_2 concentration remains constant at the level specified in the PB. If the concentration is not to change, the inflow into the compartment "atmosphere" can only be as large as the corresponding outflow. Therefore, as much fossil CO_2 can be emitted per year as is absorbed by oceans and soils each year. The atmospheric CO_2 balance [443] can be expressed as:

$$\frac{dN}{dt} = F_{\text{natural}} + F_{\text{fossil}} + F_{\text{LUC}} + F_{\text{a/s}} + F_{\text{a/b}} + F_{\text{sediment}} \qquad (4.10)$$

N	number of CO_2 molecules in the atmosphere
F_{natural}	emission of CO_2 by natural events, like volcanism or weathering
F_{fossil}	emission of CO_2 from fossil sources

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[6] `https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html`, accessed 17.7.2020

F_{LUC}	emission of CO_2 due to land use change (LUC)
$F_{\mathrm{a/s}}$	net exchange of CO_2 at the atmosphere - sea interface, minus weathering
$F_{\mathrm{a/b}}$	net exchange of CO_2 between the atmosphere and biosphere, minus LUC and weathering
F_{sediment}	burial of carbon in sediments at the seafloor

In a steady state, the number of molecules of CO_2 in the atmosphere needs to be constant ($\frac{dN}{dt} = 0$) as well as no LUC may occur ($F_{\mathrm{LUC}} = 0$). Further, both the net exchanges between atmosphere and sea as well as with the biosphere are close to zero over long time horizons. According to assessment report 5 of IPCC [350] the residence time of carbon in different compartments (e. g. soil, biomass, deep ocean, etc.) is within a human's lifetime ($< 100\,\mathrm{a}$) or within the perspective of civilizations ($10^3\,\mathrm{a}$) with only one exception: sediments. The residence time of C in sediments is $> 10^4\,\mathrm{a}$ and thus the only compartment, which can be considered as a final sink in a human perspective.

The natural volcanic emission rate is about $< 0.36\,\mathrm{Pg/a}$ (CO_2) is compensated by net weathering of about $-0.72\,\mathrm{Pg/a}$ (CO_2) [350], resulting in a net natural uptake of $F_{\mathrm{natural},CO_2} = -0.36\,\mathrm{Pg/a}$. Additionally, there is a sedimentation rate of organic carbon $F_{\mathrm{sediment},CO_2} = -0.72\,\mathrm{Pg/a}$. Volcanic emissions, sedimentation and weathering had been relatively constant over recent Earth history [350]. An examination of sediment bore cores from deep sea sites had found a variability of the sedimentation rate of about $\frac{F_{\mathrm{sediment}}(t)}{F_{\mathrm{sediment,today}}} = [0.624, 2.5]$ over the last 20 Ma [436]. During the same time period, the atmospheric concentration of CO_2 had been below 450 ppm [350], i. e. within or below the uncertainty interval of the boundary value specified by the PB framework [77]. Applying this variation on the sedimentation rate and adding the net removal through weathering processes, the fossil CO_2 emission rate can be determined.

$$F_{\mathrm{fossil},CO_2} = [0.825, 2.2]\,\mathrm{Pg/a} \tag{4.11}$$

Please note, negative emissions will be necessary to reach the target CO_2 concentration during the transition. The Meyer and Newman [422] boundary is therefore a good estimate for the efforts in the transition, however not a goal that will be relevant for beyond the transition. Future-proof products and services need to be designed for the time after the transition, acknowledging that during the transition extra efforts are necessary (e. g. CCS).

Besides that, negative boundaries will lead to meaningless results in the ERA method when using a grandfathering approach, because ERA budgets will be negative. In scenarios allowing for CO_2 removing technologies and materials, a negative boundary can be implemented in the method.

4.7.1.2 *Energy imbalance at top of the atmosphere*

The second climate change boundary is defined as $< [1, 1.5]\,\mathrm{W/m^2}$ energy imbalance at the top of the atmosphere relative to pre-industrial levels [79]. This control variable accounts for the warming effect of CO_2 and other greenhouse gases (GHG) (e. g. CH_4, CO, aerosol loading). The GWP is usually described in LCIA in terms of emissions of mass of CO_2-equivalents. Doka [104] relates the two units using the conversion factor $8.69 \times 10^{-14}\,\mathrm{Wa/m^2kg}$ for the GWP for a 100 a time horizon, which translates the boundary into $\dot{m}_{CO_2-eq} = [1.09, 1.64] \times 10^{13}\,\mathrm{kg/a}$. The same procedure with the updated conversion factor $[9.17] \times 10^{-14}\,\mathrm{Wa/m^2kg}$ from [232] translates the boundary into $\dot{m}_{CO_2-eq} = [1.09, 1.64] \times 10^{13}\,\mathrm{kg/a}$. Ryberg *et al.* [105] applies again a 300 a time horizon for the conversion, which yields a boundary of $\dot{m}_{CO_2-eq} = [2.83, 4.25] \times 10^{12}\,\mathrm{kg/a}$ in comparison to pre-industrial times; and $\dot{m}_{CO_2-eq} = [-5.1, -0.28] \times 10^{12}\,\mathrm{kg/a}$ in comparison to current energy imbalance given by [79]. Meyer and Newman [422] only consider CH_4 and N_2O emissions for this boundary and set their boundary in $CO_{2,eq}$ to $\dot{m}_{CO_2-eq} = 1.23 \times 10^{13}\,\mathrm{kg/a}$. Dao *et al.* [432] based their boundary on spreading the remaining carbon budget to stay $< 2\,°\mathrm{C}$ with 50 % confidence [350] over the years 2015 to 2100. Chandrakumar *et al.* [103], in contrast, calculates a boundary to $\dot{m}_{CO_2-eq} = 3 \times 10^{13}\,\mathrm{kg/a}$ based on the conversion factor from Doka [104] but using the $2.6\,\mathrm{W/m^2}$ irradiation imbalance from IPCC scenarios limiting global warming to $< 2\,°\mathrm{C}$ [350], which is not in line with the PB. Bjorn and Hauschild [433] propose a boundary for GWP100 of $\dot{m}_{CO_2-eq} = 3.61 \times 10^{12}\,\mathrm{kg/a}$ based on a weighting of GHG relative to the climate change indicator score in 2010 and the $1\,\mathrm{W/m^2}$ boundary.

As a boundary for our case study, we take the lower uncertainty value from Ryberg *et al.* [105] (relative to pre-industrial) and the upper value from Doka [104] (with the updated conversion factor from [350], i. e. $\dot{m}_{CO_2-eq} = [2.83, 16.4] \times 10^{12}\,\mathrm{kg/a}$. In this way, the uncertainty range covers all reviewed studies, except for Ryberg *et al.* [105] relative to current state, which is out of the scope for this method, and Chandrakumar *et al.* [103], which is not in line with the original boundary. Please note, most GHG other than CO_2 have a lifetime in the atmosphere of <100 years. And because we already have considered the longer lifetime of CO_2 in the first boundary above, it justifies to set this boundary with commonly used time horizons (100 a and 300 a).

In order to quantify GWP from inventory results, various LCIA methods are available. To account for different modelling approaches (e. g. time horizon) and variations among impact assessment methods, a rectangular distribution is formed with the minimum and maximum values among the following LCIA methods: CML 2001, ILCD 2.0 2018, IPCC 2007, IPCC 2013, ReCiPe V1.13 2016. The impact results are multiplied with the underlying inventory uncertainty (as modeled for the direct CO_2 emissions, but normalized to one as the geometric mean) to result in the total uncertainty range.

4.7.2 *Change of biosphere integrity*

The loss of biodiversity is of growing concern [10, 26], however the control variables of the PB framework are only of preliminary character [77, 79] and debated [30, 85, 302]. One control variable defines the extinction rate as $[10, 100]$ extinctions/10^6species·a, whereas the second defines the relative species abundance, or biodiversity intactness index [444], to $BII > [0.9, 0.3]$. Doka [104] provides an approach for the latter, taking the *potentially disappeared fraction of species* [104, 445–447] used in the LCIA method ReCiPe version 1.13 [445, 446]. To end up with relative species loss, *potentially disappeared fraction of species* needs to be multiplied with the species density, i. e. the total number of species on Earth. ReCiPe characterization factors are built with an approximate 1.95×10^6 number of known species [445]. Therewith the boundary can be translated to $[1.95, 13.7] \times 10^5$. Note, this value is specific to ReCiPe, it however indicates the global pressure on species loss correctly [10] and can be easily implemented in *ecoinvent* and *Exiobase*. Meyer and Newman [422] propose a different metric to evaluate the biodiversity boundary with the *percentage of disappeared fraction of species* of $< 1 \times 10^{-4}$ 1/a, whereas Dao *et al.* [432] propose to use the biodiversity damage potential (boundary < 0.16). For simplicity, we use the approach from Doka [104], as it can easily be implemented in *ecoinvent* and *Exiobase*. However, we stress the fact, that a more suitable boundary needs to be defined in accordance with state-of-the-art methods (e. g. [434]) assessing biodiversity impacts.

Different impact pathways lead to species loss (e. g. land occupation). The endpoint category of species loss is calculated from various midpoint indicators in ReCiPe [445, 446]. The impact pathways considered are climate change, land occupation, ecotoxicity, eutrophication, terrestrial acidification, water depletion for marine, freshwater and terrestrial ecosystems. The uncertainty range for the impact characterization is modeled as a uniform distribution with the minimum and maximum value from the three different scenarios in ReCiPe (i. e. hierarchic, egalitarian, individualist) multiplied with the uncertainty of the dominating inventory result (i. e. agricultural land occupation). Note, a more precise uncertainty range should be modeled using all different contributing inventory results and impact pathways (midpoints), which is simplified here for the first proof of concept of the method.

4.7.3 *Stratospheric ozone depletion*

Ozone depletion was among the first environmental problems successfully tackled by international commitment [448]. Still, it remains important to observe the boundary in the future, as not all ozone depleting substances (ODS) can be banned. The PB is defined as a permitted loss of O_3 concentration of $-\Delta c_{\mathrm{O}_3} = [14.5, 29]$ DU (DU = Dobson units).

Doka [104] translates the O_3 concentration loss into emissions of substances with ozone depleting potential (ODP) with a conversion factor of $\frac{-\Delta c_{\mathrm{O}_3}}{\dot{m}_{\mathrm{CFC-11-eq}}} = 3.42 \times 10^{-8}\,\mathrm{DU{\cdot}a/kg}$, leading to a boundary of $\dot{m}_{\mathrm{CFC-11,eq}} = [4.24, 8.48] \times 10^{8}\,\mathrm{kg/a}$. Ryberg *et al.* [105] uses a different conversion factor of $-\frac{\Delta c_{\mathrm{O}_3}}{\dot{m}_{\mathrm{CFC-11-eq}}} = 7.85 \times 10^{-9}\,\mathrm{DU{\cdot}a/kg}$, which translates to a boundary of $\dot{m}_{\mathrm{CFC-11,eq}} = [1.85, 3.69] \times 10^{9}\,\mathrm{kg/a}$. The factors consider the average effect of the emission of ODP on the reduction of O_3 concentration. Bjorn and Hauschild [433] proposes a boundary of $\dot{m}_{\mathrm{CFC-11,eq}} = 5.39 \times 10^{8}\,\mathrm{kg/a}$, which is within the uncertainty range of Doka [104]. Meyer and Newman [422] set their boundary to zero, however, it applies to substances regulated by the Montreal protocol only (does not include e. g. N_2O).

For the case study, we set the boundary to $\dot{m}_{\mathrm{CFC-11-eq}} = [4.24, 36.9] \times 10^{8}\,\mathrm{kg/a}$ using the lower value from Doka [104] and the higher value from Ryberg *et al.* [105]. Ozone depleting substances (ODS) are commonly measured in LCIA in the ODP-eqivalent CFC-11-eq. The uncertainty range for the impact assessment is modeled as uniform distribution with the minimum and maximum vales from the following impact methods: CML 2001, ILCD 2.0 2018 and ReCiPe V1.13 2016.

4.7.4 *Ocean acidification*

CO_2 uptake of the oceans from the atmosphere is the main driver for the change in pH value in the oceans' surface water. This change leads to dissolving the shells of marine species. To prevent this, the ocean surface saturation state of aragonite needs to stay $\Omega_{\mathrm{arag}} \geq [0.8, 0.7]$.

As the boundary is directly dependent on the climate change boundary, it is not operationalized in this method as it is expected, that if the CO_2 boundary is respected, so is the one for ocean acidification [79, 104].

4.7.5 *Biogeochemical flows*

4.7.5.1 *Phosphorus to oceans*

Phosphorus intake to oceans disturbs the nutrient balance and can lead to anoxic zones [77], thus the global flow of P into ocean needs to be restricted to $\dot{m}_{\mathrm{P,ocean}} < [11, 100]\,\mathrm{Tg/a}$. This PB is already in the right format and can be measured through the direct LCA inventory results P and PO_4 to ocean, soil, air and freshwater. P to ocean includes all P and PO_4 emissions to ocean, soil, freshwater, and air following the fate model employed in ReCiPe [446], as proposed by Doka [104]. This fate model characterizes non-marine P emissions to direct marine P emissions by calculating the fraction of P arriving in the oceans. For example, one kilogram of P emission to soil in this fate model leads to 0.337 kg P in the ocean. The uncertainty range is directly taken from the inventory result. Dao *et al.* [432] define an alternative boundary for P fertiliser application, which is contradicting the boundary for P to soil and therefore not considered here.

4.7.5.2 *Phosphorus to soil*

Applying mined P fertiliser on agricultural soil is the main driver for disturbed biogeochemical flows. The PB for applying mined phosphorus on agricultural soil is $\dot{m}_{\mathrm{P,soil}} < [6.2, 11.2]\,\mathrm{Tg/a}$.

The impact can be measured again from the LCA inventory results, this time for soil only as it specifically specifies application on soil. Following the precautionary principle, emissions on all soil types (i. e. industrial, agricultural, unspecified) in *ecoinvent* are considered, to account for unclear labelling and potential missing categories in agricultural soil (e. g. home gardening, infrastructure areas).

4.7.5.3 *Industrial and intentional biological fixation of nitrogen*

The nitrogen cycle is another biogeochemical cycle which is significantly changed by human activities. Therefore the PB specifies the limit on the industrial (e. g. Haber-Bosch fixation of N from air) and intentional biological fixation (e. g. through crops) of N to $\dot{m}_{\mathrm{N}} < [62, 82]\ \mathrm{Tg/a}$.

Assuming that all fixed nitrogen is sooner or later emitted as reactive nitrogen back to the environment, it is possible to count the reactive N emissions from inventory flows Doka [104]. This step is necessary as the intentional biological fixation of N is not directly accounted in LCIs. A list of reactive N compounds can be found in Doka [104], which are converted into N-equivalents based on the molecular N content.

4.7.6 *Landsystem change*

4.7.6.1 *Land use*

Landsystem change is a major driver for species loss [30, 33, 122] and climate change [384] but also an essential production factor for agriculture, renewable energy systems and infrastructure. Based on an assessment of the removal of natural land cover [383] on the climate system [384], the PB define the maximum land system change as remaining forest area [79]:

$$\frac{\text{area of forest}}{\text{area of original forest}} > \begin{cases} [75, 54]\% & \text{global average} \\ [85, 60]\% & \text{tropical or boreal forest biomes} \\ [50, 30]\% & \text{temporal forest biomes} \end{cases}$$

The PB restrict the remaining forest area only, thus leaving the question open how much of the other biomes can be used for human activities. In LCA land use in former forest biomes is usually not accounted separately. Still, Ryberg *et al.* [105] defines the boundary only for forest area ($< [1.6, 2.9] \times 10^{13}\,\mathrm{m}^2$), whereas Doka [104] assumes all biomes other than forest to be completely appropriable and sets the boundary to $< [8.5, 9.3] \times 10^{13}\,\mathrm{m}^2$. Bjorn and Hauschild [433] proposes a different boundary ($< 1.04 \times 10^{14}\,\mathrm{m}^2$) based on minimum area requirement for species conservation on all biomes equally, omitting the more strict boundaries for forests (which are based on climate sensitivity). Because of those limitations, we follow the approach in our previous work [226], combining the forest boundaries with the *nature needs half* proposal [33] for the remaining biomes. The total land boundary can be estimated to be $A_{\text{appr},p=0.98} = (6.01 \pm 0.924) \times 10^{13}\,\text{m}^2/\text{a}$ (see table 3.1).

For measuring land occupation, different land occupation categories from LCI (i. e. agriculture, industrial,. . .) are summed together. The uncertainty is defined through the basic uncertainty of the inventory flows.

4.7.6.2 *Cropland use*

The first publication on PB [77] specifies that total cropland may not occupy more than $< [0.15, 0.2]$ of the ice-free land surface, which translates into $\dot{m}_{\text{land,crop}} = [1.94, 2.61] \times 10^{13}\,\text{m}^2/\text{a}$. This boundary does not consider land conversion to pasture or infrastructure. This approach has been also used by Dao *et al.* [432]. Cropland occupation is a inventory category and can be directly measured. The uncertainty is taken from the *ecoinvent* inventory results.

4.7.7 *Freshwater use*

Freshwater consumed from the blue water stream is no longer available for freshwater ecosystems and further changes the hydrologial cycle. The PB for blue water consumption is set to $\dot{m}_{\text{w,global}} = [4000, 6000] \times \text{km}^3/\text{a}$. The withdrawal and immediate or delayed discharge into the river also has an effect on the freshwater ecosystem, especially in low flow months. Thus an additional, regional and temporal explicit control variable is set for river basins with

$$\frac{\text{monthly withdrawal}}{\text{mean monthly river flow}} < \begin{cases} [25, 55]\% & \text{low flow months} \\ [30, 60]\% & \text{intermediate flow months} \\ [55, 85]\% & \text{high flow months} \end{cases}$$

The global blue water consumption boundary is already in the suitable format and can be adopted without changes [104, 105]. Meyer and Newman [422] propose a boundary that also includes grey and green water consumption, which can be implemented in the future. Bjorn and Hauschild [433] redefine the boundary based on environmental flow requirements and water stress. The regional withdrawal boundary requires a regionalized assessment, which we have excluded in the case study. There are ongoing efforts to define refined boundaries for freshwater [83, 84], which can be implemented once available.

Blue water consumption is an explicit elementary flow in *Exiobase*, however not in *ecoinvent*. Blue water consumption for LCI is thus approximated as the sum of all water emissions to air (i. e. evaporative water consumption) [104]. Note, that these emissions also include water formed in combustion processes and excludes water which is incorporated in products.

4.7.8 *Atmospheric aerosol loading*

Aerosols have a dimming effect on the climate system, but also change precipitation and wind patterns and have a negative effect on human and ecosystem health. The control variable is defined as the Aerosol Optical Depth (AOD), which correlates to the opacity of the atmosphere, and the PB is set for South Asia to $AOD < [0.25, 0.5]$. In South Asia, there is a background AOD of 0.15 [79], thus defining an anthropogenic increase of AOD to $[0.1, 0.35]$. This boundary is not considered, as for the first application of the method we do not consider regionalized boundaries or impacts.

4.7.9 *Novel entities*

Novel materials and engineered organisms pose thread to ecosystems and human health, however there is no global boundary control variable defined yet [77, 79].

Toxicological effects are indirectly considered in the biodiversity boundary. Doka [104] suggests to set a boundary for disability adjusted life years based on the effect of novel entities on human health. Meyer and Newman [422] propose a boundary for imperishable waste, which cannot be quantified in LCA and EE-IOT yet. For the proof of concept of the method, this PB is not integrated but a potential area of future research.

4.7.10 *Energy*

CE aims at closing material cycles, which becomes increasingly energy intensive with higher recycling rates [348]. Thus the availability of sustainable energy may become a limiting factor for CE. A global boundary for renewable energy availability is therefore derived in an earlier paper [226], based on estimations for sustainable energy budgets for different RE resources. The RE boundary is estimated to be $ATP_{el,p=0.98} = (1.52^{+1.24}_{-0.81}) \times 10^{14}\,\mathrm{W}$ [226]. In a refined assessment, boundaries can be set for each RE resource separately.

The cumulative energy demand (CED) is a commonly used impact method in LCIA. The CED adds up all energy values of inventory results for energy carriers (chemical energy) and electricity provided by renewable energy resources (e. g. wind, solar but not biomass). To be inline with the boundary in electric energy, the CED values need to be converted to electricity equivalents. Therefore common conversion efficiencies are assumed for each reported energy carrier category [226].

Energy carrier inventory result in *ecoinvent* 3.5	**unit**	**conversion efficiency**	**CF to** $CED_{\mathrm{el}}/\mathrm{MJ}$
Energy, potential (in hydropower reservoir), converted	MJ	1	1
Energy, solar, converted	MJ	1	1
Energy, kinetic (in wind), converted	MJ	1	1
Energy, gross calorific value, in biomass	MJ	0.25	0.25
Energy, gross calorific value, in biomass, primary forest	MJ	0.25	0.25
Gas, natural, in ground	m^3	0.4	15.32
Oil, crude, in ground	kg	0.37	16.95
Peat, in ground	kg	0.34	3.37
Uranium, in ground	kg	0.33	186480
Coal, hard, unspecified, in ground	kg	0.34	6.49
Coal, brown, in ground	kg	0.34	3.37
Energy, geothermal, converted	MJ	1	1
Gas, mine, off-gas, process, coal mining	m^3	0.4	15.92

TABLE 4.4: Characterization factors (CF) for cumulative energy demand in electricity equivalents CED_{el} based on CF of CED in *ecoinvent* v.3.5 [401] and conversion efficiencies to electricity from [402].

In *Exiobase* the total energy use is reported. This value lacks detail on energy carrier types however for a specific year the global energy mix is known [246] and it is thus possible to calculate an overall global "efficiency" of energy conversion to electricity equivalents.

$$\eta_{\text{overall,el}} = \frac{5.3 \times 10^{12}\,\text{W}_{\text{el}}}{1.8 \times 10^{13}\,\text{W}} = 0.29 \tag{4.12}$$

Assuming an uniform energy mix for all sectors, the conversion to electricity equivalents does not have an influence on the share of energy need for different sectors, only on the total.

4.8 MEASURING IMPACTS FROM INDUSTRIAL SECTORS WITH *exiobase*

Exiobase is an EE-IOT for the global economy. It reports monetary flows from industries to industries to produce a final output to the society. For each of the 163 industries in the 43 countries and 6 rest of the world regions, the direct impacts caused are reported in the environmental extensions. We use *Exiobase* to calculate the global environmental impacts of the ESB categories and the impact share of resource production. In this way, we can allocate the ESB to resources. The definition of resource segments can be found in tab "S" in file "SoSOS_materials.xlsx" in the code files online `https://doi.org/10.5281/zenodo.3629366`.

4.8.1 *ESB impact characterization method for Exiobase*

Exiobase version 3 does not provide any impact characterization methods, but raw environmental flow data. These flows have to be translated into the PB impact categories using a characterization matrix $\boldsymbol{Q}$.

A characterization matrix $\boldsymbol{Q}$ is build to translate the flows into impacts for the PB categories (see sec.4.2.1). This impact assessment is based on ReCiPe v1.13 2016 [446] and, for global warming potential, on the CREEA impact characterization factors provided with *Exiobase* version 2.2.2 [429], which is based on LCIA methods such as CML 2001, ecoindicator 99 and usetox. Several PB categories only require elementary flows, which are directly taken from the flow matrix. The uncertainty range for impact characterization factors are modeled as uniform distributions with the minimum and maximum values among the respective impact assessment methods for each boundary. To also consider the uncertainty of the flows, $\boldsymbol{Q}_{IA}$ is multiplied with normalized uncertainty distribution (i. e. $mean = 1$)

for each elementary flow, modeled as log-normal distribution. *Exiobase* doesn't provide information on the uncertainty range, thus it is assumed, that the uncertainty of inventory flows is similar to the corresponding uncertainty in *ecoinvent* [238].

$$\boldsymbol{Q} = \begin{array}{cc} n_{\text{flows}}\downarrow & \begin{array}{ccc} 1 & n_{\text{flows}} & 1104 \end{array} \\ \begin{array}{c} 1 \\ \vdots \\ 1104 \end{array} & \left[\begin{array}{ccc} 1e^{\pm\sigma_1} & & 0 \\ & \ddots & \\ 0 & & 1e^{\pm\sigma_{1104}} \end{array} \right]_{\iddots\, n_{\text{runs}}} \end{array} a \times \begin{array}{cc} flows\downarrow & \begin{array}{ccc} 1 & n_{\text{PB}} & 11 \end{array} \\ \begin{array}{c} 1 \\ \vdots \\ 1104 \end{array} & \left[\begin{array}{ccc} & & \\ & \boldsymbol{Q}_{IA} & \\ & & \end{array} \right]_{\iddots\, n_{\text{runs}}} \end{array} \tag{4.13}$$

4.8.2 *Analysing direct impacts from industries*

The direct emissions resulting in the target segments (i. e. material related industries) can be calculated by adding up all environmental impacts of relevant industries. In the environmental extensions, emissions and resource flows (hereafter called "flows") are reported in the matrices f (flows for each product and country) and f_{hh} (flows for each final demand (FD) category (hh = household) and country. The flows for each product in the different countries $n_{\text{country}} = 49$ has to be summed up to result in global totals, reducing the product dimension from 7987 to 163 (eq. 4.14) and the FD dimension from 343 to 7 (eq. 4.15). The two flow matrices are combined to a single one in eq. 4.16.

$$f_{\text{industry}}(i) = \sum_{k=1}^{n_{\text{country}}} f_x((i + n_{\text{industry}}(k-1)) \quad \forall i = 1 \dots n_{\text{industry}} \tag{4.14}$$

$$f_{FD}(i) = \sum_{k=1}^{n_{\text{country}}} f_{\text{hh}}((i + n_{\text{hh}}(k-1)) \quad \forall i = 1 \dots n_{\text{FD}} \tag{4.15}$$

$$f = \left[\begin{array}{c|c} f_{\text{industry}} & f_{\text{FD}} \end{array} \right] \tag{4.16}$$

These direct impacts, however do not include impacts caused by inputs in this segment from the rest of economy, e. g. electricity.

4.8.3 *Including supply chain impacts*

The approach chosen here [259, 438, 439], isolates the target industries (i. e. the outputs form industries of interest, here: primary material production) from the rest of the economy (RoE). It then allocates all environmental impacts from inputs from target and non-target industries to the final output of the target industries. e. g. steel (itself a target industry) necessary to produce aluminum, such as for production infrastructure, is allocated to the aluminum output as is required electricity (non-target industry). The procedure effectively allocates all upstream environmental impacts to the output of a target industry, supplied to the RoE and FD.

The total demand $\vec{x}$ is calculated from an input-output table $\boldsymbol{A}$ and the FD $\boldsymbol{y}$. The FD is reported in 7 categories for the $n_{\text{countries}} = 49$ countries and rest-of-world regions. The overall FD is then the sum over all categories, which results in a FD vector $\vec{y}$. Per country $n_{\text{industry}} = 163$ different industry categories are reported.

$$\begin{aligned} \vec{x} &= \boldsymbol{A} \times \vec{x} + \vec{y} \\ \vec{x} &= (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{y} = \boldsymbol{L} \times \vec{y} \end{aligned} \tag{4.17}$$

The values of $\vec{x}$ express the total output of each industry and region, including the output supplied to other industries. In order to calculate the output of the target segment of the economy, without double counting the output which is consumed within the target segment itself, the whole input-output table is split into target (t) and other (o) industries [438].

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{tt} & \boldsymbol{A}_{to} \\ \boldsymbol{A}_{ot} & \boldsymbol{A}_{oo} \end{bmatrix} \qquad \boldsymbol{L} = \begin{bmatrix} \boldsymbol{L}_{tt} & \boldsymbol{L}_{to} \\ \boldsymbol{L}_{ot} & \boldsymbol{L}_{oo} \end{bmatrix} \quad \boldsymbol{L}_{all-t} = \begin{bmatrix} \boldsymbol{L}_{tt} \\ \boldsymbol{L}_{ot} \end{bmatrix} \tag{4.18}$$

The overall production volume of each industry within the target segment $\vec{x}_t$ needs to equal the production necessary to supply the final output of the segment $\vec{x}_{t,wdc}$ (wdc. . . without double counting). This output of the segment is required by direct FD $\vec{y}_t$ and by the requirements of the ROE to produce the FD from all other industries $\vec{y}_o$ [439].

$$\vec{x}_t = \boldsymbol{L}_{tt} \times \vec{x}_{t,wdc} \tag{4.19}$$

$$\vec{x}_{t,wdc} = \vec{y}_t + \boldsymbol{A}_{to} \times \boldsymbol{L}_{oo}^T \times \vec{y}_o \tag{4.20}$$

Environmental extensions are reported in *Exiobase* in elementary flow matrices $\boldsymbol{f}$ for the total production output $\vec{x}$ and $\boldsymbol{f}_{\mathrm{FD}}$ for the FD $\vec{y}$. The emission intensity $\boldsymbol{F}$ for each industry can then be calculated by dividing each column in $\boldsymbol{f}$ with the respective total production output. Finally, the elementary flows associated with production of the segment's output is calculated in eq. 4.21.

$$\boldsymbol{f}_{t,wdc} = \boldsymbol{F} \times \boldsymbol{L}_{all-t} \times \hat{\boldsymbol{x}}_{t,wdc} \tag{4.21}$$

$$\underbrace{\begin{bmatrix} & & \\ & \boldsymbol{f}_{t,wdc} & \\ & & \end{bmatrix}}_{1104\times n_t} = \underbrace{\begin{bmatrix} \\ \boldsymbol{F} \\ \\ \end{bmatrix}}_{1104\times 7987} \times \underbrace{\begin{bmatrix} & & \\ & \boldsymbol{L}_{all-t} & \\ & & \end{bmatrix}}_{7987\times n_t} \times \underbrace{\begin{bmatrix} \ddots & & 0 \\ & x_{t,wdc}(i) & \\ 0 & & \ddots \end{bmatrix}}_{n_t\times n_t}$$

The total elementary flows for the whole world economy is simply the sum over all industries, FD categories and regions. The flows for the RoE is then the difference between the FD and target segment from the total flows.

$$\boldsymbol{f}_{total} = sum(\boldsymbol{f},2) + sum(\boldsymbol{f}_{FD},2) \tag{4.22}$$

$$\boldsymbol{f}_{\mathrm{RoE}} = \boldsymbol{f}_{total} - sum(\boldsymbol{f}_{t,wdc},2) - sum(\boldsymbol{f}_{FD},2) \tag{4.23}$$

Industries can be grouped into sectors using a sector matrix $\boldsymbol{S}$. The target segment "materials", as the subject of this study, consists of multiple sectors, which are groupings of industries by material classes (e. g. metals, construction materials,. . .). Each industry can only be assigned to one sector to avoid double counting. Note, that the sectors can be assembled in different ways, which is subject to the modeler's choice.

$$\boldsymbol{f}_{sector} = \boldsymbol{f}_{t,wdc} \times \boldsymbol{S} \tag{4.24}$$

The impacts on the PB categories are calculated as follows:

$$\boldsymbol{q}_{t,wdc/FD/total} = \boldsymbol{Q}^T \times \boldsymbol{f}_{t,wdc/FD/total} \tag{4.25}$$

The impact results are then further converted into relative shares, i. e. the share of the impact from one product or sector in relation to the total impact by all products/sectors is determined.

$$\begin{aligned} \boldsymbol{SoSOS}_{t,wdc} &= \frac{q_{t,wdc}}{q_{total}} && (4.26) \\ \boldsymbol{SoSOS}_{sector} &= \boldsymbol{SoSOS}_{t,wdc} \times \boldsymbol{S} && (4.27) \end{aligned}$$

4.8.4 *Calculation of the oversize factor*

By calculating the supply chain impacts for the target segment, all impacts associated with the final output to the rest of the economy are accounted to the final output. This final output is, however, lower than the overall production in the respective target industry, as this industry also supplies materials to other target industries. For example, steel is not only used in the RoE, but also to produce plastics. The supply chain impacts for plastics already include the impacts associated to the steel necessary for plastic production. Through the double-counting correction procedure [259, 438], the output of steel is reduced by the amount required in plastics. Therefore, the overall production in each target industry needs to be larger than the final output to the RoE by the oversize factor:

$$\begin{aligned} \omega &= \frac{\dot{m}_{\text{overall production}}}{\dot{m}_{\text{production output}}} && (4.28) \\ &= \frac{\vec{x}_t}{\vec{x}_{t,wdc}} && (4.29) \end{aligned}$$

4.9 ESB IMPACT CALCULATION AND PROCESS SELECTION IN *ecoinvent*

Many ESB can be measured with inventory results directly (CO_2 emissions, P to ocean, P to soil, N emissions, land-use, and blue water consumption). For these impacts, the uncertainty is modelled with a log-normal distribution with the variance provided in the *ecoinvent* quality guideline [238]. For all other boundaries, which require impact assessment methods, the uncertainty is combined as the inventory uncertainty and a rectangular distribution for the variation of different LCIA methods. For all boundaries, used LCIA methods and LCI uncertainty function are listed in table 4.5.

For the ERA method, the impacts resulting from extraction, processing and final treatment of the resources is required. Therefore, representative processes from the *ecoinvent* database have to be selected. The cut-off system

Impact categories	**Unit**	**LCIA method**	**Uncertainty distribution**
Direct CO_2 emission to air	kg CO_2	-	Log-normal
Global warming potential	kg $CO_{2,eq}$	CML 2001, ILCD 2.0 2018, IPCC 2007, IPCC, 2013, ReCiPe 2016	Uniform
Potentially disappeared species	species·a	3 scenarios of ReCiPe 2016	Uniform
Ozone depletion potential	kg $CFC_{10,eq}$	CML 2001, ILCD 2.0 2018, ReCiPe 2016	Uniform
Phosphorus to ocean	kg P	-	Log-normal
Phosphorus to soil	kg P	-	Log-normal
Nitrogen emission	kg N	-	Log-normal
Land-use	m^2a	-	Log-normal
Water emission to air	m^3	-	Log-normal
Cumulative energy demand	MJ eq	-	Log-normal

Table 4.5: Impact categories selection, characterization, and uncertainty models

model has been used [401] so that cumulative impacts for processed material already includes the impacts of the up-stream supply chain (i. e. mining, transportation, processing) and the impacts for final treatment start with the point where the resource becomes final waste. The selected processes for the case study are listed in table 4.6. Because the case study on the ERA method aims to calculate global resource budgets, the requirement is to choose global production and waste treatment processes from the *ecoinvent* database.

Ecoinvent often reports country or region specific production processes only. Thus, global weighted averages are formed based on multiple production/ waste treatment processes available in *ecoinvent* for a specific material. For example, the process *primary production of aluminum (ingot)* exists in *ecoinvent* for ten countries/ regions. The global average impacts for this process can therefore be weighted with their respective market share.

Metal	**Primary production**	**Incineration**
Aluminum	Aluminum, primary, ingot (China; Africa; Asia w/o China; EU; Gulf council; Russia; South America; Northern America; Oceania; Rest of the World)	Scrap aluminum, incineration (Switzerland; EU; Rest of the World)
Copper	Copper production, primary (Australia; Asia; Europe; Latin America and the Caribbean; Northern America; Rest of the World)	Scrap copper, incineration (Switzerland; EU; Rest of the World)
Steel	Steel production, unalloyed, converter (Europe; Rest of the World)	Scrap steel, incineration (Switzerland; EU; Rest of the World)
Cast iron	Cast iron production (Europe; Rest of the World)	Scrap steel, incineration (Switzerland; EU; Rest of the World)
Zinc	Market for zinc (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Lead	Primary lead production from concentrate (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Tin	Market for tin (global)	Treatment of scrap tin sheet, municipal incineration (global)
Nickel	Market for nickel (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Gold	Market for gold (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Silver	Market for silver (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Platinum	Market for platinum (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Titanium	Market for titanium, primary (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Chromium	Market for chromium (global)	Treatment of hazardous waste, hazardous waste incineration (global)
Stainless steel	Chromium steel 18/8, hot rolled (global)	Scrap steel, incineration (Switzerland; EU; Rest of the World)

TABLE 4.6: *Ecoinvent* processes for selected metals

5

RESOURCE PRESSURE

> *Climate crisis is a crisis of imagination*
> — Rob Hopkins

BIBLIOGRAPHICAL DATA

Title	Resource pressure – A circular design method
Authors	Harald Desing, Empa Gregor Braun, Empa Roland Hischier, Empa
Journal	Resources, Conservation & Recycling, Elsevier
Date	submitted: 18 May 2020; published 1 October 2020

KEY FINDINGS

- The pressure on primary resources of a product or service can be measured as a combination form the primary material input and the final losses generated as an output.
- Reducing the resource pressure of a product depends on six parameter of the product and the ecological resource budget of the chosen material(s).
- The resource pressure method can be used throughout the design process for the guidance towards reduced environmental impacts associated with resources.

THE AUTHOR'S CONTRIBUTION

Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review and editing, Visualization,

THE CO-AUTHORS' CONTRIBUTION

Gregor Validation, Formal analysis, Investigation, Writing – original draft, Writing – review and editing
Roland Supervision, Project administration, Funding acquisition, Writing – review and editing

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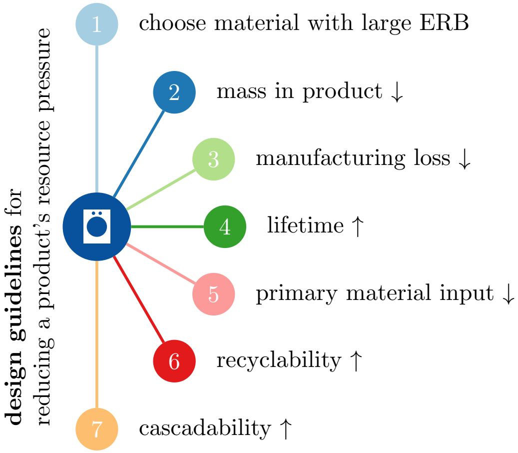
ABSTRACT

Extraction, processing and final disposal of primary resources is responsible for a major share of global environmental burdens, many of which are already beyond safe limits today. Design is pivotal for defining the quality and quantity of resources that are required as an input to produce a product (or service) as well as the generated output by its use and final disposal. In order to improve the environmental performance of our society, it is therefore essential to provide adequate design guidance. To this end, we present in this paper the resource pressure method allowing to reduce the pressure on primary resources, and therewith on planet Earth, through circular strategies. This resource pressure is calculated out of six design parameters: mass in product, product lifetime, manufacturing losses, primary material content, recyclability and cascadability. The method enables a straightforward quantitative assessment of design decisions and offers clear guidance during the design phase. We further derive qualitative guidelines with the objective to provide direction during design conception. A first application on a heat exchanger illustrates the advantages as well as the further development potential of the method. In comparison to the results from a life cycle assessment study of this case study, it could be seen that the resource pressure method guides towards reducing the overall environmental impacts.

GRAPHICAL ABSTRACT



5.1 INTRODUCTION

Designing products and services[1] for a sustainable circular economy (CE) [56] has the potential to greatly reduce primary resource needs and improve the availability of secondary material for further utilization in the economy. Primary resource extraction and processing contributes significantly to the global environmental burdens today [122, 449], thus reducing demand for primary material is essential to build a sustainable CE. In fact, as the pressure on many vital Earth system processes (e. g. climate or biodiversity) is beyond safe limits today [10, 15, 77, 79], it is necessary to reduce the use of resources in the economy to a sustainable level [449]. In the design phase of a product, the quality and quantity of materials and energy required for production and operation of the product are defined. Additionally, the design also determines, up to a certain extent, the quality and quantity of materials that are recoverable at the end of the product's life [159, 164] as well as the amount of unavoidable final losses (e. g. abrasion, corrosion, dispersion [121]). Therefore, design has a significant leverage to improve material utilization in society [159] and reduce environmental impacts [163–167].

Over the last decades, a multitude of eco-design tools have been developed, either specific to aspects of CE (such as design for disassembly [187], design for resource circulation [180], design for remanufacture [450], design for product life extension [184], cradle-to-cradle^{TM} [20], design for recycling [451]) or more general to improve the environmental performance (e. g. in form of guidelines [171, 174, 178, 180, 181], diagram tools [179] or simplified life cycle assessment (LCA) approaches [182]; see also [166, 175, 452]). However, many of these eco-design tools are not applied in industry, because they either require time-consuming and complex procedures and depend upon specific knowledge [166, 167], or offer insufficient guidance in trade-offs [174, 182, 190]. It is further often difficult to choose the appropriate tool from the variety of possibilities for the specific requirements of the company [166]. In this context, guidelines have proven to be the most useful eco-design tools in industry, because they are easy to use and informative already for design conception [452]. The main inconvenience of such guidelines is, that they are often too general – unless customized to single product groups [177] – and, as they are often selected based on perceived benefits, may lead to hidden burden shifting and trade-offs [174]. And even

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[1] In this paper we use products as a synonym for products and services, i. e. services are always included when we write about products.

though the usefulness of such design guidelines is widely recognized, they mostly lack quantitative decision support, as only few of them are tied to quantitative indicators.

Life Cycle Assessment (LCA) is a well established tool to quantify environmental impacts of a product [191, 192]. However, being a quantitative assessment tool, it requires detailed data, which usually is available only in later design steps or even at the very end of the design process [171]. It offers a very detailed but *ex post* analysis of the environmental performance, either relative to a reference product or against absolute benchmarks [98, 101, 105, 107, 430], and is therefore not very useful to influence design decisions [167]. In the past few years, so-called *ex ante* or prospective modelling approaches for LCA have been published by various research groups (for an overview see e. g. [453]). Common challenges in these approaches are the issues of data availability and their comparability (in order to be able to keep a minimum degree of consistency in the model), as well as the various uncertainty challenges (especially when such new technologies are compared to existing products). Hence, such *ex ante* LCA studies require even more specialist knowledge than an *ex post* analysis.

In regard to CE, specific indicators have been proposed to measure the degree of material circulation [193, 200, 203], avoided environmental impacts [153] or saved costs [198, 199]. However, they either require data not available during design (e. g. LCA results [153]) or measure circulation irrespective of environmental impacts (e. g. [203]). In fact, what is needed is an easily applicable method [166] that (i) can inform product designers from the very beginning [184], (ii) gives them clear direction/guidance and (iii) can be used by them without too much (additional) knowledge or training.

To this end, we propose a new design decision support method focusing on the utilization of resources. The method measures the pressure exerted by the product on sustainably available resources (i. e. amount of resources available within Earth system boundaries [449]) with key CE design parameters that can be estimated during the design process. Therefore, we call it the "resource pressure" method. Further, we derive design guidelines based on the resource pressure indicator, that can be considered early in the design phase. In this combination, the method provides both qualitative guidance as well as an *ex ante* assessment of the "circularity" of the product to quantitatively influence design decisions.

5.2 METHOD DEVELOPMENT

With the resource pressure method developed in this section, we intend to guide the selection of materials and circular strategies from early design phases onward. This method does not intend to provide any guidance on toxic or harmful substances, but its aim is to allow a designer (i) to reduce the pressure on primary resources and (ii) to maximize the utility of materials within the socio-economic system. Environmental impacts are considered in so far as they result from primary material production and losses of these materials to final sinks, and are included in the calculation of the material's ecological resource budget (ERB) (see section 5.2.1, [449] and bottom part of figure 5.1). The embodied impacts of resources (including materials, food and fuels) generally show a significant share of the total impacts of a final product [175, 454] and are globally responsible for about 1/2 of greenhouse gas emissions [122, 449], dominate agriculture related impact categories like water stress [122] and contribute about 1/3 of particulate matter related health impacts [122] as well as to energy demand [449]. As the choice of material influences the design strongly (e. g. in regard to manufacturing technologies or lifetime), we focus for this first version of the method on environmental concerns related to the required amounts of primary materials only, acknowledging the need to further develop this method – or develop other, complementary methods – to address environmental impacts from further life cycle stages, particularly from recycling and cascading.

For the design method, after having defined the ERB (section 5.2.1), we then need to define the resource pressure as a quantitative indicator (section 5.2.2) and afterwards link it to the six design parameters shown in figure 5.1 (section 5.2.3). The design method itself consists of this quantitative indicator for the evaluation of the resource pressure as well as of qualitative guidelines that are derived from it in section 5.2.4.

5.2.1 *Ecological resource budgets as a benchmark*

How much of a material can be produced within Earth system boundaries? To answer this question, we have proposed the method of ecological resource availability (ERA) [449], which estimates the annual material production that is possible for all materials without violating any boundary with more than a defined probability. This method requires the allocation of the global boundaries to resource segments (e. g. all metals) and the defi-

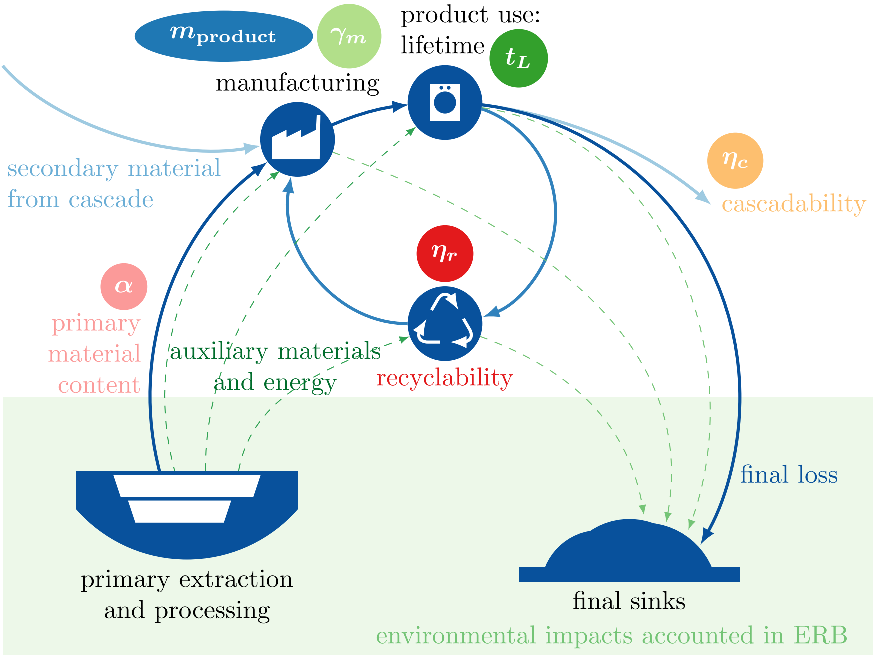

FIGURE 5.1: Overview of the resource pressure design method. The six parameters (in bubbles) considered are described in detail in section 5.2.2. Environmental impacts are captured in the method in regard to extraction and losses to final sinks (processes inside green box), i. e. impacts considered in the calculation of ecological resource budgets (ERB) (section 5.2.1). Environmental impacts caused by manufacturing, use, recycling or cascading (processes outside green box) are not captured, unless resulting from the extraction and final disposal of auxiliary materials and energy.

nition of shares within these segments. Different allocation scenarios, the optimization of production shares and alternative production technologies (e. g. steel making with hydrogen [442]) can be analysed on their effect on ERA. Calculating ERA budgets based on grandfathering[2] is one possible allocation scenario, however, everything but optimal for society as it simply rescales the current economy to fit within Earth system boundaries. The transformation to a sustainable CE requires not just rescaling, but a shift in resource production and use. Using the grandfathered ERA as a benchmark

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[2] i. e. allocating global boundaries to resources according to today's impact shares and setting the share of production as in today's pattern of resource use, see [449]

for design is hindering such a transformation, because it entrenches the status quo of today's unsustainable resource use. Defining a sustainable ERA, which is an optimized composition of society's resource use to provide for needs and desires [441, 455] within the limits of the planet, is still an open question, both in research and politics. Optimizing the use of such a desirable ERA would be a valid design objective.

Until such a scenario is available, we propose to use the *ecological resource potential* (ERP) for design guidance, which is based on the material's impact intensity alone. The ERP shows the maximum theoretical potential for producing one material within Earth system boundaries, when no other anthropogenic activity would take place. Hence, it only depends on the impact intensity on the boundaries and does not require any allocation. Using ERP as a benchmark for the design therefore minimizes the pressure on Earth system boundaries, as it favours materials with low environmental impacts in the most limiting boundary category. This reflects the design objective for minimizing environmental impacts in regard to Earth system boundaries.

These ERPs can be calculated with a slight modification of the ERA method [449] by omitting all steps for allocation and production shares and calculating the ERP for each material separately. The ERP is then defined as the production mass flow that leads to a violation of no global boundary with more than a chosen probability of violation P_v. In concordance with the ERA method [217, 449] (see section 5.8), we choose $P_v = 0.01$, i. e. each boundary is respected with a confidence of at least 99 %. Data necessary for calculating ERP are the uncertainty distributions of Earth system boundaries and cumulative impacts (for all boundary categories) of the extraction and production of primary material as well as its final disposal. Note, the most limiting boundary is defining the ERP, therefore no weighting between impact categories is necessary.

In the resource pressure method, either the ERA or the ERP can be used as the (limiting) ecological resource budget ERB, depending on the availability of data and the question to answer. For example, the grandfathered ERA [449] can be used for an analysis of the resource pressure exerted by a current societal activity (e. g. company or country). However, setting future targets and designing related policies requires building scenarios for sustainable ERA. Thus, in a future-oriented product design either ERP can be used for the objective of minimizing environmental impacts or a yet-to-be-defined desirable ERA for the objective of optimizing the use of these limited resources. ERB is a mass flow of primary material to society, usually measured in the unit kg/a.

$$ERB = \begin{cases} ERA & \text{for analysis and design for optimizing the use of ERA} \\ ERP & \text{for design for minimizing impacts} \end{cases} \tag{5.1}$$

5.2.2 *Resource pressure*

Products need material input and generate output in form of emissions and solid waste. Sooner or later, every input is turned into an output, latest at end-of-life (EoL) due to mass conservation. Providing the product's functionality over time requires a product system, consisting of a continuous flow of replacement products. Averaging the material flows induced by such a product system over time, it can be considered in steady state, i. e. requiring constant inputs and generating constant outputs. The design of the product thereby essentially defines the necessary inputs as well as the generated outputs, both in terms of quantity and quality. These inputs and outputs can be attributed to one of the following three groups of materials:

- Consumed materials: represents the required primary input (e. g. gasoline fuel) as well as all final losses (e. g. combustion emissions).
- Cascaded materials: secondary material input from higher technical quality level and output to lower technical quality level (e. g. aluminium wrought alloy → cast alloy).
- Recycled materials: closed loop recycling, where output is a possible input within the same product system, at least in principle (e. g. PET bottle-to-bottle recycling). In reality, recycling without losing quality can also take place between product systems (e. g. glass bottle to glass container [161]).

Primary material input consumes a part of the material's ERB, which we define as the resource pressure τ. The less material a specific design requires from the sustainably available primary resource base (i. e. from ERB), the lower also the pressure on this specific resource and the lower the associated environmental impacts. The resource pressure cannot only be calculated for the materials contained in the product, but also for energy and auxiliary materials throughout the product' life cycle, covering the respective environmental impacts (see figure 5.1). Direct impacts from life cycle stages (e. g. manufacturing or recycling) are not covered with the resource pressure method, however, generally contribute little to the overall impact. The resource pressure can therefore be indicative for the selection of different materials and circular strategies in early design stages, but does not replace a more detailed *ex post* analysis, as not all environmental impacts are covered. The resource pressure τ is evaluated for each material separately and aggregated in the end for products containing more than one material. The resource pressure τ is dimensionless and can be defined as the mass flow of primary material required $\dot{m}_{\text{prim}}$ divided by ERB.

$$\tau = \frac{\dot{m}_{\text{prim}}}{ERB} \tag{5.2}$$

In the current global societal metabolism, the inflows of primary materials are larger than the outflows, as material stocks are growing [7], leading to a time lag between when an inflow is turned into an outflow [147]. But when looking at the resource flow over time, the output equals the input due to mass conservation. In a sustainable CE [56], where resource use is restricted to what is possible within Earth system boundaries, the metabolism tends towards a steady state when the resource use is maximised for society (i. e. stocks are constant, and as a consequence inflows equal outflows). Looking at the mass conservation, the resource pressure τ can be measured from two sides: (i) input compared to ERB, or (ii) output compared to losses to final sinks[3], with the latter being equal to ERB in steady state (see figure 5.2). However, this measurement from both sides is only equal for the entire socio-economic system. When looking at a single product, the primary input and the final losses do not have to be equal. For example, a product can be built from cascaded material only (i. e. no primary input), but become waste completely at its EoL (i. e. $\dot{m}_{\text{loss}} = \dot{m}_{\text{product}}$). Therefore from a product perspective, both of these two sides are relevant to measure the exerted resource pressure. While the use of primary material directly induces primary material production, final losses lead to a demand for primary material elsewhere in the socio-economic system and thus are like this responsible for a resource pressure as well. In other words, to create an environmentally benign product, it is necessary to reduce both the direct primary material intake as well as the creation of final waste. And the design of a product influences the resource pressure on both

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[3] Final sinks are stockpiles of materials no longer available in a useful form to society. In principle, these materials can be made available again with equal or more effort than primary production (e. g. CO_2 capture from air). A glossary of key terms is provided in the SI.

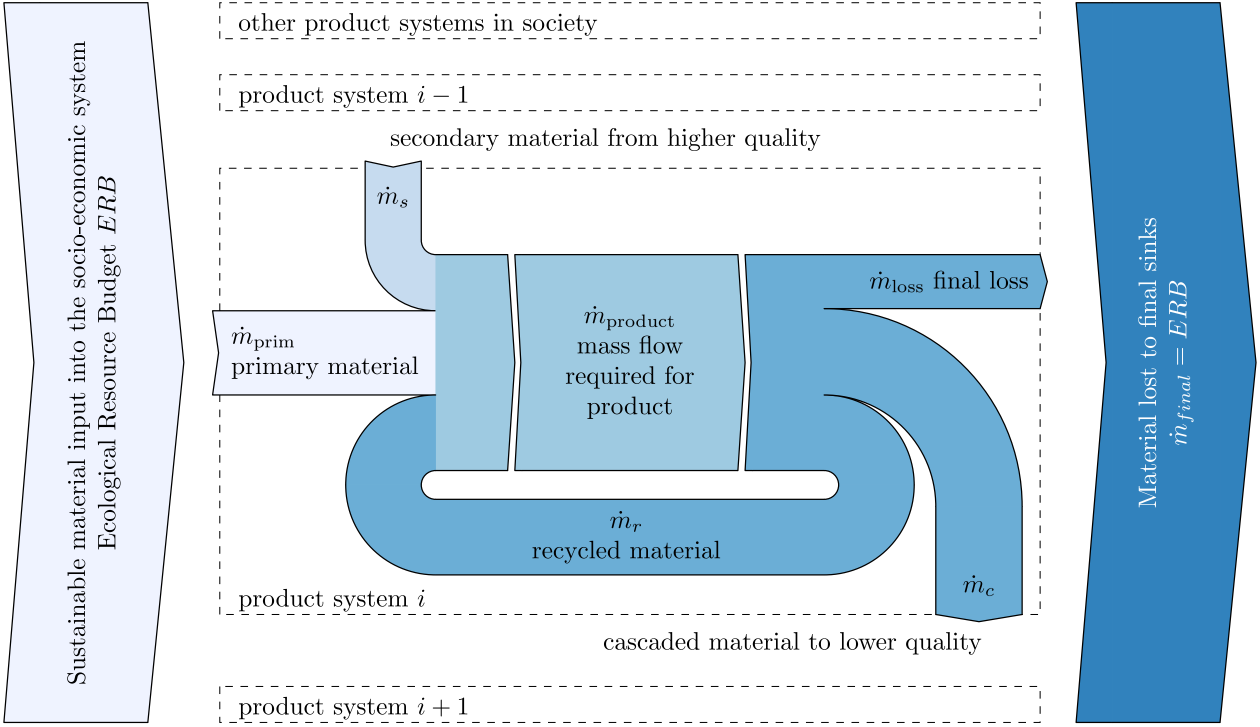

FIGURE 5.2: Flow of a material through the socio-economic metabolism in steady state. ERB is utilized in different product systems i, which can exchange materials from higher to lower quality levels (cascading) as well as recycle material at the same quality level within the product system. Material that can neither be recycled nor cascaded to another product system is lost to final sinks.

sides (e. g. through the choice of material (input) or connections between different materials affecting the recyclability (output)). Thereby, material that can be recovered with the same quality (recyclability, i. e. can potentially be used as an input to produce the same product) or at a lower quality level (cascadability) [456] remains available in the socio-economic system without exerting pressure on the respective primary resource. Making these secondary materials available again, however, entails the use of auxiliary materials (e. g. solvents) and energy for the reconditioning, i. e. inducing pressure on those resources.

Hence, in order to include both the input and output perspectives, we modify the pressure indicator τ (eq. 5.2) and define it as the average from both perspectives (eq. 5.3).

$$\tau = \frac{1}{2}\frac{\dot{m}_{\text{prim}}}{ERB} + \frac{1}{2}\frac{\dot{m}_{\text{loss}}}{ERB} = \frac{\dot{m}_{\text{prim}} + \dot{m}_{\text{loss}}}{2 \cdot ERB} \tag{5.3}$$

Equation 5.3 can also be interpreted as an equal measurement of the resource pressure on ERB and the pressure on final sinks. This equity is based on the assumption of a steady state, i. e. the capacity of final sinks is equal to ERB (see figure 5.2, [449]). In principle, different weights could be given to the input and output sides, however, in our opinion they are equally important in product design.

5.2.3 *Linking resource pressure and design parameters*

To be useful in the design process, equation 5.3 needs to be linked to design parameters, which are described in the following subsections. This link is established here based on a simplified material flow in the product system (figure 5.2). The total mass flow required by a product is composed of its related primary ($\dot{m}_{\text{prim}}$), secondary ($\dot{m}_s$, i. e. cascaded from higher quality) and recycled ($\dot{m}_r$, i. e. closed loop recycling at same quality) material flows. Similarly, the output flows generated (at EoL but also during other life cycle stages, e. g. corrosion) of such a product divides into final losses $\dot{m}_{\text{loss}}$, cascading $\dot{m}_c$ and recycling $\dot{m}_r$ flows. Recycled material $\dot{m}_r$ is the mass flow of material that is recovered at a quality high enough to be used in the production of the same product again, at least in principle. It is defined as the output of the closed-loop recycling system [161]. Losses during the recycling processes are contained in the final loss $\dot{m}_{\text{loss}}$ or cascading $\dot{m}_c$ flows. As the system is modeled in a steady state, the recycling flow that can be recovered at EoL equals the recycling flow available as an input (see figure 5.2). The mass balance for one material in the product system (eq.

5.4) is the basic equation to relate the primary material inflow $\dot{m}_{\text{prim}}$ and the final outflow $\dot{m}_{\text{loss}}$ with design parameters:

$$\dot{m}_{\text{product}} = \dot{m}_{\text{prim}} + \dot{m}_s + \dot{m}_r = \dot{m}_{\text{loss}} + \dot{m}_c + \dot{m}_r \tag{5.4}$$

5.2.3.1 *Mass flow required for the production of a product*

We can calculate the (theoretical) continuous mass flow of one material $\dot{m}_{\text{product}}$ required to provide the functionality of the product over time by spreading the required mass for the product over its lifetime t_L. The required mass of a material for the product is thereby the mass contained in the finished product m_{product} enlarged by the manufacturing losses γ_m.

$$\dot{m}_{\text{product}} = \frac{m_{\text{product}}}{t_L}(1 + \gamma_{\text{m}}) \tag{5.5}$$

This mass flow is a theoretical construct, valid for the assumption of a steady state of the product system under investigation. It can also be scaled with the expected production numbers to evaluate the resource pressure exerted by the product sales. Similarly, the pressure on a specific resource from one cooperation, sector or country can be estimated by inserting the (measured) mass flows on the respective levels. In this paper, we however focus on single products only.

FUNCTIONAL EQUIVALENCE The mass of the material in a product m_{product} is usually different for two designs based on different materials, although every design variant needs to fulfil the same functionality (e. g. bending stiffness for a beam). In most cases, there are several material options possible to fulfill a certain function in a product, while the material choice can significantly influence the design of a product. Weight differences of designs due to the choice of alternative materials can be estimated based on material properties of the respective materials [168, 169, 182]. For example, a pillar with the same load bearing capacity out of different materials will have a different weight in relation to the difference in the material's strength. Weight differences can also be estimated by developing design sketches detailed enough to allow a calculation of how much mass is required to fulfill the function. As a result, for each design alternative the final mass in the product can be estimated.

PRODUCT LIFETIME Prolonged service life reduces the material intensity per service unit directly. The lifetime of different design variants can differ due to the materials chosen (e. g. vulnerability to corrosion) or due to engineering parameters (e. g. sizing, surface roughness, surface treatment) [224]. Depending on the product type, the lifetime t_L represents a physical time (e. g. for a bridge), an operating time (e. g. for a power plant) or a number of service cycles (e. g. for a coffee machine).

The lifetime t_L is defined in this paper as an attribute specific to the part the material is used in. For example, an engine block can have a higher lifetime than the engine, if it is used in a new engine again (remanufacturing). As a counterexample, a bearing that has to be replaced in regular intervals has a shorter lifetime than the product it is used in. In this manner, circular strategies with no or minor changes to the integrity of parts – like reuse, remanufacturing, repair, refurbish, upgrade and similar – can be considered through their change in lifetime of the concerned parts.

MANUFACTURING LOSSES Possible material alternatives are likely to require different manufacturing technologies, leading to different manufacturing losses (e. g. casting vs. machining). The total material requirement for a specific design is the mass in the final product plus these manufacturing losses. These losses can be expressed as mass fraction of the finished product.

$$\gamma_m = \frac{m_{\text{lost}}}{m_{\text{product}}} \qquad \in [0, \infty) \tag{5.6}$$

For certain manufacturing technologies, such process losses can be circulated internally (e. g. casting channels in a foundry). Such internally recycled material is not part of the losses, as defined in this method. All other losses that have to be treated in other processes or industries (such as off-cuts and swarf from machining) are lost for the manufacturing process and need to be counted as such. They may, however, be recycled or cascaded and are not necessarily final losses.

5.2.3.2 *Specifying material input and output*

The required mass flow for the product can be provided by primary, cascaded or recycled material inputs. At the EoL of the product or during its service life, these inputs are transformed into final losses, cascadable or recyclable material outputs (see figure 5.2). These six flows need to be specified. The mass balance equations at the in- and output side (eq. 5.4) and the condition that the recyclable output equals the recycled input allow to calculate three out of six flows, making it necessary to specify three flows explicitly. We choose to specify the recyclability, cascadability and primary material content, which are described in the following paragraphs.

RECYCLABILITY At the end of the product's life, some material ($\dot{m}_r$) can be recovered to be used as an input to produce the same product again, at least hypothetically. This condition ensures, that the recycled material needs to have the same quality (often also called closed-loop or functional recycling). As materials degrade (e. g. polymer chain length reduction), get contaminated with unwanted elements (e. g. alloying elements of other parts [118]) and are chemically transformed during service life (e. g. corrosion) or EoL treatment (e. g. slag [156]), only part of the recoverable material flow can satisfy the quality requirement for closed loop recycling. The recyclability η_r is determined by the functional requirement in the design as well as the contamination with impurities at EoL [456]. Some proposals exist in the literature to estimate the recyclability of a product based on recycling process simulations [158, 451, 457, 458], which are data intensive and require detailed process knowledge. There is a need to develop design support methods to estimate recyclability by the product design team itself [456]. If the recyclability is unknown, it needs to be set to zero.

$$\eta_r = \frac{\dot{m}_r}{\dot{m}_{\text{product}}} \qquad \in [0, 1) \tag{5.7}$$

CASCADABILITY When material cannot be used for the same function again, they may be used for lower quality applications and cascaded as an input to another product system [117, 120, 151]. The cascadability η_c is the fraction of the product mass flow, that can be used as an input in another (and lower) function.

$$\eta_c = \frac{\dot{m}_c}{\dot{m}_{\text{product}}} \qquad \in [0, 1 - \eta_r] \tag{5.8}$$

The remaining material that cannot be recycled at the quality level required for the initial function of the product leaves the quality level and *cascades* to one or multiple, lower quality levels. This procedure can be repeated multiple times while gradually reducing quality levels. For example, once the threshold for alloying elements in an aluminum wrought alloy is crossed, it can be used as a cast alloy, which allows higher alloying element concentrations [117]. Cascading prolongs the useful service life of a material, even if it is no longer suitable for its initial quality. Each added cascading step increases the utilization of the respective material. Therefore, keeping the cascaded material in the socio-economic system reduces the pressure on primary resources. In this initial version, we don't consider different quality levels [56, 153], which is a potential area for further research.

A material flow is only then considered cascadable, if there is a (potential) market for it (i. e. it needs to be determined how "resource like" the waste stream is [201]). Materials, which have too low quality for any feasible use or if there is no (big enough) market for it, have to be considered final waste. Market feasibility studies usually precede product design, therefore data on market potential for material outputs can, in principle, be estimated during design. For example, truck tarpaulin is to a small extent further processed into hand bags after its intended use. This cascading reduces the resource pressure exerted by the tarpaulin only to the extent of the market for secondary material. The large amounts of tarpaulin, which are not cascaded to a second application because the market is too small, have to be considered final waste. On the other hand, the bag producer uses 100 % cascaded material and thus does not exert pressure on primary resources, however on final sinks at the end of the bag's life. In comparison to virgin material intake for a bag, the resource pressure is reduced by half.

PRIMARY MATERIAL CONTENT The primary material mass fraction α for one material is determined as the flow of primary material $\dot{m}_{\text{prim}}$ contained in the material flow required by the product $\dot{m}_{\text{product}}$.

$$\alpha = \frac{\dot{m}_{\text{prim}}}{\dot{m}_{\text{product}}} \qquad \in [0, 1 - \eta_r] \tag{5.9}$$

Due to the mass balance at the input, the primary material mass fraction needs to satisfy $\alpha \leq 1 - \eta_r$, i. e. it depends on the recyclability η_r as the sum of all input flows needs to equal the mass flow required for the product. In some cases, a certain primary material content α is required in the product (e. g. to satisfy impurity thresholds). Then it can also happen that the recyclability is restricted by the requirement for primary material content α (i. e. $\eta_r \leq 1 - \alpha$). The cascading material flow $\dot{m}_s$ results from the mass balance (eq. 5.4): $\dot{m}_s = \dot{m}_{\text{product}}(1 - \alpha - \eta_r)$.

However, often primary material content is known for the inflow of material to the product system (i. e. $\dot{m}_{\text{prim}} + \dot{m}_s$), before the recyclable material flow $\dot{m}_r$ is added (see figure 5.2). It is therefore useful to define a modified primary material content α', which is the relation of primary material mass flow $\dot{m}_{\text{prim}}$ to the combined mass flow of primary and secondary (i. e. cascaded from higher quality) material ($\dot{m}_{\text{prim}} + \dot{m}_s$).

$$\alpha' = \frac{\dot{m}_{\text{prim}}}{\dot{m}_{\text{prim}} + \dot{m}_s} = \frac{1}{1 + \frac{\dot{m}_s}{\dot{m}_{\text{prim}}}} \in [0, 1] \tag{5.10}$$

$$\alpha = \alpha'(1 - \eta_r) \tag{5.11}$$

The modified primary material content is as a parameter independent from the recyclability. Furthermore, it corresponds to the primary and secondary[4] material content of material supplied from global markets to the product system. Global data on secondary material content (e. g. [162, 459, 460]) can therefore be used as a first estimate to determine α'.

5.2.4 *Design evaluation and guidance*

Using the design parameters introduced in section 5.2.3 and the mass balance (eq. 5.4), we can rewrite equation 5.3 to:

$$\tau = \frac{1}{2} \frac{m_{\text{product}}}{ERB} \frac{1}{t_L} (1 + \gamma_{\text{m}}) (1 + \alpha - \eta_r - \eta_c) \tag{5.12}$$

$$= \frac{1}{2} \frac{m_{\text{product}}}{ERB} \frac{1}{t_L} (1 + \gamma_{\text{m}}) \left(1 + \alpha'(1 - \eta_r) - \eta_r - \eta_c\right) \tag{5.13}$$

Equation 5.13 links for each material the parameters specific to the design directly to the resource pressure τ. It can be therefore used during the design process to identify the most effective strategy to reduce the pressure on the sustainably available primary materials.

Most products consist of more than one material. Therefore, the resource pressure needs to be calculated for each material used in the product separately and aggregated to an overall value for the design. The resource pressure can be also calculated for consumables during the service life (e. g. fuels, lubricants, cleaning detergents, water) and energy [226]. To arrive at an overall value for a design d, the cumulative resource pressure $\tau_{cum,d}$ is calculated as the sum over all resources j required.

$$\tau_{cum,d} = \sum_j \tau_{j,d} \tag{5.14}$$

A quantitative indicator (eq. 5.13) can only become useful, once the required data is available. During the fuzzy front end of innovation [461],

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[4] Secondary material content is often referred to as recycled content, however, in the terminology used in this paper, it is cascaded material from higher quality.

which is the early phase of product design when everything is still fuzzy, this required data is not available yet. As many important and far reaching decisions are taken already in this step, qualitative guidelines can be a useful tool to support these decisions.

Hence, to extent the applicability of our developed design method to earlier design phases, we derive general design guidelines in figure 5.3 from the quantitative resource pressure indicator (eq. 5.13). These general rules of thumb can be considered already at early design stages when conceptualizing alternative designs. Please note, the guidelines are not meant to be exhaustive, but rather specific to the scope of the method developed here (i. e. the reduction of the pressure on sustainably available resources).

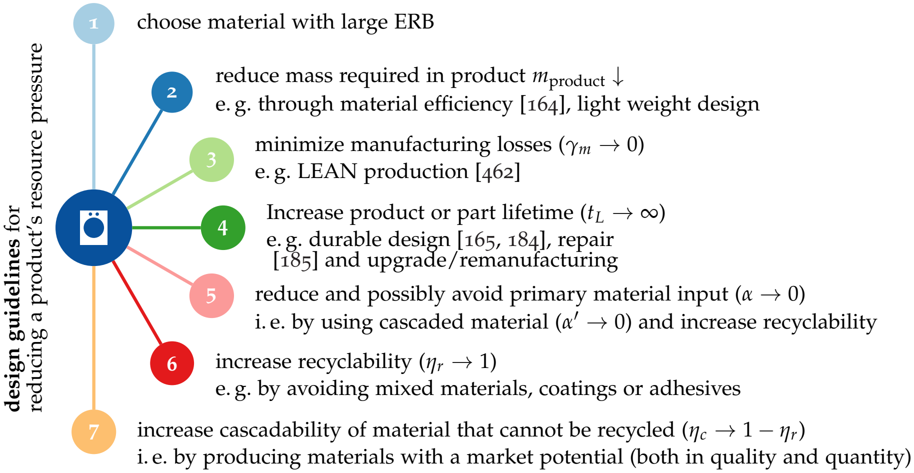

FIGURE 5.3: Design guidelines to reduce the resource pressure of a product

5.3 CASE STUDY AND RESULTS

Together with V-Zug[5], a Swiss appliance manufacturer, we tested the above presented design method on a heat exchanger for a tumble dryer as a first case study. Highly efficient tumble dryers for households require a

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[5] www.vzug.com

heat pump, which greatly reduces the electricity demand. The heat pump system consists of two heat exchangers (evaporator and condenser), a compressor and a throttle valve. The heat exchanger was selected because (i) the designers want to evaluate which material alternative (aluminium or copper) was preferable from an environmental point of view and (ii) changes in the design of the heat exchanger have a negligible effect on the performance of the device in the use phase. This is because every design variant needs to deliver the same thermal performance (i. e. transferred heat flux) and the pressure loss in the tube can be held constant by adjusting the diameter in relation to the length. Consequently, the investigated design variants can be evaluated independent of the rest of the device. The details of the studied heat exchangers are described in the SI. The ERP for Cu and Al are calculated with process data from *ecoinvent* v.3.5 [401] and a probability of violation of $P_v = 0.01$ to $ERP_{\mathrm{Cu}} = 5.68 \times 10^{10}\,\mathrm{kg/a}$ (biodiversity boundary is limiting) and $ERP_{\mathrm{Al}} = 4.36 \times 10^{10}\,\mathrm{kg/a}$ (CO_2 boundary is limiting) [217].

5.3.1 *Description of design variants*

The initial design is a heat exchanger with tubes and fins from aluminium (Al/Al). It is cheap to manufacture because the fins are stacked on the continuous tube, requiring an elongated hole and leading to manufacturing losses of $\gamma_{m,Al/Al} = 0.11$, which are collected and can be recycled without losing quality. The elongated hole results in a small contact surface between tubes and fins, leading to a poor heat transfer and a bulky design ($m_{\mathrm{product,Al/Al}} = 1.04\,\mathrm{kg}$, see figure 5.4).

Virgin aluminium is necessary, as the required alloys (1XXX) are very pure ($\alpha' = 1$) [117]. At the EoL, the devices are currently treated in the Swiss e-waste management system (the devices are sold on the Swiss market exclusively). In this system, the devices are shredded, sorted and further processed. Through the shredding, the Al stream is heavily contaminated with other elements (e. g. Fe, Cu), therefore we do not know how much of this Al can be recycled at the same quality ($\eta_{r,Al} = 0$). Consequently, the Al fraction is cascaded to cast alloys. And as contaminant concentrations are generally smaller than what is tolerated in various Al cast alloys (e. g. AlSi12Cu1(Fe)), we consider it marketable as a whole. In the cascading processes there are losses of about 20 % [145], leading to an overall cascadability of $\eta_{c,Al} = 0.72$. The manufacturing losses are directed to closed loop recycling with a yield of approximately 90 % [145], leading to an overall recyclability of $\eta_{r,Al} = 0.09$.

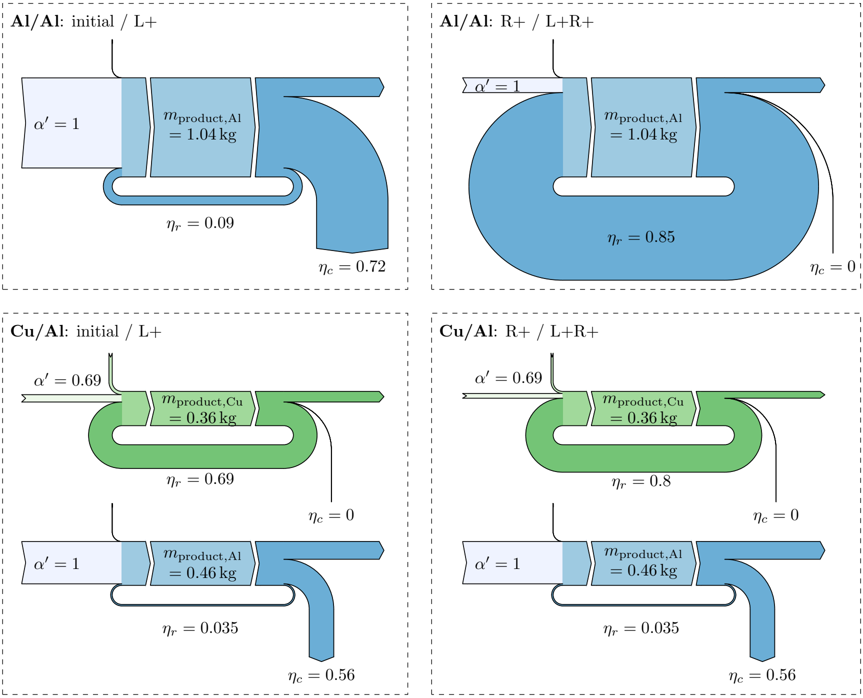

FIGURE 5.4: Flow diagrams for the four different designs: Al/Al in current waste management system in CH (top left, initial), Al/Al with dismantling and separate recovery (top right, R+), Cu/Al initial (bottom left) and Cu/Al R+ (bottom right). Each of the four design options are evaluated with basic lifetime (15 a) and double lifetime (L+), simply scaling all flows with the factor 1/2. The values for the parameters necessary in equation 5.13 can be found in the supplementary material and are used in the case study. Arrow widths are to scale relative to each other and the label to each flow can be found in figure 5.2.

To improve the technical performance, a design with copper tubes and aluminium fins (Cu/Al) is considered. Fins are stacked on hair-pin shaped tubes, which are connected with U-bends. This design increases the contact between fins and tubes and therefore the thermal performance. Simultaneously, the manufacturing losses for Al are reduced ($\gamma_{m,Al,Cu/Al} = 0.04$) as well as the overall size ($m_{\text{product,Cu/Al}} = 0.84\,\text{kg}$). The required copper can be sourced from the world copper market, containing secondary material ($\alpha'_{Cu} = 0.69$) [463]. Shredding of the mixed material heat exchanger will lead to a low separation due to the ductile materials. Both the Cu and Al fraction will contain a significant amounts of the respective other material, which is lost for its recovery. We estimate that 30 % of each material is lost to the other fraction. In the Cu processing, the Al content is removed [159] and the Cu content recovered with high purity and a yield of approximately 98 % [464]. Therefore, the recyclability of Cu is $\eta_{r,Cu} = 0.69$ and and no material is left for cascading ($\eta_{c,Cu} = 0$). In the Al processing, the Cu is not removed, leading to very high concentrations of Cu in the resulting Al-alloy. The alloy has to be diluted with primary material to meet a cast alloy's specification, but it is still considered marketable for such a dilution process. We therefore estimate for Al the recyclability (resulting of manufacturing losses) to $\eta_{r,Al} = 0.035$ and cascadability (resulting from EoL output) to $\eta_{c,Al} = 0.56$.

Both designs are integral parts of the device and thus have the same lifetime ($t_L = 15\,\mathrm{a}$). However, there is no technical reason inhibiting the reuse of the heat exchanger in a new device, i. e. giving it a second life. This scenario (L+) requires the take-back of the old devices, dismantling, cleaning and leak-testing of the heat exchanger as well as the standardization of this component for other designs. The design of the heat exchanger itself does not have to be altered for this scenario.

To increase the recoverability of the metals contained in the heat exchanger, dismantling and separate recovery is investigated in the scenario R+. For the Al/Al design, the dismantled part can be smelted without further processing (and thus without contamination), leading to a very high recyclability $\eta_{r,Al/Al,R+} = 0.85$, leaving no material to be cascaded ($\eta_{c,Al/Al,R+} = 0$). For the Cu/Al design, a manual separation of fins and tubes is too labour-intensive to be economically viable and therefore a shredding process is still necessary to separate the two materials. This leads to still low recovery of Al ($\eta_{r,Al,R+} = 0.035$, $\eta_{c,Al,R+} = 0.56$) but increased recovery for Cu ($\eta_{r,Cu,R+} = 0.8$, $\eta_{c,Cu,R+} = 0$).

In total we examined eight scenarios formed out of the combination of the design variants mentioned before (see figure 5.4). The resource pressures on auxiliary materials and energy are neglected in this case study for simplicity and because they are expected to give minor contributions.

5.3.2 *Results*

The results for the eight scenarios (see figure 5.5) show that for the comparison of the two material alternatives in the initial scenario, the Cu/Al

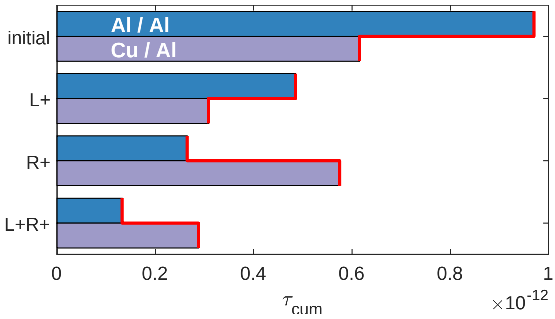

FIGURE 5.5: Comparison of the resource pressure τ_{cum} for the eight design variants. Al/Al L+R+ variant shows the lowest resource pressure.

variant has a lower resource pressure and is thus preferable. The same holds true for simply doubling the lifetime (L+), as this has a direct effect on the resource pressure for both variants. The picture changes when considering dismantling and separate recovery for the heat exchanger. In this scenario (R+), the Al/Al variant shows significantly larger reduction in resource pressure (factor 3.7 and 7.3 for R+ and R+L+ respectively) than the Cu/Al variant (factor 1.7 and 3.4 for R+ and R+L+ respectively) due to the increased recyclability.

As a design conclusion, the Al/Al variant is preferable in combination with a modular design to allow both reuse in a new product and easy dismantling for separate recovery. If dismantling and separate recovery is not possible, the Cu/Al variant is preferable. However, increasing the lifetime – which requires a modular design – leads to a larger reduction in resource pressure than changing materials.

5.4 DISCUSSION

In contrast to most existing design methods, the proposed method is both qualitative (guidelines, section 5.2.4) and quantitative (resource pressure indicator, eq. 5.12–5.14). The guidelines are derived specific for the objective of reducing the resource pressure and not meant to be exhaustive. Also, increasing the lifetime of a product is not in all cases preferable from an environmental point of view, as it may be beneficial to replace early-stage technology prematurely with more efficient alternatives [308]. In these cases, the environmental impacts caused in the use phase need to be considered, leading to an optimal environmental lifetime. For mature technology and products that do not cause impacts during their service life, however, increasing the lifetime is an effective strategy to reduce environmental impacts. Additionally, lightweight design may need to be balanced with increasing lifetime, as reducing the weight may reduce the lifetime and vice versa.

For the calculation of the quantitative indicator, only six parameters are necessary, which can be estimated throughout the design process. The calculations are simple (e. g. can be done in a spreadsheet) and can be performed timely during the design process, providing results that give clear design guidance in regard to resource utilization. The influence of each parameter on the resource pressure can be quickly evaluated, allowing to focus the design efforts on the most effective circular strategies.

The presented method is based on a combination of the effect of the in- and output flows on the resource pressure. This underlines the importance of design for defining the quality and quantity of both material in- and outputs [159]. Thus far, the bottle-neck to apply the method is the estimation of recyclability and cascadability. In this paper, we have estimated these two parameters based on experience with the Swiss e-waste recycling industry and literature data. Another approach is to define these parameters through detailed process simulations [457]. However, both require specific knowledge and thus cannot be applied by a design team easily. Therefore, there is a need to develop an easy-to-apply method correlating design parameters with the recyclability as well as the cascadability in the future [456]. Further, the method does not yet distinguish different quality levels of cascaded material [56, 153], which is a potential area for further research. It is possible in principle to also consider upwards cascading in the method, which requires to define objective criteria for when it can be considered an improvement of technical properties.

When comparing the resource pressure to results from a simplified LCA (see section 5.7), we find that reducing τ is indicative for reducing impacts across different impact categories (figure 5.6). The relative ranking of the design variants with both the resource pressure and 15 different impact categories from the environmental footprint (EF) method [465], is rather similar, though not in all impact categories. On the one hand, LCA can provide a much more in-depth analysis than the resource pressure method. On the other hand, the overall LCA results do not necessarily give a clear guidance, which design is superior to the other in environmental terms. For example, in the initial scenario, the Al/Al is superior in the impact categories fresh-

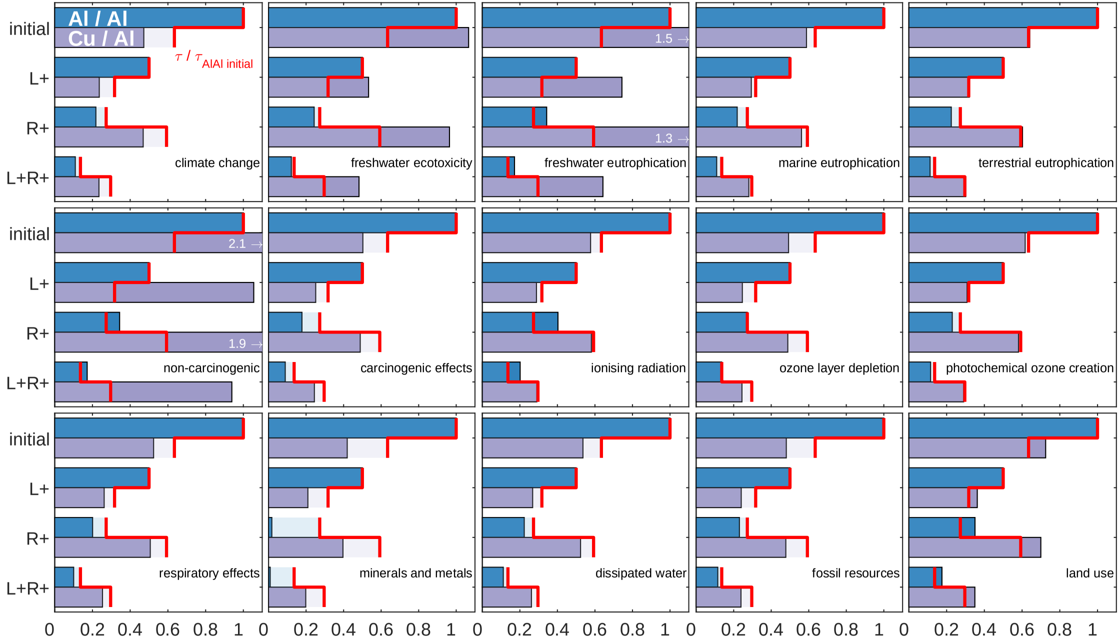

FIGURE 5.6: Results of the LCA study for 15 EF 3.0 midpoint [465] impact categories, each of them relative to the score of the Al/Al initial design variant, in comparison to $\frac{\tau}{\tau_{AlAl,initial}}$ (light bars with red lines, see figure 5.5). The impact categories displayed are: climate change: total (kg CO_2-eq. 100 a); ecosystem quality: freshwater ecotoxicity (CTUe), freshwater eutrophication (kg P-eq.), marine eutrophication (kg N-eq.), terreestrial eutrophication (mol N-eq.); human health: non-carcinogenic effects (CTUh), carcinogenic effects (CTUh), ionizing radiation (kBq rel. to ^{235}U), ozone layer depletion (kg CFC-11-eq.), photochemical ozone formation (kg NMVOC-eq.), respiratory health effects from particulate matter (decease incidences); resource use: minerals and metals (kg Sb-eq.), dissipated water (kg), fossil resource depletion (MJ), land use (soil quality index).

water ecotoxicity, freshwater eutrophication, and non-carcinogenic human health effects while it is e. g. inferior in the categories for climate change, carcinogenic effects and ozone layer depletion. LCA shows the trade offs, however does not provide a clear guidance for the designer when considering different impact categories, which would require weighting between impact categories. In contrast, weighting of impacts is not necessary when calculating ERB, even though multiple impact categories are considered, as the most critical boundary is limiting the resource budgets (see [217, 449]). In this way, multiple impact categories are considered and still a clear guidance is possible.

All parameters (except ERB) necessary for the calculation of the resource pressure are also used as an input for a LCA calculation, however the latter additionally requires process data. The resource pressure can thus serve as an indicative method during the design process, which then should be validated with a LCA study of the (final) engineered product. The presented case study shows that the method is both easily applicable during the design process as well as effective in guiding towards a design that results in reduced environmental impacts across many impact categories.

The method presented in this paper focuses on the utilization of ERB and thus includes environmental impacts from primary material production as well as EoL treatment. Impacts during other life cycle phases, which result from the use of resources (e. g. energy), can be considered, however, makes the analysis more complex. As impacts from recycling correlate non-linearly with the recyclability [466–468], it will be useful to develop an approach to account for these impacts directly in the method. A possible way forward is to reduce the ERB proportional to the impacts resulting from increased recycling, i. e. the larger recyclability, the smaller the primary material budgets. Exergy could serve as a proxy for this scaling [115], as it correlates to the physical effort necessary for the reconditioning.

5.5 CONCLUSION AND OUTLOOK

Design is pivotal to reduce the resource pressure at the level of products and instrumental to reduce the consumptive use of resources on a global level. The here described method allows to both analyse societal activities and guide product design to a lower resource intensity, contributing to reach the global vision of a sustainable circular economy [56]. Various, currently ongoing trials for the application of the method in Swiss companies indicate that it meets the desired objective of (i) providing guidance for product design from the very beginning through qualitative guidelines, (ii) indicating clear direction for design decisions with a single score indicator and (iii) being straightforward to apply with little training by the designers themselves. We can conclude that the resource pressure method is already useful to guide design decisions towards more sustainable products, i. e. for a relative assessment using the ecological resource potentials (ERP). It thereby does not replace well established tools like LCA, but rather complements them in the sense that it offers a quantitative assessment throughout the design phase. The resource pressure is designed as a tool preceding a LCA study, providing clear guidance in regard to the effectiveness of design choices on the resource pressure of the product. It further prepares for the detailed LCA assessment, as parameters necessary in the resource pressure are also required in the LCA.

The method is thereby not limited to a relative assessment, but can also be turned into an absolute sustainability tool, when ERA is used as a benchmark. ERA provides an absolute sustainability benchmark for primary material use globally [449], making the resource pressure indicator τ essentially absolute as well. The global economy can be considered sustainable in regard to the use of a resource, if the cumulative pressure on it is smaller or equal to one, i. e. if its global use is equal or smaller than ERA. For a single product, company or even country, the absolute sustainability is however not straight forward to assess. To do so, there is a need to develop an approach to connect the contribution for reducing primary resource use by a single product/company/country with the global goal for reaching sustainability, i. e. connecting the bottom-up and top-down perspectives. Resource intensity reduction targets can be defined for the product under investigation (e. g. determined by technical feasibility [303] or necessity for a decent life [441]) and/or by allocating ERA to the area of investigation (e. g. an economic sector, company or country).

The resource pressure method is in fact not limited to the objective of reducing the pressure on primary resources and final sinks (i. e. increasing the utility of a material to society). For example, carbon capture and storage has the objective to remove CO_2 from the atmosphere and store it in final sinks. In this case, the resource pressure on CO_2 should be increased. Another objective could be to remove harmful or toxic substances from anthropogenic material cycles and therefore require to increase their final losses and at the same time decrease primary input.

Furthermore, a successful implementation of improved designs requires to align business models with the design [189], making it necessary to treat design as an integral part of the business model innovation process [57]. Design of both, the business model and the product, can have a significant influence on the user behaviour and consequently the overall environmental performance. For example, resource wasteful behaviour can be made more effortful for the user by a design encouraging an efficient use [469]. Also these aspects have to be addressed to create products for a sustainable future.

Supplementary Material

This supplementary material contains details about the heat exchanger designs of the case study, a description of the simplified LCA, a list of abbreviations and a glossary. Details on the ecological resource availability (ERA) method can be found in [449] and its adaption to calculate ecological resource potentials (ERP) in the companion MethodX-article [217] and the source code with the link `https://doi.org/10.5281/zenodo.3827142`.

5.6 heat exchanger

The heat exchanger is used for a heat pump system in a tumble dryer. The heat pump system consists of two heat exchangers (evaporator and condenser), a compressor and a throttle valve. The part investigated in this paper is used as the evaporator. It consists of tubes, where the refrigerant liquid flows through, and fins, which are attached to the tubes and increase the surface that is in contact with the airflow on the outside. The heat from the airflow over the fins is transported to the refrigerant, which is evaporated inside the tubes. The heat transport from fins to tubes is determined by the contact between the two parts. The Al/Al (see figure 5.7) variant has a continuously bent tube, which requires an elongated hole in the fins to fit the fins and tube together. In contrast, the Cu/Al (see figure 5.7) variant has U-shaped tubes, that are soldered together after the fins had been stacked on the tubes. Therefore, the fins have a good contact to the tubes, which decreases the thermal resistance.

Figure 5.7: Pictures of the Cu/Al (left) and Al/Al heat exchanger (right).

The thermal performance of the heat exchanger does not reduce significantly with increased lifetime. It is to expect, that the channels between the fins can be blocked by dust from the air stream, which will require cleaning of the part, in case it is reused (L+ scenario). The part can be easily removed and fitted in a new device, if the dimensions and the requirement for the thermal performance does not change for subsequent designs. This requires a standardization and long term planning for future design concepts; however does not entail any changes in the design of the heat exchanger.

If the part is shredded together with the rest of the tumble dryer, it will be heavily contaminated with other materials. This contamination keeps the recyclability very low, as a high purity is required for the sheet rolling alloy. In contrast, designing the tumble dryer so that the heat exchanger can be easily removed enables both the separation before EoL treatment (i. e. before shredding the device), leading to an improved recyclability, and the reuse of the heat exchanger in another, new or refurbished, device.

Input data for the case study and the results for τ are provided in table 5.1 and 5.2. Please note, the recyclability and cascadability are estimated based on experience with the Swiss e-waste recycling system and described in the main text.

Lifetime			L+		L+
Recovery				R+	R+
Variable	Unit	Al / Al			
$m_{product}$	kg	1.04			
γ_m	-	0.11			
α'	-	1			
t_L	a	15	30	15	30
η_r	-	0.09	0.09	0.85	0.85
η_c	-	0.72	0.72	0	0
ERP	Tg/a	43.6			
$\tau = \tau_{max} = \tau_{cum}$	10^{-13}	10.1	5.1	2.7	1.32
$\frac{\tau_{cum,Al/Al}}{\tau_{cum}}$	-	1	2	3.83	7.67

TABLE 5.1: Al/Al heat exchanger input parameters and results for resource pressure

Lifetime				L+				L+	
Recovery						R+		R+	
Variable	Unit	Cu	Al	Cu	Al	Cu	Al	Cu	Al
$m_{product}$	kg	0.36	0.46						
γ_m	-	0	0.04						
α'	-	0.69	1						
t_L	a	15		30		15		30	
η_r	-	0.69	0.04	0.69	0.04	0.8	0.04	0.8	0.04
η_c	-	0	0.56	0	0.56	0	0.56	0	0.56
ERP	Tg/a	56.8	43.6						
τ	10^{-13}	1.17	5.11	0.58	2.56	0.71	5.11	0.36	2.56
τ_{max}	10^{-13}	5.11		2.56		5.11		2.56	
τ_{cum}	10^{-13}	6.28		3.14		5.82		2.91	
$\frac{\tau_{cum,Al/Al}}{\tau_{cum}}$	-	1.61		3.23		1.74		3.48	

Table 5.2: Cu/Al heat exchanger input parameters and results for resource pressure

5.7 LIFE CYCLE ASSESSMENT

This chapter shortly describes the structure and content of the simplified LCA mentioned in the discussion of the main paper. LCA is a useful tool to assess the environmental performance along a product's life from raw material extraction through material processing, manufacture, distribution, use, maintenance, and disposal [191, 192, 260]. In this study, a simplified LCA is done for both heat exchangers with the goal to compare the results of the LCA to the outcomes of the newly developed resource pressure method. It is a simplified LCA, as no proper inventory processes are modeled, but all the elements are modelled with readily available standard datasets from the LCA database *ecoinvent* (v3.6). The scope of the LCA includes the extraction and processing of the raw materials (Al and Cu), the actual manufacturing of the heat exchangers by applying the sheet rolling dataset and the EoL treatment in form of recycling, cascading and incineration. For Cu, the world market for copper that includes secondary material is taken as an input to reflect the fact, that cascaded material is contained in the input flow. For Al, global primary Al processes are taken as a raw material input, as the use of cascaded material for this application is not possible. The manufacturing process approximated with the rolling of sheets, as this step has a significant energy demand [470], whereas the other manufacturing steps have minor contributions (stamping, tube bending, assembly, soldering). The use-phase is excluded from this study as those impacts do not change with the material choice, as the heat exchangers have the same technical specifications (heat transfered and pressure loss). The τ-method considers three EoL options (recycling, cascading, and final losses) that are also included in the LCA. Recycling is modeled with a recycling process that has the same output material as the material required as an input to the product. Cascading is modeled for Al with a recycling process which produces cast alloy instead of wrought alloy. Final losses are modeled as incinceration process in Switzerland. The detailed processes selected for both products are given in table 5.3.

For impact assessment, we have chosen the EF 3.0 (midpoint) method, because it is used for the product environmental footprint (PEF) of the European Commission [465]. It consist of 19 indicators, where 4 are sub-indicators of climate change. Therefore we consider 15 indicators, with climate change aggregated to the total. The impact categories span four dimensions [465]:

1. Climate change: measured with the global warming potential for a time horizon of 100 a.
2. Ecosystem quality:
    - Freshwater ecotoxicity: comparative toxic unit for ecosystems (CTUe), from USEtox 2.1
    - Freshwater eutrophication: P reaching freshwater end-compartment, from ReCiPe
    - Marine eutrophication: N reaching marine end-compartment, from ReCiPe
    - Terrestrial eutrophication: accumulated exceedance (AE) of N-eq., from accumulated exceedane
3. human health:
    - non-carcinogenic effects: comparative toxic units for humans (CTUh), from USEtox 2.1
    - carcinogenic effects: CTUh, from USEtox 2.1
    - ionizing radiation: Human exposure efficiency relative to ^{235}U, from human health effect model

life cycle stage	**Al/ Al**	**Cu/ Al**	**location**
extraction/ production	aluminum ingot, primary, wrought alloy market	market for cooper	global (GLO)
Manufacturing	sheet rolling, aluminum	sheet rolling copper	Region Europe (RER)
EoL: recycling	treatment of aluminum scrap, at refiner (wrought alloy)	treatment of copper scrap by electrolytic refining	RER
EoL: cascading	treatment of aluminum scrap, at remelter (cast alloy)	-	
EoL: incineration	treatment of scrap aluminum, municipal incineration with fly ash extraction	treatment of scrap copper, municipal incineration with fly ash extraction	Switzerland (CH)

TABLE 5.3: Inventory processes for both heat exchangers.

  - ozone layer depletion: ozone depletion potential (ODP), from WMO
  - photochemical ozone formation: tropospheric ozone concentration increase, from ReCiPe
  - respiratory effects: human health effects associated with exposure to particulate matter $PM_{2.5}$, from UNEP

4. resource use:
  - minerals and metals: abiotic resource depletion (ADP), from CML 2002
  - dissipated water: User deprivation potential, from AWARE
  - fossil resources: ADP of fossil fuels, from CML 2002
  - land use: soil quality index, from JRC

All other inputs for the LCA are equal to the tau-method such as mass in product, manufacturing losses, etc.

5.8 ECOLOGICAL RESOURCE POTENTIAL METHOD

The following text in this section is reproduced with permission from the co-submitted article to the journal "Methods X". Published version under `www.doi.org/10.1016/j.mex.2020.101151`

Title	Ecological resource potential
Authors	Harald Desing*[a], Gregor Braun[a], Roland Hischier[a]
Affiliations	[a] Empa - Swiss Federal Laboratories for Material Science and Technology, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland
Keywords	Earth system boundaries Resource impacts Precautionary principle
Direct or co-submission	Co-submission to article "Resource pressure – a circular design method"
Subject area	Environmental science
More specific subject area	Environmental impacts associated with extraction, processing and end-of-life treatment of primary resources
Method name	Ecological resource potential
Name and reference of original method	Ecological resource availability: Desing, H., Braun, G., Hischier, R., submitted. Ecological Resource Availability – A Method to estimate resource budgets for a sustainable economy. Global Sustainability.
Resource availability	ERA method: `https://doi.org/10.5281/zenodo.3629366` ERP method: `https://doi.org/10.5281/zenodo.3827142`

ABSTRACT

The ecological resource potential (ERP) method allows to calculate the amount of one material that can potentially be produced within Earth system boundaries, if no other anthropogenic activity would take place. It indicates the uppermost potential of one resource extracted, processed and disposed after use with a specific set of technologies and a defined probability of violating Earth system boundaries. This method is an adaption of the ecological resource availability (ERA) method, which calculates the amount of a resource that can be produced within an allocated share of the global boundaries, i. e. when considering all other anthropogenic activities. While more realistic, its allocation can be done in multiple ways and based on a variety of different objectives, which requires scenario modelling. The ERP method, in contrary, only requires information on environmental impacts from resource extraction, processing, and final disposal. The customization of the original ERA method comprises:

- omitting all steps for allocating global boundaries to single resources or resource segments
- changing the calculation procedure so that ERP is calculated for each resource separately.

METHOD DETAILS

The ecological resource budgets (ERB) necessary for the resource pressure design method [440] are defined either based on the ecological resource availability (ERA) or ecological resource potentials (ERP). The ERP method is a simplification of the underlying ERA method [449], therefore we provide a brief introduction and explanation of the method. For a detailed explanation, please see [449]. After the description of the ERA method, we provide details for its adaption to calculate ERP.

ECOLOGICAL RESOURCE AVAILABILITY METHOD The extraction, processing and disposal of primary resources contributes significantly to the global environmental pressure on natural ecosystem. The ERA method aims to answer the question, how much primary resources can be extracted, processed and disposed, without transgressing critical Earth system boundaries (ESB). In other words, what is a sustainable level of resource consumption by our society?

ESB represent the carrying capacity of planet Earth, i. e. the safe operating space for society [77]. Crossing these boundaries, leads to a shift of the Earth system state to a new and likely less hospitable state [74]. One proposal to quantify ESB in literature is the planetary boundaries framework [77, 79]. For the purpose of the ERA method, this framework is seen as one specific set of indicators, that can be extended or replaced by other boundaries. Once having described the ESB, an allocation of the boundaries to the various resource segments of the economy is necessary. This allocation step, however, is a normative choice. In other words, how much of the global safe operating space can be occupied by the extraction, processing and final disposal of a group of materials (e. g. metals)? Different allocation principles are possible, e. g. based on economic value [107] or technical feasibility [303]. In the ERA paper [449], we exemplify the allocation with a grandfathering approach, which allocates global boundaries to resource segments according to today's impact share and defining the share of production for each resource within a segment according to today's resource use pattern.

The boundaries are allocated like this to a specific resource segment and can then be used to calculate the amount of the various materials that can be produced within this segment, while staying below the boundaries. As the boundaries, their allocation and the impacts on these boundaries are uncertain, the ERA method builds on a precautionary and statistical approach. None of the boundaries is allowed to be crossed with more than a defined probability of violation (see figure 5.8). I. e. if some possible impacts are larger than possible boundary values, this boundary is violated. The probability of violation is a parameter to be chosen for the ERA method. It reflects the level of risk society is willing to accept in regard to ESB. For exemplification of the ERA method, we have chosen $P_v = 0.01$ [449].

Note, all inflows into the socio-economic system will leave the system over time again as final wastes or emissions. Material cycling thereby increases the utility of material to society, however, as cycles cannot be fully closed, primary input and final disposal remain necessary parts of a CE [5, 56, 121].

In Desing et al. [449] the ERA method is tested for major metals used today with a grandfathering approach. The ERA budgets are listed in table 4.2. They are compared to the production volume today. The share of production indicates the relative production share of one single material to a combination of similar materials. For example, steel's share of production in the metal sector is about 90 %. The resource budget for the whole resource segment *metals* is 40 times smaller than the production volume in 2016.

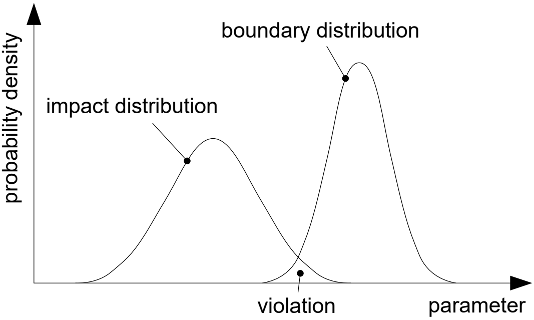

Figure 5.8: Schematic representation of the concept of ERA and ERP [449]. The resource budget for a single resource (e. g. steel) or a resource segment results from the overlap of the probability distribution of the environmental impacts with the distribution of the respective boundary. For ERA the boundary is an allocated boundary to the resource segment, for ERP it is the global boundary.

Therefore, rescaling the current socio-economic system to fit within ESB with a confidence of at least 99 % requires the reduction of use of metals by 40 times. As this is not practically achievable, especially because rescaling other parts of the economy by the same factor (e. g. food) will result in a system that cannot provide for basic needs, it is necessary to optimize and refine the ERA budgets through scenarios on different allocation methods, new production technologies and optimizing the share of production.

ECOLOGICAL RESOURCE POTENTIALS The ERP method is based on this ERA method, however, does not require any allocation. ERP describes the amount of a material that can be extracted, produced and safely disposed within ESB, assuming that no other anthropogenic activity would exert pressure on ESB. In this way, ERP gives the maximum theoretical production potential that is possible within ESB when produced with a specified (e. g. current) technology. A material that has a large ERP has automatically a low unit impact and is therefore preferable to use in the economy.

For the calculation of ERP, the following data is necessary:

- Definition of ESB in a unit that can be measured with LCA. Any number of boundaries in this format is acceptable to the method. The boundaries need to be specified with an uncertainty range, i. e. an interval or uncertainty distribution of likely boundary values. The following boundaries are considered in the ERA method [449] and therefore also used to calculate ERP:

1. Climate change: direct fossil CO_2 emissions to air [15, 79]
2. Climate change: global warming potential for a time horizon of 100 a [79, 104, 350]
3. Biosphere integrity: potentially disappeared species (reversible) [79, 445, 446]
4. Stratospheric ozone depletion: emission of O_3 depleting substances (ODS) [79, 104, 105]
5. Biogeochemical flows: P to oceans [79, 104]
6. Biogeochemical flows: P to soil [79]
7. Biogeochemical flows: industrial and intentional biological fixation of N [79, 104]
8. Land system change: appropriable land area [33, 79, 226]
9. Land system change: appropriable land area for cropland [77]
10. Freshwater use: blue water consumption [79, 104]
11. Energy: appropriable technical potential for renewable energy resources in electricity equivalents [226]

Any other quantitative boundary can be used in the method given that it is defined in measurable LCIA units.

- Unit impacts (UI) for the production of one unit of a material (usually one kilogram). The impacts have to be reported in the same unit as the corresponding boundary and include an uncertainty distribution of the impact. UI comprise the cumulated impacts for the primary production (extraction and processing) of the material as well as for the final treatment of the same amount of material (can be incineration, landfill, wastewater treatment and/or dispersion). The uncertainty range for each cumulative impact needs to be provided as well. The following LCIA and LCI results were used to compile the uncertainty range:

    1. Inventory result for fossil CO_2 emissions to air
    2. GWP indicators from a variety of impact assessment methods: IPCC 2013, 2007, ILCD 2.0 2018, ReCiPe v.1.13 2016 CML 2001
    3. ReCiPe v1.13 2016: endpoint ecosystem quality; uncertainty from egalitarian, hierarchic and individualist scenarios

4. Emissions of ODS expressed in CFC-11-eq; from CML 2001, ILCD 2.0 2018 and ReCiPe v1.13 2016
5. Inventory results for P and PO_4 emissions to oceans, air, soil and freshwater. Fate factors from compartments other than ocean to ocean are taken from [104].
6. Inventory results for P and PO_4 emissions to soil
7. Inventory results for reactive N emissions
8. Inventory results for land occupation
9. Inventory results for cropland occupation
10. Inventory results for water emissions to air (evaporative water consumption) [104]
11. Cumulative energy demand in electricity equivalents, i. e. inventory results for energy carrier flows converted to electric energy [226, 402, 449]

The uncertainty of UI are build from the minimum, maximum and average (if available) of the LCIA methods considered. Additionally, the basic uncertainty of the LCI result is considered for the underlying inventory flows. The error propagation is calculated in the Monte Carlo simulation.

- Define the probability of violation P_v, i. e. the probability that impacts are higher than boundary values. In line with the ERA method we choose $P_v = 0.01$.

- Number of simulation runs n_{runs} for the Monte Carlo simulation. The larger the number, the more accurate the results and the longer the simulation time. We suggest to use at least $n_{\text{runs}} \leq 10^5$, which leads to a simulation-to-simulation variability of the results of < 0.008 and a simulation time of $< 30\,\text{s}$.

For the calculation of ERP, random values are picked n_{runs}-times for both the UI and the boundaries from among the specified uncertainty range. The initial guess for ERP (i. e. ERP_1) is calculated as the fraction of the $P_v/2$-quantile of the ESB distribution and the $(1 - P_v/2)$-quantile of the UI distribution. The different boundary categories k are thereby elements of the column vector, resulting in a column vector for ERP, i. e. each element is the ERP possible within the respective boundary alone. The smallest value is the ERP for the material and the respective boundary limiting.

$$\begin{aligned} ERP_{k,1} &= \frac{ESB_k|_{P_v/2}}{UI_k|_{1-P_v/2}} \quad (5.15) \\ ERP_1 &= \min_k ERP_{k,1} \quad (5.16) \end{aligned}$$

ERP_1 is then scaled up or down until the probability of violation, resulting from the overlap of UI distribution and ESB distribution, equals the required value of P_v (see figure 4.2). This numerical approach is necessary, as the overlap between the two distributions depends on their shape, which is calculated numerically with the MC simulation. During this procedure the probability of violation needs to be checked for each boundary category k, to avoid that another boundary becomes limiting through the up or down scaling of ERP.

$$ERP_{i+1} = \begin{cases} ERP_i \cdot (1 - 5 \cdot P_v(1 + P_{v,i})) & P_{v,i} > P_v \\ ERP_i \cdot (1 + P_v - P_{v,i}) & P_{v,i} < P_v \end{cases} \quad (5.17)$$

ERP METHOD VALIDATION The ERP results for $P_v = 0.01$, calculated with process data from *ecoinvent* (v3.5) and ESB as specified in [449]. The final resource budgets of metals based on the ERP method are given in table 5.5. All ERP budgets for metals are limited by the CO_2 boundary, except Cu, which is limited by the biodiversity boundary. Please note, the ERP budget for steel is smaller than global output in 2016, meaning that current production is not possible within ESB even when no other anthropogenic activity would take place.

The results for each metal can also be displayed with the overlapping probability density functions of impacts and boundaries (see figure 5.9). One boundary category is always limiting, when the probability density functions of impacts and boundaries overlap with a probability of $P_v = 0.01$. In some cases, also a second boundary (or possibly more) overlap with a probability of $P_v < 0.01$ (see e. g. case of Gold). Generally, for most boundaries the PDFs do not overlap, i. e. $P_v = 0$.

Metal	$\dot{m}_{\text{output,2016}}$ / kg/a	**limiting boundary**	ERP / kg/a
Aluminum	4.21×10^{10}	CO_2	4.36×10^{10}
Copper	1.69×10^{10}	biodiversity	5.68×10^{10}
Steel	1.09×10^{12}	CO_2	4.99×10^{11}
Cast iron	1.54×10^{9}	CO_2	5.52×10^{11}
Zinc	8.44×10^{9}	CO_2	1.27×10^{11}
Lead	3.09×10^{9}	CO_2	1.96×10^{11}
Tin	1.81×10^{8}	CO_2	3.98×10^{10}
Nickel	1.19×10^{9}	CO_2	6.91×10^{10}
Gold	1.62×10^{6}	CO_2	5.92×10^{7}
Silver	1.31×10^{7}	CO_2	2.85×10^{9}
Platinum	9.90×10^{4}	CO_2	3.26×10^{7}
Titanium	8.37×10^{7}	CO_2	2.88×10^{10}
Chromium	1.59×10^{10}	CO_2	3.14×10^{10}
Stainless steel	2.82×10^{10}	CO_2	1.91×10^{11}

TABLE 5.5: Production output in 2016 $\dot{m}_{\text{output,2016}}$ (i. e. production volume [437] corrected with double counting [259, 438, 449]), limiting boundary and ERP for the investigated metals (in comparison to ERA, see table 4.2 on p.126).

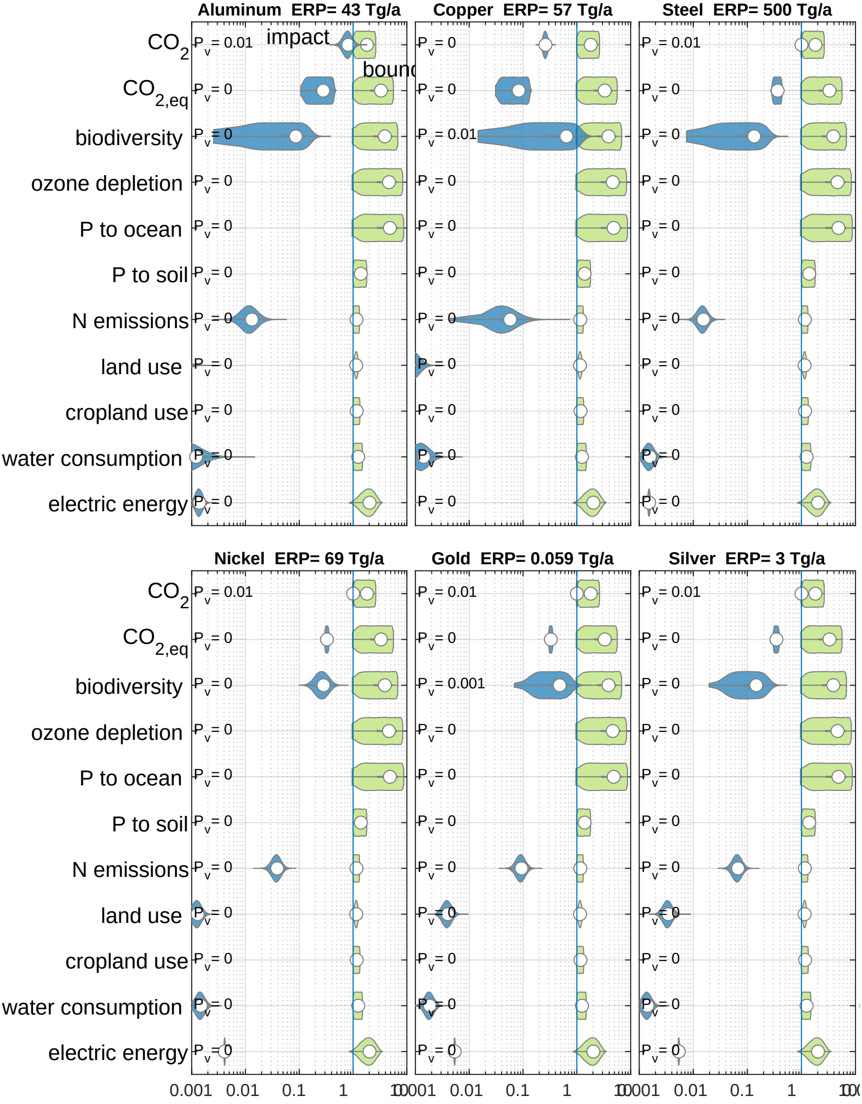

Figure 5.9: Graphical representation of probability density function (PDF) of impacts (blue) on global boundaries (green) for each boundary category and each ERP for selected metals.

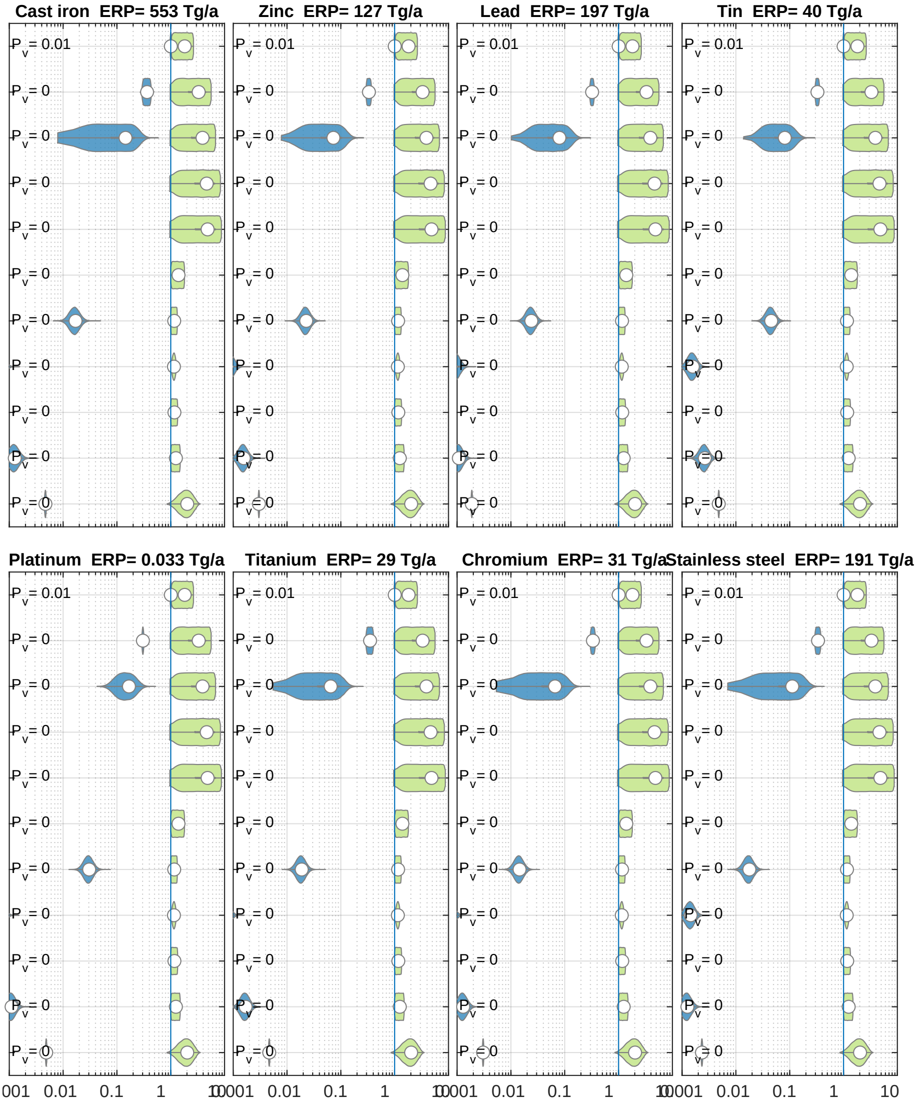

FIGURE 5.9 continued

6

DISCUSSION AND OUTLOOK

All models are wrong, but some are useful
— George E. P. Box

6.1 SYNTHESIS

This doctoral thesis builds on four publications (chapters 2-5). The first publication "A Circular Economy within the planetary boundaries: towards a resource-based, systemic approach" (chapter 2, [56]) proposes a conceptual framework to define and align the two concepts of *circular economy* and *sustainability*. In this interdisciplinary effort, we identify the conditions under which a circular economy can be considered sustainable. The Earth represents the non-negotiable frame for all human activities. Besides physical laws, human actions need to respect environmental boundary conditions (e. g. as described by the planetary boundaries framework [77, 79]) in order to ensure environmental sustainability. Society is part of the Earth system and organizes itself according to normative and negotiable principles. Even though specific rules and regulations in society depend on the region and are subject to change over time, we acknowledge the need to establish inter- and intra-generational equity (understood as equal opportunities and responsibilities across space and time). This necessitates to respect human dignity and well-being. The economy is part of society and provides the services required by society within the bio-physical frame of the Earth. This conceptualization of a sustainable economy and society is in contrast to the mainstream *triple bottom line* (planet, people and profit), which places the three dimensions on the same level, suggesting that they can be traded for each other [212, 214]. Such a trade can be, for example, observed in climate negotiations, where economic concerns still largely prevent from climate action. Our approach explicitly introduces a hierarchy (or cascade), where any sustainable economy needs to be designed as a consequence of environmental and social requirements.

One such requirement is, that resource consumption needs to be limited by the bio-physical capacity of the Earth system to absorb, regenerate and tolerate associated impacts. Therefore the intake of primary materials into the socio-economic system needs to be limited. In order to utilize these limited resources most efficiently, it is necessary to aim at keeping them useful and functional as long as possible within the socio-economic system. This is where circularity comes into play, increasing the resource utilization intensity through different strategies (such as prolonging lifetime, re-manufacturing, recycling, cascading). To conceptualise differences between these strategies, we have introduced entropy as a proxy for the effort to re-utilize materials[1]. The larger the entropy change through a re-utilization strategy, the larger the associated effort and thus environmental impacts. E. g. the breakdown of polymers to monomers and re-polymerization to new polymers is associated with a large change in entropy (first destroying order and then restoring it), whereas the re-use of a component in a new product (re-manufacturing) only destroys the order of the initial product and leaves the order of the component intact. This analysis of entropy leads to the fundamental requirements for a CE to minimize entropy production. Besides minimizing the specific entropy (i. e. per unit of material), also the absolute size needs to be minimized (i. e. material efficiency) and the speed of material circulation reduced (i. e. durability).

The idea of limited resources due to environmental consequences, which are available as an input to a sustainable CE, leads to the second (for energy) and third publication (for materials). The second paper "Powering a Sustainable and Circular Economy – An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries" (chapter 3, [226]) explores the question how much renewable energy can be appropriated globally to power a sustainable economic system. The developed method considers Earth system boundaries for the appropriation of renewable energy resources (i.e. land and water), the human demand for chemical energy (e. g. food, fodder, fiber) and state-of-the-art conversion technologies. Not considered are environmental impacts from production, installation and decommissioning of specific technologies and the distribution (and necessary infrastructure) of the harvested energy in space and time. The method is based on a precautionary approach and provides estimates for the appropriable technical potential (ATP) for renewable energy resources with a chosen confidence level. In the paper we provide initial results, reported for a confidence level of 99 %. The resulting ATP is dominated by solar energy conversion on the built environment and in deserts. All other

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[1] In parallel, a very similar idea has been proposed by Blomsma and Tennant [471], relating the resource's state to material entropy and classify CE strategies according to the change in entropy levels in the material.

resources are of minor importance globally. Therefore, there is a clear design requirement for new products, services and systems to provide the life cycle energy predominantly from solar. For example, buildings can be designed to be built and operated exclusively through solar energy harvested on its envelope. To achieve this in a cost effective manner, energy demand needs to be generally low (efficiency) and managed so that it occurs when the supply is high (i.e. to reduce the required storage capacity). This logic can be applied to other products or production processes.

The third paper introduces the ecological resource availability (ERA) method (chapter 4, [449]). The ERA method goes beyond the scope of the second paper, as it estimates the availability that can be achieved within Earth system boundaries when considering the impacts associated with extraction, production and EoL treatment of the material or resource, when using specific (sets of) technologies. The ERA method requires an allocation of the global boundaries to individual resources. This allocation can be done in various ways and its effect on ERA is a potential area for further research. In the paper, we exemplify a grandfathering allocation in a two step approach. First, ESB are allocated to resource segments using historic data for impacts generated in the segments, calculated with exiobase. The segment boundaries are then "filled" with impacts from various resources within this segment, where each resource is produced with the current relative share of production. The impacts are calculated with process data from ecoinvent. This grandfathering approach represents the question of "What if we rescale the current economy to fit within ESB?". This approach shows how far away the current economic system is from environmental sustainability. Even though resource use according to grandfathered ERA would be environmentally sustainable, it may be unable to provide basic needs for the currently still growing population [372]. For example, reducing the provision of food, which is also a resource, by the same factor as metals (or any other societal activity, as they are rescaled uniformly; ≈ 40), will not be able to provide sufficient nutrition to today's population. Rescaling the consumption per person is not possible in all areas of needs in the same way. In view of this, there is a need to find different allocation options and scenarios to provide basic needs to a stabilized world population.

The forth and last paper of this thesis aims to guide and evaluate the design of products and services towards an efficient use of limited resources (chapter 5, [440]). Circular strategies can reduce the pressure on primary materials and energy. ERA estimates the sustainable level of primary material use, however, grandfathered ERA is not a desirable benchmark for society, because it entrenches the current unsustainbale resource consumption patterns. Therefore, we propose another type of resource budget, which we call ecological resource potentials (ERP) (section 5.8, [217]). ERP is calculated through a modification of the ERA method, leaving out all allocation steps. ERP estimates the annual production amount, that is possible within ESB, if only this material would be produced. As such, it reflects the impact intensity on ESB only. It is interesting to observe, that for several materials, the current production is larger than ERP, i. e. current production of these materials can not even be sustainable, if no other anthropogenic activity would take place. Regardless if ERA or ERP is used as a resource budget, the resource pressure method measures how much pressure is exerted on the budget by a product. It considers thereby not only the direct primary material demand, but also the losses to final sinks. A loss to final sinks has to be replaced as an input somewhere in the socio-economic metabolism by primary material and is as such responsible for resource pressure. This combination of input and output view is necessary, because from a product perspective, primary material intake is not in all cases necessary (e. g. by using cascaded materials). However, also a product, that doesn't use primary input can reduce its resource pressure by reducing losses to final sinks and thus increases the utility of a resource in the overall socio-economic system. The same logic applies to products with no losses to final sinks. To measure the resource pressure, the method requires six parameters for each material contained in a design: mass in the final product, manufacturing losses, lifetime, recyclability, cascadability and primary material content. These parameters can be estimated throughout the design process and therefore can be used to guide the design towards a reduced resource pressure. In order to inform even earlier design steps, where the parameter cannot yet be estimated, we have derived specific design guidelines for the objective of reducing resource pressure. The method does not yet evaluate the effectiveness of resource use (i. e. the absolute sustainability), however, as ERA is an absolute sustainability metric, it can be used for an absolute assessment. This, in turn, will require to define a desirable ERA.

In the following sections of this chapter, I will critically reflect on the work presented in terms of relevance and limitations. I will further derive future research topics out of the shortcomings and conclusions from this thesis.

6.2 SCIENTIFIC AND PRACTICAL RELEVANCE

In the scientific debate on CE, bottom-up conceptualisations and the question on how to operationalise them best dominate the discourse. In this thesis, my co-authors and I want to contribute a different perspective with a top-down and systemic approach, placing environmental realities at its core. It is thereby not a simple addition of aspects (e. g. "design out poverty" alongside with "design out waste" [472]) but a fundamental re-thinking of the aim and purpose of CE. The overarching aim should be to create a sustainable economic system, allowing humanity to prosper for millennia to come on our limited planet. The condition to achieve this is to stay within the bio-physical capacity of the Earth system. Consequently, the appropriation of resources to use in such an economic system has to be limited to environmentally sustainable levels. The purpose of CE is then to maximise the utility of these limited resources for society. Thereby, the provision of needs to the world's population shall be given priority over desires [441, 455].

The motivation in mainstream CE concepts is to maintain economic growth [61], as it is the basic driver for any business in the current system. Contrary to that, we intentionally do not deal with the question of economic growth, as the economic performance is a mere outcome of the CE providing needs and desires to society within the bio-physical limits of the planet. Furthermore, our approach is able to accommodate alternative economic systems, in fact leaves the question open which economic system can deliver the so defined purpose best.

Building on this concept, we have proposed several methods (ATP (chapter 3), ERA (chapter 4), ERP (section 5.8)) as a first step to quantify the sustainable resource base. To my knowledge, only few attempts for specific resources had been made so far (e. g. sustainable forest management [216]. food [24, 215]), but no general method existed. The methods are intended to be used as scenario tools, evaluating the effects of different allocation principles, technological choices and political actions on the sustainable resource base, and also as absolute benchmarks for resource consumption of societal activities. To facilitate this, all methods, source code and data examples are made available online.

Looking at resource utilisation, we have proposed the resource pressure method (chapter 5) as a first step to connect product and service design (bottom-up) with sustainable resource consumption (top-down). The method comprises both a quantitative indicator (resource pressure τ)

and qualitative guidelines specific to the purpose of reducing the pressure on the sustainable resource base. The indicator is a single score, even though it represents multiple environmental dimensions (ESB). No weighting is necessary, as the most limiting boundary defines the ecological resource budget. The indicator can be also useful beyond design guidance, e. g. for absolute assessments of resource consumption on different societal levels or the evaluation of policy interventions on resource flows in society.

The methods and frameworks proposed by this thesis are not only relevant to the scientific community, but can be equally relevant to practitioners in various fields. The framework presented in chapter 2 contributes an ideal-type benchmark for a sustainable and circular economy. Business leaders, for example, can take this framework as a "north star" to derive a business strategy [57] and policy makers can identify requirements for resource governance within a sustainable CE.

The ERA method offers a tool to evaluate different societal options and the effect of policies on the availability of resources within ESB. For example, policies changing the energy system or changing values in society and therefore allocation principles can be evaluated for the effect on ERA of other resources (e. g. metals). In this way, a policy or set of values can be tested on its effectiveness to increase the sustainable resource base for society (e. g. a change of technology, tax system or access rights to resources), helping to prioritise policy interventions and informing the societal discourse. The ERA method can be used by both policy makers, evaluating the effectiveness of a resource governance proposal, as well as scientists across disciplines, exploring the landscape of options for resource use within ESB.

Designers and engineers are the target group for the resource pressure method. They are, to my knowledge and own experience, generally not very familiar with LCA, especially when it comes to impact categories other than climate change. Despite this lack of knowledge, there is an increasing necessity to include environmental considerations in the design, as a result of both external requests and internal motivation. As designers and engineers already have to handle a multitude of aspects (e. g. technical, operational, user interaction, ergonomics, regulations, standards, manufacturing, costs, time), asking them to consider environmental aspects in full detail additionally is perhaps not very realistic to implement. The approach developed in this thesis simplifies the problem for the designers and engineers in so far, as the environmental aspects are considered in the calculation of resource budgets. Maximising the utilization of these resource budgets comes down to a typical engineering task (as it is concerned with mass flows only). However, the approach is not yet fully operational, as it requires further research (see section 6.4) on, for example, the evaluation of recyclability and cascadability, defining a desirable ERA as a design benchmark, or making the method readily available, e. g. in an online-based tool.

There is a strong interest from industry in the resource pressure method. During my Ph.D., I had several discussions with designers and engineers in various companies within and outside the LACE project. They confirmed the shortcomings of established environmental tools (like LCA) and appreciated the idea of this method. In particular, I have contributed the methods and ideas in several workshops at V-Zug during the design process for a new circular washing machine platform. Furthermore, I had several workshops on the design guidelines with other companies within and outside the LACE project (Logitech, Tisca Tischhauser AG, Schoeller Textiles, Stadler Rail, Helbling Technik). In all workshops the need and applicability of the method was confirmed, especially appreciating the single score indicator that allows clear design guidance.

6.3 CRITICAL APPRAISAL

This thesis builds on several important assumptions and value choices and their implications are discussed in this section.

As argued in chapter 2, a strong conceptualisation of sustainability is adopted. The environment is seen as the overall and non-negotiable frame for all human activities, which has to be safeguarded with highest priority. In this view, natural capital cannot be traded for – or replaced by – artificial capital [212, 473]. As a consequence, all methods developed in this thesis focus on environmental sustainability only, as this has to be ensured first and foremost. There is an ongoing debate in science and society whether to follow a strong or weak sustainability paradigm [213, 473]. The weak sustainability concept places equal importance on the environment, society and economy. It perceives natural capital as replaceable, allowing negotiations and trade between the three spheres of sustainability. In this power struggle, the environment has potentially a weak stand as it lacks a "strong voice" in comparison to society and economy [214]. For example, this can be observed in the climate negotiations, where the power of political and economic interests hinder deliberate and fast climate action. However, ignoring environmental concerns may erode the very basis of society and economy in the long run [73]. This, in turn, is an argument for the strong sustainability paradigm, where the environment is safeguarded with highest priority, enabling society and economy to prosper in the long run. Some authors search for a "middle ground" [212], i. e. a compromise between the two extremes. In this view, some parts of natural capital is tradeable, whereas other parts are not [212].

Had this thesis been based on the weak (or middle ground) conceptualisation of sustainability, it would have been also necessary to consider the social and economic aspects in the methods, including a procedure to deal with the unavoidable trade-offs and compromises. For example, if cost was included in the resource pressure method, it would have been necessary to define a decision criterion (e. g. through weighting) in order to provide clear guidance on design prioritisation in case of diverging results. Costs remain still an important factor to every company, however, it can be influenced by appropriate business models [57], economies of scale, market response or legislative change. It is possible – at least in principle – to make the environmentally optimal solution work economically; whereas in a weak sustainability paradigm, it is unclear whether to give priority to either of the environmental or business aspects.

Another normative choice in this thesis is the application of the responsibility principle. The actor introducing a new artefact to society (can be e. g. a primary resource or a new product) is responsible for the impacts caused not only up to the point of introduction, but also when it leaves society again. For primary resources this means that impacts have to be accounted not only for cradle-to-gate but also for EoL. A resource once introduced may eventually leave the socio-economic system again as emission or final waste. These impacts are attributed to the primary resource before it enters society. In this way, the potential impact caused by the resource itself over time is already accounted at the point where it is introduced to society. Alternatively, the EoL treatment could be treated as a separate human activity and all impacts accounted separately. This "end-of-pipe" approach pushes the responsibility into the future and out of sight. EoL impacts are, however, significant for several resources. For example, about as much CO_2 is emitted when producing several main plastics as is when burning them at EoL. Accounting the EoL impacts separately would require to allocate sufficient impact allowances to the waste treatment sectors, which is challenging when considering changing primary inputs. This can be avoided by using the responsibility principle.

Similarly, this principle is also applied for product design. In the resource pressure method, the pressure on primary input and on final sinks is weighted equally. In this way, design decisions are equally responsible for the quantity and quality of resources that are required to produce a certain product or service and also for what becomes of these resources at EoL. It would equally be possible to separate the beginning- and end-of-pipe perspectives, where the product design is only responsible for the beginning-of-pipe effects. Then the recovery of resources from EoL products is a detached operation, as is present in most recycling systems today. The performance of the overall system can potentially be much improved, when considering and taking responsibility for EoL treatment already in the design.

A third normative choice is the precautionary principle. It takes uncertainties into account and requires the results to be on the safe side, i. e. possible with high confidence. The precautionary approach can, however, only cover the known (or estimated) uncertainties. It cannot cover unknown influences, which are common in complex systems, like the Earth system. Alternatively, a deterministic approach could be taken, neglecting both the known and unknown uncertainties, or still considering known uncertainties but calculating median results (i. e. 50 % probability) with standard deviation. Both alternative approaches are common in industrial ecology (and many other fields), as the former requires simple calculation procedures and provides clear results whereas the latter provides an estimate for the likely value (median) and the uncertainty range (standard deviation). Both approaches do not require a normative choice on the confidence required in the results. However, communicating median results or using deterministic values can be greatly misleading when facing large known uncertainties, as this is common in Earth system science. For example, the known uncertainty of the remaining carbon budget to stay below 1.5 °C is large [15, 230], still the median value is taken for communication and the design of suitable transition pathways. However, adhering to the so determined pathways means that there is a 50 % chance that the temperature target is missed.

In many fields – from engineering to medicine – the precautionary approach has been successfully implemented and ensures safe use of technology for society. Much the same way, the use of technology shall be equally safe to the environment, which is the very basis for society. In regard to the methods developed in this thesis, the precautionary approach can be omitted by setting the required probability of violation to 50 % and additionally report the standard deviation. For the resource pressure method, a deterministic approach is applied for the relative design comparison. Uncertainties of parameters (e. g. recyclability) can be evaluated using different scenarios. When the method is further developed into an absolute assessment tool, the precautionary approach shall be applied as well.

Sustainability entails a long – theoretically infinite – time horizon. An economy can be only considered sustainable, if it can be sustained over time. Given the environmental boundary conditions, this leads to a steady state of resource use in the long run. The current economy is far from being in a steady state [7, 9, 144, 147] as stocks in society are growing, especially for minerals and metals [7]. The system will nevertheless tend towards a steady state, if the material inflow to society is limited to a sustainable level (ERA). It will only reach steady state, once the utilization effectiveness in society approaches physical limits (e. g. for recycling, life extensions). Also in regard to utilization of resources, the current system is far from reaching the maximum potential [9]. Furthermore, environmental boundary conditions are not necessarily constant over time, as changes in the system may entail changed boundaries.

As we are far from constant inputs and maximum utilization, one can argue, that assuming a steady state for this analysis is invalid. Stock growth delays the availability of secondary materials [147], therefore it cannot be used as an input to produce products. When we consider one product reaching its EoL, in contrast, the material becomes available at the point in time, when a replacement product needs to be produced. In this sense, the steady state assumption is a hypothetical construct to simplify the problem, and valid when looking at an established product system. It is not valid for the first generation of products (because there is no EoL product available to source recycled material from) and can only approximate the situation when products change significantly from generation to generation. These dynamics are not accounted in the resource pressure method yet, however, it can be in principle applied to a dynamic analysis as well.

Furthermore, the transition towards this theoretical situation of resource use on a sustainable level (i. e. the question of how to reach ERA?) was not addressed in this thesis. Could the use of a steady state benchmark for product design still be useful today? The transition to a sustainable society will require extra efforts (e. g. CO_2 removal and storage, restoration of habitats, clean up of persistent pollutants in the environment), though (hopefully) it will be finished at some point in time. For the time thereafter, it is necessary to gain knowledge and experience on managing the limits within which our society can operate. When designing new products and services, striving for such a vision enables us to learn how to make future-proof decisions. This collective learning will take time and can be already part of the transition period; therefore I think it is legitimate to use the steady state benchmark already today.

The question of transition can, in my opinion, only be addressed in a meaningful way, once a desirable goal (or several equally desirable ones) for ERA could be defined. The definition of ERA budgets depends very much on the choice of allocation principles. The grandfathering approach can be illustrative to show how far the current society is away from a sustainable state. However, implementing grandfathered ERA budget may lead to a dysfunctional society, especially, because it will not be able to provide for basic needs. Therefore, we should further explore the solution space for sustainable resource consumption, in order to find desirable solution(s) for ERA. With such solution(s), transition pathways can be constructed to reach them starting from the current state. When finding desirable ERA proves impossible, it would need to be classified a *wicked problem*, which does not have a solution, only a process, which is better or worse for the majority of stakeholders involved [474].

The concept of Earth system boundaries (ESB) may suggest that only the impacts which exceed the boundaries are a problem. In fact, an impact will always remain a negative consequence on the environment. The ESB shall therefore not be misunderstood as a "right" to pollute and impact the environment up to the level of the boundaries. In this thesis, ESB are treated as the maximum permitted impact. As many boundaries are currently exceeded by far, at least a reduction of these impacts to the boundary value is required to become environmentally sustainable. Once a situation is reached where no boundary is crossed any more, the goal must be to further reduce the impacts.

Regarding renewable energy, the calculation of appropriable technical potentials (ATP) presented in chapter 3 has the major drawback of not including impacts and resource needs associated with necessary harvesting technologies; it rather focuses on very specific allocation problems (e. g. for land) and boundary settings (e. g. for forest biomass). ATP therefore demarcates an upper limit for ERA for RE. ERA for RE may, however, be much lower than ATP due to the impacts from production and EoL treatment of harvesting technology. Using ATP, similar to ERP, as resource budgets for design consideration is therefore favouring the use of the largest potentials, being aware that these potentials cannot be achieved in practice. The types of potentials are different for ATP and ERP. ATPs are potentials in the sense that they do not account for impacts associated with the production, installation and EoL treatment of the necessary technologies. They only consider impacts (in particular land occupation and freshwater withdrawal) associated with the use phase of the technology, i. e. the energy harvest. All ATPs from different RE resources are calculated simultaneously and summed up to the total potential, i. e. allocating the limited resources "land" and "freshwater" to the different RE harvesters. This allocation is not very sophisticated for most RE resource as they do not compete with each other. For example, wind power on agricultural land does not impede agricultural production, however, solar power does and therefore it is limited to the already sealed surface of the built environment.

ERPs, on the other hand, are calculated for each resource individually. ERP does not need any allocation, but it accounts for all impacts from production up to the point where the resource is used in society (for RE that is electric energy) and EoL treatment. The ERP of one resource fills the ESB completely, i. e. no other anthropogenic activity, with an effect on the limiting boundary, may take place. For example, calculating ERP for solar energy harvest through solar PV (multi-crystalline Si) produced with current technology and energy mix results in $ERP_{\text{PV}} = 1.4 \times 10^{12}\text{W}$ with CO_2 as the limiting boundary. ATP for solar energy (combined of solar on built environment and in deserts) is with $ATP_{\text{solar}} = 7 \times 10^{13}\text{W}$ more than one order of magnitude larger as it only accounts for land requirements (see figure 6.1). However, would the solar panel be produced with solar energy instead of the current mix, ERP will likely not be limited by CO_2 anymore. The opposite is the case for ATP from wood. Here ERP is an order of magnitude larger than ATP, because ATP is much more detailled on the sustainable harvest rate of wood, whereas no such boundary is currently implemented in the ERP method. ATP can thus serve as an upper boundary value for the calculation of ERP (and ERA) for RE. Alternatively, the more detailed boundary conditions used in ATP (e. g. sustainable harvest of wood) can be included as boundary categories in the ERP method. While no ATP is defined for fossil energy, ERP can be calculated for fossil energy resources as well. It is interesting to note that ERP for each fossil energy resource individually (coal, oil and gas) is more than one order of magnitude smaller than production in 2016.

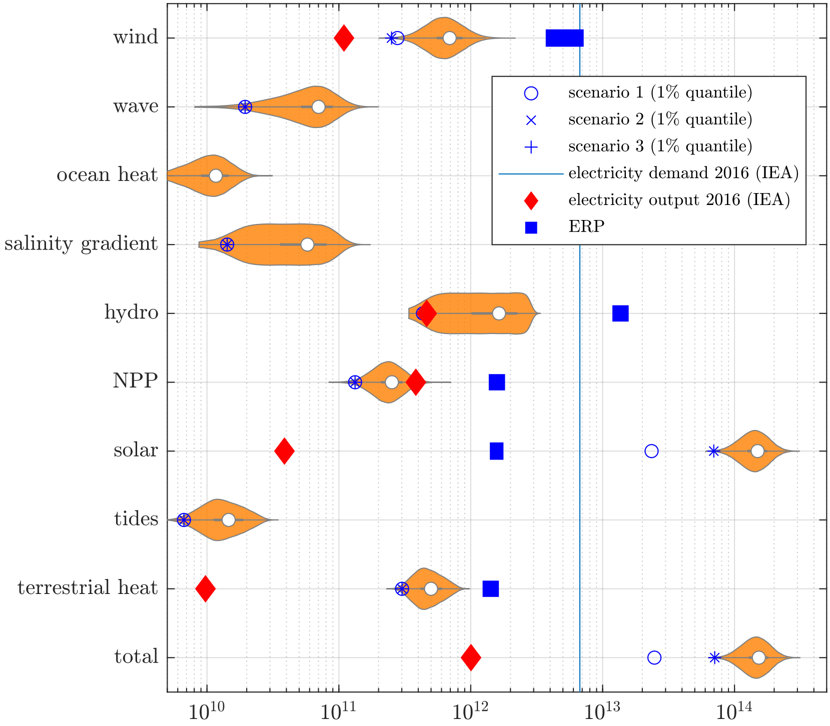

FIGURE 6.1: Comparison of ATP (violins) (see figure 3.3 on page 86) with ERP (blue bars) and current output from RE resources (red diamonds) [246].

ERA budgets are calculated without double counting impacts for all materials. That means, that all impacts associated with the production of material A are accounted in this material, also if material B is required for A's production. The impact for the amount of material B necessary to produce A is then included in A's impacts (cradle to gate). This, however, also means that ERA represents the production output to the rest of the economy, not to overall production, as the amount of this material necessary to produce other materials is already deducted and accounted in other materials' impacts. Production data, on the other hand, is commonly reported as the overall output of an industry and not divided into output that goes to other material productions and output that goes to the rest of the economy. For the production of products and services, the amount of material that is provided to the rest of the economy is relevant and how much more material needs to be produced to provide all materials is not of concern. In this sense, the correction of double counting is right. For the status quo, the overall production amounts can be converted in material output to the rest of the economy, by deducting the output necessary for other materials [259]. Changing the economy's resource use pattern (i.e. anything else than grandfathering [475]), however, may also change the amount of material that is needed for other materials' production. Calculating the overall production output from ERA, which is necessary for setting production limits, is then not straight forward but requires an evaluation of all other materials' inventories.

It would be also possible to calculate ERA budgets as total output of an industry. This requires to account UI without other materials necessary to produce the output to avoid double counting of the associated impacts. This approach could be implemented through developing a procedure to account for all impacts in the supply chain of a material, except for those associated with other materials. The advantage of this approach would be having ERA budgets directly comparable to the total output of an industry, therefore useful to set targets and develop policies for the industry directly (e. g. setting a sustainable annual production limit).

The design guidelines in section 5.2.4 are derived from the objective to reduce the resource pressure. Similar or identical recommendations have been formulated in literature based on life cycle assessments [171, 178] or specific objectives (e. g. design for disassembly [186, 187, 476]). The design guidelines from the resource pressure method are compared in table 6.1 to more general *design for environment* (DfE) guidelines based on a literature review [171]. Other guidelines can help to implement the resource pressure guidelines (e. g. design for remanufacturing [450] can contribute to increase the lifetime of parts). The resource pressure guidelines are therefore not exhaustive and can also be contained in guidelines derived from different objectives (e. g. minimizing environmental impacts).

The resource pressure method, as it is proposed here, leaves several important questions open, which can be evaluated implicitly, however, not explicitly. First, increasing the lifetime of a product is not in all cases environmentally beneficial [308]. If impacts during the use-phase of the product are significant and there is an evolution in terms of efficiency for new products over time and/or efficiency declines during the use phase, it might be beneficial to replace old products at their optimal environmental lifetime [164]. For mature technologies, efficiency improvements in new

No.	**RP guidelines**	No.	**DfE guidelines** [171]
1	choose material with large ERB	10	specify resource with low emissions
2	reduce mass in product	17	specify lightweight materials and components
3	reduce manufacturing losses	18	structure the product to avoid rejects and minimize material waste in production
4	increase lifetime	49	reutilize resource intensive components
		53	protect products from dirt, corrosion and wear
5	reduce primary material input	2	specify recyclable or recycled resources
6	increase recyclability	13	recover emissions and output
		68	make incompatible materials easily separated
		2	specify recyclable or recycled resources
7	increase cascadability	13	recover emissions and output

TABLE 6.1: Comparison of resource pressure (RP) design guidelines [440] and design for environment (DfE) guidelines [171].

designs are often marginal (e. g. for washing machines [477] or hydro turbines [353]) and efficiency losses during the life time can be compensated by repair and maintenance. The resource pressure method is capable, in principle, to capture these effects when the resource pressure is calculated for resources (materials and energy) during the use phase as well. As this may be a bit cumbersome for a quick analysis, finding a better metric to explicitly determine the optimal environmental lifetime may be useful.

The same applies to recycling and cascading. Environmental impacts resulting from the required energy and auxiliary materials can be accounted through the pressure on those resources. It is not straight forward to include these aspects in the method, so a more direct consideration would facilitate the practical application. Increasing recyclability and cascadability is not in all cases environmentally beneficial. The effort to recycle increases with the recycling rate, as recycling would start with the fraction of the material which is easiest to access. In theory, the effort increases to infinity to recycle the last bit of material [478]. For example, recycling the part of a shoe's sole, that is still attached to the EoL shoe is easy, but collecting the part which is distributed on the walkways would require infinite effort (i. e. exergy).

For cascading, the resource pressure method does not distinguish on the different quality levels, a cascaded material is used. Using it for a higher quality level would obviously be preferable as it enables multiple cascading uses. However, cascading is also a question of demand as for certain potential applications there might not be high enough demand. Nevertheless, the quality of the cascading application matters and the objective should be to bring as much material as possible into the highest possible quality application (see figure 2.4 on page 45). This aspect has not yet been considered in the resource pressure method.

Lastly, the resource pressure method cannot be used to measure the impacts associated with the use phase of the material, if they are not traced back to impacts from auxiliary materials and energy.

6.4 FURTHER RESEARCH TOPICS

Several aspects of the developed methods need further refinement in order to be applicable in practice. Other research ideas emerged that can be investigated using these methods. And additional research is necessary to complement the analysis for aspects currently not addressed (see figure 6.2). In this section, ideas for potential research topics to build on and advance the research of this thesis are described.

ACCEPTANCE OF RISK IN SOCIETY For the precautionary approach, the acceptable probability of violating Earth system boundaries needs to be defined. This selection is based on a value choice and reflects the risk a society is willing to tolerate in regard to the consequences of crossing ESB. As described in section 1.5.1, society tolerates a very small risk associated with the use of certain technologies, especially when they pose physical danger. There are many regulations and standards requiring such technologies to prove their level of safety. The perceived risk by individuals, in contrast, may not be in concordance to these regulations and standards. For example, many people perceive air transport as more dangerous than driving a car,

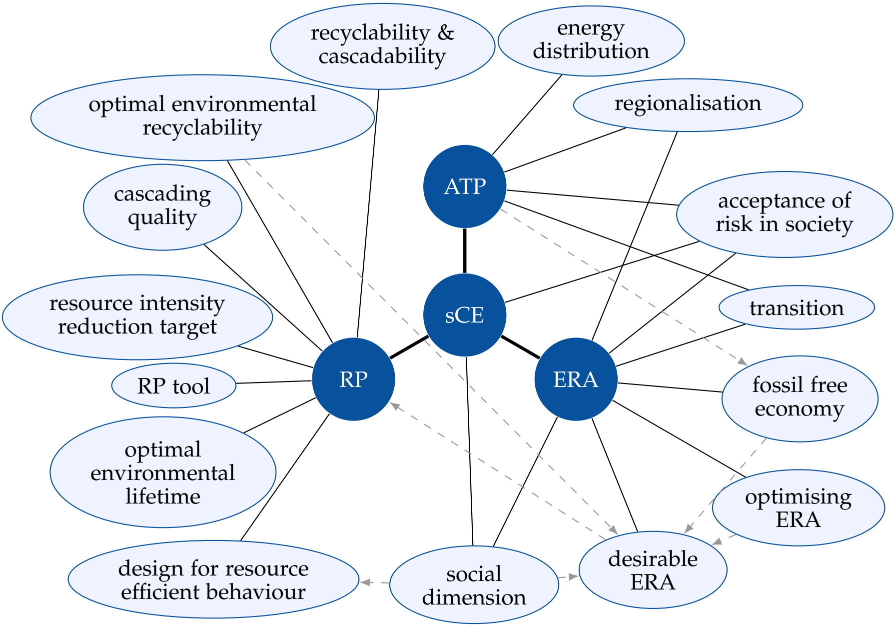

FIGURE 6.2: Overview of further research topics derived from the four central concepts: sustainable circular economy (sCE), appropriable technical potential (ATP) for renewable energy, ecological resource availability (ERA) and resource pressure (RP).

even though the measured probability of death is a thousand times higher in a car than in an aircraft. Similar to technical artefacts, the risk aversion by society is also high for public health, as we are experiencing it during the Covid-19 pandemic. Uncertainties had been high in regard to risks and dynamics of the pandemic in the onset, still most governments set fast and strong measures. In contrary, environmental risks are still largely underestimated by society, or put in another way, large risks are implicitly accepted. There is a need to investigate the differences in the approach towards risk in different domains. In the ATP [226] and ERA [449] methods, we have set the probability of violation to $P_v = 0.01$, which stands in between the technical and environmental risk acceptance today and was selected as a starting point for a societal discussion. Therefore, a possible research topic is to understand the differences of risk acceptance in different areas and their likely consequences in order to prepare the societal discourse on managing long-term environmental risks.

REGIONALISATION The ATP and ERA methods are exemplified for global totals in this thesis. Considering global supply chains in most products, this approach is a reasonable starting point. However, there are many resources, which are traded regionally (e. g. cement, energy), making it necessary to regionalise these methods. ATP can be calculated for countries or regions, requiring regional data on the availability of physical energy resources (e. g. solar irradiation) as well as technical system's performance (e. g. temperature effects on efficiency of PV). The regionalized ATP mixes are likely to be different for countries with a concentration of a specific RE resource (e. g. hydro power in Norway or solar power in Egypt). Such regionalized ATP give a better guidance on energy policy and investments for specific regions. To regionalize ERA, an allocation of global boundaries to countries or regions is necessary in addition to regionalized data concerning impacts. It may also be possible to integrate in this way regional boundaries, e. g. for freshwater consumption [83, 84].

ENERGY DISTRIBUTION The ATP method calculates the energy potentials for the first conversion step from Earth system energy to energy that can be used in society (i. e. electric energy equivalents). As RE resources are neither distributed evenly in space nor time, there is a need for a distribution infrastructure in space (i. e. grid) and time (i. e. storage). The extent of such an infrastructure, however, greatly depends on the demand and its timely and geographically distribution. For example, if the demand is small compared to ATP, it can be satisfied by over-sizing the installed capacity so that the demand is met at any time. The investment into the over-sized harvesting infrastructure may be environmentally beneficial over the investment in distribution infrastructure. Next, the demand can be timed and located to a certain extent to when and where RE resources are available. As an example, energy intensive processes in industry can be timed at peak sun hours instead of during the night, when fossil or nuclear energy is cheapest today. Or factories can be relocated to places with a high solar irradiation (e. g. in or near the deserts). Different distribution options (e. g. chemical batteries, H_2, pumped hydro storage, super-conducting grids) have different resource requirements, turnaround efficiencies and therewith environmental impacts. Consequently, a study on the distribution of RE needs to find the environmental optimum between the harvesting and distribution infrastructures for providing energy to society.

TRANSITION The transition from current society to the sustainable state with respect to material and energy use is not considered in this thesis. Dynamic simulations are necessary to identify policies, business strategies and demand patterns [96] creating pathways to reach the sustainable state fast enough [15, 479, 480]. The target of reaching a sustainable level of resource use (i. e. ERA) needs to be accompanied by additional requirements concerning the dynamics of the transition. For example, such requirements could be to minimize cumulative CO_2 emissions during the transition or a target point in time, when the transition needs to be completed. Such an analysis can show what is feasible due to the dynamics of change.

SOCIAL DIMENSION The social dimension of sustainability has not been addressed in this thesis. The focus lies on the environmental dimension, as it is the highest priority in the cascading approach (see figure 2.1 on p. 36). Society is the second priority and providing for a decent life within the bio-physical limits of Earth needs to be ensured in order to satisfy the social sustainability dimension. Social aspects can be addressed in various ways. First, the material enablers (basic needs) for a decent life [441] can be given priority over desires [455] when allocating global boundaries. E. g., providing sufficient nutrition to everyone [24, 25, 215] needs to have priority over indulgences like ice cream. Similarly, a minimum shelter with adequate temperature control needs to first be fulfilled for everyone before increasing floor space or comfort can be considered [481].

As this covers the material requirements only, an additional approach to require minimum social thresholds directly is necessary. One threshold can be, for example, a minimum duration of education [373]. While for the environmental boundaries the sustainability criterion is to stay below, for the social foundation [314] it is to stay above the respective limits [72]. In principle, social boundaries can be implemented in an extended ERA method, where environmental boundaries need to be observed and the resource mix is then optimized until all social requirements are achieved. The quantification of these direct social indicators with estabished tools like LCA is, however, still at its beginning (i. e. social LCA [482–484]). Achieving the sustainable development goals [373] within the limits of the planet will be a fundamental challenge [94].

FOSSIL FREE ECONOMY Imagine a society powered solely by renewable energy (RE) without any use of fossil or nuclear fuels anymore. How would the environmental impacts for production and consumption change? To answer this question is not straight forward, as all supply chains contain fossil inputs in one way or another. Usually, LCA background databases (e. g. ecoinvent [401]) try to capture the status quo in the society as good as possible; yet they do not offer a straightforward evaluation of "what if" scenarios throughout the value chain consistently. E. g. solar PV cells necessitate production of materials and transportation, which is based on fossil fuels in the current economy (and thus also in such databases). There are so far no studies that estimate how the environmental impacts would change, if the whole value chain would be fossil free. Consequently, there is a need to create a calculation procedure to make a fossil-free version of background databases. All fossil inputs in such a database need to be replaced with a mixture of renewable energy resources. This replacement RE mix is thereby dependent on ESB, as all RE resources will reach a limit. Special care needs to be taken for the replacement of fossil based heat and transport by renewable energy. A fossil free background database enables the calculation of fossil free ERA (What is the potential of decarbonisation to increase ERA?) and ERA for RE, as the impacts of most RE technologies greatly depends on the energy they are produced with. ERA for RE thereby has an influence on the RE mix used in the background database, as it sets the maximum limit for RE. Calculating such a fossil free scenario is therefore an iterative process.

DESIRABLE ERA All ERA budgets are by definition within ESB and therefore environmentally sustainable. But they are not all equally desirable for society. The ERA method requires several allocation steps. Firstly, the global boundaries need to be allocated to resource segments and secondly, the resources within the segment must be allocated a share of it. Furthermore, the global ERA budgets need to be further allocated in form of resource use rights to geographic regions (e. g. country), population, economic sectors, product groups or areas of needs [481]. The production technology has also a fundamental influence on ERA. For example, impacts can be calculated based on state-of-the-art, best available [485–491] or future technology (e. g. hydrogen steel making [442]) (see also the paragraph on "fossil free economy"). Depending on the scenario design, ERA may or may not be able to fulfil the basic needs [24, 441] and desires [455] of the world's population [372]. An ERA that is not able to fulfil basic needs, has to be rejected as not desirable (e. g. the grandfathered ERA presented in chapter 4). Furthermore, the definition of what is desirable needs to also take into account inter- and intragenerational equity [213], for example by considering the geographic distribution of in-use stock of materials or the economic ability, and the possibility of acceptance by society [455].

OPTIMIZING ERA Another way to increase ERA and therewith the availability of sustainable resource to society is to optimize it based on different optimisation objectives (e. g. mass, strength, electrical conductivity). The relative share of each resource can thereby be varied between upper and lower bounds and the optimisation prefers the resource with low unit impacts in regard to the optimisation objective. In other words, ERA for all resources can increase when decreasing the use of high impact resources, allowing to increase low impact resources. Such an optimisation has the boundary of substitution of resources with each other (upper and lower bounds) [170], however, can show the potential of practically possible substitutions.

RECYCLABILITY AND CASCADABILITY BY DESIGN In the resource pressure method, the two parameters *recyclability* and *cascadability* describing the technical potential to close material cycles are required. As both parameters are not straight forward to estimate, there is a need to develop methods to link product design decisions with the potential for circularity.

Circularity is thereby not a property of the material alone, as it strongly depends also on its (potential) applications, e.g. through the combination with other materials and the management throughout the life cycle (e.g. take back schemes at EoL or predictive maintenance during use). Being able to estimate the circularity potential of different design choices during material and product development is necessary in both research and industry. Accordingly, a new method is required suitable for researchers and product designers/engineers in industry to optimize the circularity potential already during the design stage of novel materials and applications. Even though the circularity is a property of the socio-technical system, it is important to find the technical potential for circularity, i. e. the upper bound that is technically feasible. Therefore, factors influencing the recyclability and cascadability from a material science and product development perspective need to be identified and analysed. An example could be to define how the connection type, number of connections and number of different materials influence the recyclability and cascadability. Approaches to estimate this with detailed process simulations [457, 458] are not easy to apply in practice. Finding correlations between design features and the circularity potential, either empirically or theoretically, may facilitate practical application. Such correlations can then be summarized in, for example, look-up tables or regression curves.

CASCADING QUALITY Cascading is treated in the resource pressure method irrespective of the target quality. For example, it makes no difference in the method, if a packaging glass is cascaded to insulation material (glass wool) or used as glass sand. To make the distinction on the quality, an objective measure is needed. One possibility can be, for example, to use entropy, as it represents the state of order in the material [471]. The requirement of minimizing entropy production (chapter 2) will then lead to target the highest possible quality cascade, as this leads to the smallest gain in entropy.

Cascading is depicted in the resource pressure method as unidirectional from higher to lower quality. However, there is no physical reason, why it would not be possible to increase the quality through cascading, only it is more energy intensive. Most practical examples, however, show a downgrading in material properties. For example, Al alloys are downgraded to alloys containing higher alloying element concentrations – and therefore also tolerating contamination [117]. I have come across one example, which possibly can be considered upwards cascading from a technical perspective. The traditional Japanese planners for woodworking consist of a metal blade of a soft and a hard layer. The hard layer forms the cutting edge, whereas the soft layer provides mechanical stability. In the highest quality blades, the soft layer is forged from steel, which is taken from anchor chains (or other massive EoL steel parts) that had been produced before 1900 [492]. At that time, silicon carbides had not been removed from steel, which does have a positive effect on the sharpening behaviour of the planner's blade. In this case, a low end application (anchor chain) is converted into a high-end product (planner's blade) with specific properties. It remains to be demonstrated, if it is an upgrade in material properties or the material's properties were simply unused in the previous application.

OPTIMAL ENVIRONMENTAL RECYCLABILITY The impacts from recycling increase non-linearly with the recyclability [348]. As the impacts from primary production can be assumed to be independent from the recyclability, there is an optimum recyclability where impacts are minimal [348, 478]. Being able to express the relationship between impacts and recyclability, allows to consider the effects on Earth system boundaries from increased recycling in the resource pressure method. For example, ERB can be down-scaled in relation to the impacts from recycling in order to exert the same pressure on ESB. Further, an optimal environmental recyclability can be calculated and used as a target value for design. An indicator proportional to the impacts can express how much more impacts are generated with a specific recyclability in comparison to the (lowest) optimal impact.

To establish such a relationship, it is necessary to find empirical and/or theoretical relations between the requirement of energy and auxiliary materials (e. g. solvents) for all recycling steps (i. e. collection [478], pre-processing and processing [467]) and the overall recyclability.

OPTIMAL ENVIRONMENTAL LIFETIME One major CE strategy is to prolong the service life of the produced goods [165, 184]. The longer a product serves its intended use, the lower the share of resources required and environmental impacts caused in production and EoL treatment per service unit. While this is true for products that cause no (significant) environmental impact during their use phase (e.g. a table or a building's structure), it is not automatically the case for products that cause impacts in the use phase (e.g. a washing machine). As for such products the efficiency degrades over its lifetime and new products become more efficient through technological innovations and improvements, there is an optimal environmental lifetime, which leads to minimal overall environmental impacts. Finding such an optimal lifetime requires to describe the efficiency loss over time, the efficiency improvements of new products entering the market and the reduction of impacts from production of replacement products.

RESOURCE INTENSITY REDUCTION TARGET The resource pressure method aims at reducing the resource intensity of a product by design. However, how much is it necessary to reduce the resource intensity in order to achieve a sustainable resource use? This question can also be addressed with the resource pressure method when using ERA as a resource budget. If the global sum of all τ_m for a specific material m is larger than one ($\sum \tau_m > 1$), the material is used more than what is sustainably available. Consequently, the resource use of this material is unsustainable. This analysis is straight forward on a global level. In contrast, it gets difficult when we want to assess the absolute sustainability of a single product or activity. In one way or the other it needs to be determined, how much a single product is allowed to contribute to the total resource pressure.

One possible way is to define resource intensity reduction targets for a specific resource's application. This requires to allocate resource use rights from global (or regional) ERA to sectors or actors and then measure, how far current resource use of this sector or actor is away from the allocated use rights. This distance can be expressed as the target for reducing resource pressure in every activity carried out by this sector or actor. For example, a similar approach is taken by the automotive industry, which has to reduce the fleet's fuel consumption to a certain value (target). This value has to be reached as an average over the whole industry, allowing some products (e. g. SUVs) to have a higher fuel consumption, if compensated by vehicles with a lower than average value (e. g. hybrid cars).

RESOURCE PRESSURE TOOL The resource pressure method, as presented in chapter 5, can be applied by using, for example, a spreadsheet. To facilitate its practical application and relevance, an online tool should be developed that allows quick design evaluations without having to build up the calculation in a spreadsheet. Such an online tool should contain a background database for ERB and a graphical user interface to facilitate easy applicability in companies. Furthermore, updates of the method (e. g. concerning recyclability, optimal environmental lifetime) can be integrated continuously.

DESIGN TO ENCOURAGE RESOURCE EFFICIENT BEHAVIOUR One essential leverage for improving the resource efficiency of a product or service is the user behaviour, which is not addressed in the resource pressure method yet. The design influences the behaviour of the user (e. g. consider the user behaviour of a smart phone in comparison to a cell phone), so there is a need to investigate how design can be used to encourage resource efficient behaviour. For instance, most washing machines have several programs, some of them are optimized for low resource pressure (in regard to water and energy), others for convenience (e. g. quick cycle) or hygiene (e. g. high temperature). Usually, all these different programs require same efforts to operate. Research on resource use behaviour suggests, that the more effort (can also be mental effort) it takes to consume resources, the less likely it takes place [469]. Therefore, a simple solution to encourage the use of the most resource efficient washing cycle would be to make it the easiest to operate (default settings, lets say press one button). All other cycles, which consume more resources, are made more difficult to start (e. g. by having to press an increasingly difficult combination of buttons). Another way to influence the consumer's behaviour on choosing washing cycles is making information about the amount of resources each cycle consumes readily accessible.

6.5 CONCLUSION

How to design products and services for a sustainable circular economy? This question was motivating this thesis and the framework and methods developed are an attempt to contribute to an answer. The main ideas presented in this thesis can be summarised as follows: Resources are limited due to environmental boundary conditions and a circular economy should aim at maximising the utility from these limited resources to society. Products and services should therefore be designed in a way, that they use resources with large ecological resource budgets preferably and minimise the pressure on primary input as well as final losses.

In this way, this thesis contributes an approach to connect global environmental limits with decision making on a product level. The develop methods allow to estimate the sustainable resource base. Resources bring value to society and are the physical currency of the economy, therefore they are at the heart of decision making. It highlights that no resource is inherently (un)sustainable; it is rather about the scale of its consumption. The ERA method is a means to find this environmentally sustainable level of resource consumption. Furthermore, the resource pressure method allows to quantify how well resources are utilized in a product system, which can be used to support design decisions.

A

APPENDIX

LIST OF ABBREVIATIONS

ABBREVIATION	MEANING
Al	Aluminum
ATP	Appropriable technical potential
AOD	Aerosol optical depth
BECCS	Bioenergy carbon capture and storage
BII	Biodiversity intactness index
CCS	Carbon capture and storage
CE	Circular economy
CED	Cumulative energy demand
CSP	Concentrated solar power
Cu	Copper
DAC	Direct air capture
DU	Dobson Units
EE-IOT	Envionmentally extended input output table
EoL	End of life
ERA	Ecological Resource Availability
ERB	Ecological resource budget
ERP	Ecological resource potential
ESB	Earth system boundaries
FD	Final demand
FO	Forward osmosis
GIS	Geographical information system
GWP	Global warming potential
HANPP	Human appropriation of net primary production
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System

ABBREVIATION	MEANING
IPCC	Intergovernmental Panel on Climate Change
LACE	Laboratory for applied circular economy
LCA	Life cycle assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventories
LCIA	Life Cycle Impact Assessment
MC	Monte Carlo simulation
NPP	Net primary production
PB	Planetary Boundaries
PDF	Probability density function
PET	Polyethylene terephthalate
PM	Particulate matter
PV	Photovoltaic
ODP	Ozone depletion potential
ODS	ozone depleting substance
RE	Renewable energy
RoE	Rest of economy
RoL	Rest of land
SB	Segment boundary
SM	Supplementary materials
SNSF	Swiss national science foundation
SoP	Share of production
SOS	Safe Operating Space
SoSOS	Share of Safe Operating Space
UI	Unit impacts

GLOSSARY

TERM	DESCRIPTION
ATP	Appropriable technical potential is the energy flux appropriable for society in the form of electric energy that can be produced with state-of-the-art technology after subtracting the appropriable chemical potential and respecting Earth system boundaries. It is the appropriable potential minus what is needed to provide the appropriable chemical potential, plus the energy that can be recovered as technical energy from chemical use and minus technical conversion losses.
Accessibility	Can be reached for human appropriation.
Appropriability	That can be appropriated.
To appropriate	Taking something that belongs to someone else usually without having the right to do so.
Auxiliary material	Is a material that is necessary for production, use or recovery, but does not become part of the product, e.g. solvents or fuels.
Availability	The fact that something can be used, or utilized (e.g., by the Earth system or humanity).
Built environment	Surfaces dominated by settlements, infrastructure, mining, etc. This includes parks, gardens, green belts along with infrastructure area.
Built-up area	Ground area of spatial units containing buildings or parts thereof [391].

TERM	DESCRIPTION
Cascadability	Material that can be recovered from the product's material output (i.e. at end-of-life or during use phase) and used at a lower quality than the product it was used before. A material can be used on multiple quality levels, i.e. cascaded multiple times. A material is considered cascadable, if there is a large enough market for it. Material without a market potential (e.g. because it has too low quality) or with a too small market has to be considered final loss.
Circular economy	The circular economy is a model adopting a resource-based and systemic view, aiming at taking into account all the variables of the system Earth, in order to maintain its viability for human beings. It serves the society to achieve well-being within the physical limits and planetary boundaries. It achieves that through technology and business model innovation, which provide the goods and services required by society, leading to long-term economic prosperity. These goods and services are powered by renewable energy and rely on materials which are either renewable through biological processes or can be safely kept in the technosphere, requiring minimum raw material extraction and ensuring safe disposal of inevitable waste and dispersion in the environment. CE builds on and manages the sustainably available resources and optimizes their utilization through minimizing entropy production, slow cycles, and resource and energy efficiency [56].
Chemical energy	Chemical energy is understood as the energy used to supply humanity with food and biogenic materials (fodder, fibers, timber, etc.).
Climax vegetation	Equilibrium vegetation that would be reached according to environmental parameter (e.g., temperature, humidity) if undisturbed.

TERM	DESCRIPTION
Earth system	The entirety of the Earth's interacting physical, chemical, and biological processes.
Earth System Boundaries	Limits to Earth system processes that, if crossed, significantly disturb the interacting web of processes with potential to trigger fast and irreversible change to a new equilibrium.
Earth system needs	Energy and material flows that are required by Earth system processes to maintain functionality.
Energy	The cumulative flux, i.e.. its integral over a given period of time.
Emission budget	The quantification of the PB to to annual emission allowances. If the socio-economic system does not emit/ extract more than the budgets allow, it can be considered sustainable in the long run
Exergy	The useful work that can be extracted from an energy flow.
Final demand	Comprises the purchase and use of goods and services by the end-consumer (e.g., household) in the Exiobase database
Final sink	A stockpile of material, that is no longer useful to society, e.g. landfill, or dispersed in the environment, e.g. CO_2 emissions to the atmosphere. Materials in final sinks can, in principle, be made accessible again with large investments of energy (e.g. CO_2 direct air capture), which, by it's nature, is similar to the exploration of natural resources.
Final loss	Flows of material to final sinks, e.g. emissions to the environment or waste stream to landfill.

TERM	DESCRIPTION
Flux	The surface integral of the orthogonal component of the flux density. It represents, e.g., the em power emitted, reflected, transmitted or received by this surface. The same term and procedure is also used for non-energy quantities, e.g., magnetic flux. In other disciplines, "flow" is the preferred and synonymous term, e.g., mass flow.
Flux density	In the context of electro-magnetic radiation, the vector field "flux density" refers to the directed power emitted, reflected, transmitted or received by an infinitesimal surface. Here, we adhere to radiometric SI terms and units.
HANPP	Human appropriation of NPP comprises direct harvest (e.g., food production, timber) and human induced changes in productivity (e.g., land use change, fire) [11].
Industry	A single industry in the Exiobase database (e.g., iron ore extraction)
Infrastructure surface	Built-up plus other sealed surfaces, such as roads, railways, airports, bridges, etc.
Irradiance, solar	Consists of electromagnetic radiation (i.e., photon flux) of solar origin.
NPP	Net primary production [11].
Planetary Boundaries	A specific set of Earth System Boundaries compromising nine planetary processes (stratospheric ozone depletion, nitrogen/phosphorus cycle change, global freshwater use, land use change, biodiversity loss, atmospheric aerosol loading, chemical pollution, climate change, and ocean acidification) within which society must remain to avoid the risk of setting off a cascade of irreversible change.

TERM	DESCRIPTION
Primary material	Material that is extracted and converted into a useful material from an in-mobile stock, e.g. Earth crust, a forest (i.e. a stock of living trees) or a landfill. In that sense, the recovery of material from a final sink is treated the same way as the exploration from natural resources.
Product	(Or a service) is a functional entity that provides a functionality for it's user. E.g. a washing machine (product) provides the function of cleaning clothes to it's user. Similarly for a service, the service of a taxi ride provides the function of moving from A to B.
Product system	A system of products that provide a continuous functionality to society over time. E.g. providing the function of cleaning clothes does not only require one washing machine, but rather a flow of washing machines over time, replacing products when they reach their EoL.
Prospective technology	Lab-scale, prototype or pilot systems that have not proven successful in the market yet.
Radiation, solar	Consists of photon flux and particle flux i.e. electromagnetic (em) waves and solar wind (i.e., particles such as electrons and protons).
Recyclability	Material that can be recovered from the product's material output (i.e. at end-of-life or during use phase) and used for the same function again, at least in principle. I.e. the material is circulated at the same quality level.
Resource	The smallest unit in the ERA method representing a stock of one material
Resource budget	The maximum annual production of a resource which does not exceed its assigned emission budgets

TERM	DESCRIPTION
Resource segment	Includes all industries in the Exiobase database that produce the same kind of material (e.g., aluminum is part of the metal segment)
Resource pressure	The fraction of the ERA necessary to provide a function to society.
Rest of economy	Holds all activities of the Exiobase database that are not part of any resource production value chain (e.g., manufacturing of end-user devices)
Safe Operating Space	Environmental impacts that can be safely exerted on the Earth system, without risking (i.e., with very low probability) the destabilization of the Earth System due to human interference. Synonym for carrying capacity
(RE) potential, theoretical	The available (RE) flux in the Earth system (replace (RE) with any RE type or combinations thereof). For example, the NPP potential is the calorific value of the net primary production. For the total incoming energy, it is the sum of the three energy flows entering the Earth system (solar, geothermal, tides), i.e.. approximately 174000 TW
(RE) potential, appropriable	The appropriable fraction of the theoretical (RE) potential, i.e., the theoretical (RE) potential minus Earth system needs. For example, the appropriable NPP potential is the Earth's entire climax NPP minus the minimum NPP required to respect Earth system boundaries.
Secondary material	Material that is cascaded from a higher quality level and used as an input in a product.
Segment Boundary	Boundary value assigned to an activity (e.g., 10 tons of phosphorus assigned to textile sector); needs to be smaller than global boundary ($SB \leq ESB$).

TERM	DESCRIPTION
Share of Safe Operating Space	Relative part of the global Safe Operating Space allocated to a production or consumption activity (e.g., 30 % of nitrogen allowance level assigned to agriculture)
Share of production	The relative production share of one single material to a combination of similar materials. For example, steel's share of production of the metal sector is about 90 %
State-of-the-art technology	Widely used technology, available in the market in various different products.

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education

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2003–2008	Höhere Technische Lehranstalt (HTL) Innsbruck, Austria *Matura* (Specialization: Mechanical Engineering)

professional experience

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PUBLICATIONS

Articles in peer-reviewed journals:

1. Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K. & Hischier, R. A circular economy within the planetary boundaries: Towards a resource-based, systemic approach. *Resources, Conservation and Recycling* **155**. `www.doi.org/10.1016/j.resconrec.2019.104673` (2020).
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8. Desing, H., Böni, H. & Hischier, R. *Environmental and engineering aspects of a new top down approach to Circular Economy* in *SETAC LCA Symposium* (BoKu Wien, Austria, 2018).

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10. Desing, H., Braun, G., Böni, H. & Hischier, R. *Making best use of limited resources – from the choice of resources to eco-efficient engineering* in *Life cycle management* (Poznan University of Technology, Poznan, Poland, 2019).
11. Desing, H. *How to split the carbon budget for buildings based on Planetary Boundaries* in *Transition towards a net zero built environment* (TU Graz, Austria, 2019).
12. Desing, H. *Ethical, environmental and economic consequences of new economic models* in *Sustainable Economies: Conceptualization and Assessment* (University of Freiburg, Freiburg im Breisgau, Germany, 2019).
13. Desing, H., Bill, A., Böni, H., Hischier, R. & Wäger, P. *Material selection in product design based on closed loop recycling efficiency* in *International Conference on Final Sinks* (ed Rechnberger, H.) `http://www.icfs2019.org/wp-content/uploads/2019/11/Se05-03_Desing_Material-Selection-In-Product-Design-Based-On-Closed-Loop-Recycling-Efficiency.pdf` (TU Wien, Austria, 2019).
14. Desing, H. *Resource pressure: A circular design method preceding LCA* in *74th LCA Discussion Forum* (ETH Zürich, Switzerland, 2020).