Responsible Production of Materials

in the light of Sustainable Development Goal 12.

Development of a systemic assessment scheme for an environmentally

responsible material production cycle –

Case study Aluminium

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Abstract

Society is facing a series of societal challenges, the most important ones being the drastic global population increase, simultaneous economic growth of developing nations and a technological and energy revolution. All of this indicates a mineral intensity in volume and variety that is currently publicly and scientifically underestimated in the whole sustainability discussion. The environmental impact of producing the projected amounts of raw materials if no mitigation actions towards more responsible processes are implemented will be vast. Sustainable Development Goal 12 addresses this issue to some extent by proposing a decrease in environmental impact with an increase in industrial activity but does not address how this seeming paradox called *decoupling* can be attained. Various other prominent sustainability theories promote directions in which the journey may go. There is, nevertheless, not a single easily accessible and transferrable framework from which concrete sectoral actions and interventions could be deducted. Especially in the raw materials field such a framework for systematic and systemic assessment of production processes is needed. The question that is thus addressed is how the targeted environmental impact decoupling and responsibility proposition of SDG 12 can be systematically identified in the extensive world of materials, in a way that they are of significant relevance in todays' environmental and responsibility debate and that will lead to solutions.

Therefore, the aim of this thesis was to develop an analysis method that allows for such systematic decoupling identification. A concrete environmental responsibility assessment scheme for material production systems that can be transferred was designed. It is based on the consolidation of various prominent sustainability theories and the lessons learned, which yielded as base requirements an environmental, circular approach with a focus on single system components and the planetary boundaries as suitable indicators. A case study with the scheme was carried out with the highly relevant future material Aluminium, which resulted in an easily accessible graphic matrix overview of the sustainability status of the material Aluminium in each unit process. It highlights exactly where in the production process improvements or changes have to take place to decrease environmental impact, thus illustrating the point of decoupling.

Kurzfassung

Die Gesellschaft steht vor einer Reihe von gesellschaftlichen Herausforderungen. Die wichtigsten davon sind der drastische Anstieg der Weltbevölkerung, das gleichzeitige Wirtschaftswachstum der Entwicklungsländer und eine technologische und energetische Revolution. All dies deutet auf eine Mineralienintensität in Menge und Vielfalt hin, die derzeit in der gesamten Nachhaltigkeitsdiskussion öffentlich und wissenschaftlich unterschätzt wird. Die Umweltauswirkungen der Produktion der prognostizierten Rohstoffmengen werden enorm sein, wenn keine Abhilfemaßnahmen in Richtung verantwortungsvollerer Prozesse umgesetzt werden. Das Ziel 12 der Nachhaltigen Entwicklungsziele (SDGs) geht auf diese Frage bis zu einem gewissen Grad ein, indem es eine Verringerung der Umweltbelastung mit einer Zunahme der industriellen Aktivität vorschlägt, geht aber nicht darauf ein, wie dieses scheinbare Paradoxon, die so genannte Entkopplung, erreicht werden kann. Verschiedene andere prominente Nachhaltigkeitstheorien fördern Richtungen, in die die Reise gehen kann. Es gibt jedoch keinen einzigen leicht zugänglichen und übertragbaren Rahmen, aus dem konkrete sektorale Aktionen und Interventionen abgeleitet werden könnten. Insbesondere im Bereich der Rohstoffe ist ein solcher Rahmen für eine systematische und systemische Bewertung von Produktionsprozessen erforderlich. Die Frage, die damit angesprochen wird, ist, wie die angestrebte Entkopplung der Umweltauswirkungen und der Verantwortungsvorschlag des SDG 12 in der umfangreichen Welt der Materialien systematisch so identifiziert werden können, dass sie in der heutigen Umwelt- und Verantwortungsdebatte von erheblicher Bedeutung sind und zu Lösungen führen.

Ziel dieser Arbeit war es daher, eine Analysemethode zu entwickeln, die eine solche systematische Entkopplungsidentifikation ermöglicht. Damit wurde ein konkretes, übertragbares Bewertungsschema für die Umweltverantwortung materieller Produktionssysteme entworfen. Es basiert auf der Zusammenführung verschiedener prominenter Nachhaltigkeitstheorien und den daraus gewonnenen Erkenntnissen, die als Basisanforderungen einen umweltbezogenen, zirkulären Ansatz mit Fokus auf einzelne Systemkomponenten und die planetarischen Grenzen als geeignete Indikatoren hervorbrachten. Eine Fallstudie mit dem Schema wurde mit dem hochrelevanten Zukunftswerkstoff Aluminium durchgeführt, die eine leicht zugängliche grafische Matrixübersicht über den Nachhaltigkeitsstatus des Werkstoffs Aluminium in jedem Prozessschritt ergibt. Sie zeigt genau auf, wo im Produktionsprozess Verbesserungen oder Veränderungen stattfinden müssen, um die Umweltbelastung zu verringern, und veranschaulicht so den Punkt der Entkopplung.

Content

List of Abbreviations

“,”	Comma[1]
Al	Aluminium
BAT	Best-available-technology
BAP	Best-available-practice
CFC	Chlorofluorocarbon
DMC	Domestic Material Consumption
EC	European Commission
EEA	European Environment Agency
EU	European Union
FSSD	Framework for Strategic Sustainable Development
GDP	Gross Domestic Product
GHG	Green House Gases
GSDR	Global Sustainable Development Report
HCFC	Hydrochlorofluorocarbons
HDI	Human Development Index
IEA	International Energy Agency
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
MF	Material Footprint
NASA	National Aeronautics and Space Administration (USA)
OECD	Organisation for Economic Co-operation and Development

[1] According to ISO 80.000 and the International System of Quantities (ISQ) a comma “,” is used throughout this thesis as a decimal separator and as the thousands separator a point “.”

PB	Planetary Boundary
RCP	Responsible Consumption and Production
SDG	Sustainable Development Goal
SWEIs	Social Wealth Economic Indicators
t	tonne, metric unit of mass equal to 1,000 kilograms (metric ton)
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UP	Unit Process
USGS	United States Geological Survey
WMD	World Mining Data

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1 INTRODUCTION

Society is currently facing a series of societal challenges, one of the most important ones being the strong global population increase and simultaneous economic growth of developing nations. Additionally, a technological and energy revolution is looming at the global doorstep. As our society is and will be a material one, all of this brings with it a mineral intensity in volume and variety that is currently publicly underestimated but also partially scientifically ignored in the whole sustainability discussion. The environmental impact of supplying the projected amounts of raw materials if no mitigation actions are implemented will be vast. Sustainable Development Goal 12 addresses this issue to some extent by proposing a decrease in environmental impact with an increase in industrial activity. It does not, however, address how this seeming paradox called decoupling can be attained. Various other prominent sustainability theories promote the environment as the basis of all societal (and) economic systems and point towards a direction in which the journey may take humanity. There is, nevertheless, no single framework that is easily accessible or directly addresses existing environmental issues in relation to sectoral actions that should be implemented. Especially in the raw materials field such a framework for systematic and systemic assessment of production processes from which interventions can be deducted is needed.

This thesis therefore aims at assessing and consolidating multiple prominent sustainability theories with a specific focus on SGD 12 as baseline in order to establish an assessment scheme that makes it possible to systematically assess materials as single system components in an environmentally relevant way, in a manner that allows for deduction of concrete actions once completed. The assessment scheme is designed in a way that identifies the exact decoupling space, as this is where impact of production can be reduced or ideally be cancelled out.

In this thesis specifically, after thorough analysis of the societal context and multiple sustainability theories and SDG 12 as base premise it was decided that an assessment scheme to be developed would need an environmental, circular approach and focus on single system components such as a single material. A planned outcome of the thesis is thus the development of an assessment scheme that can be transferred to life cycles of various materials to assess their environmental sustainability and responsibility factor. The system component Aluminium was selected as the material of choice and as the most relevant indicator framework applied in the scheme, the planetary boundaries were identified.

As such the thesis at first intensively deals with the societal context that it is embedded into to establish a broad understanding of how the assessment scheme to be developed is relevant. In chapter three a variety of very prominent sustainability theories are highlighted and their common understanding of sustainability notions filtered out. Chapter four is concerned with deducting the research question specifically from the lessons learned in the foregoing work. Chapter five then constructs the case for how and why the planetary boundaries as indicators and Aluminium as system components were chosen and explains how the case study is constructed and which methodology applied. Then further on in chapter six and seven, the indicators planetary boundaries and the selected system component Aluminium are highlighted and discussed in detail. After this in chapter eight, the specific production process of Aluminium is outlined and brought into relation with the planetary boundaries where possible. This serves as the basis for the case study in chapter ten and the following evaluation, discussion and conclusion in chapter ten.

2 Context of the Thesis

> Preservation of the environment, promotion of sustainable development and particular attention to climate change are matters of grave concern for the entire human family. No nation or business sector can ignore the ethical implications present in all economic and social development. With increasing clarity scientific research demonstrates that the impact of human actions in any one place or region can have worldwide effects.
>
> Pope Benedict XVI (2007)

2.1 The basis of human societal existence

The expression “societal challenges” is an omnipresent concept in today’s society, a society that is facing numerous of these societal challenges in its current development stage. Specific to local circumstances, these challenges range from the health status of the population, education, food supply and nutrition to digitalization, the green energy transition, new mobility concepts and many others. The basic underlying challenge, however, to all these specifically formulated challenges is a much more sophisticated one, namely how it can be ensured that every person on the planet has a minimum level life-standard that at the very least ensures sufficient nutrition, health, education and shelter.

In the way the societal system has come to function, a given minimum amount of wealth is required for somebody to have in order to be able to obtain a certain minimum life-standard. This implies that economic, or more specifically industrial activity, is needed in order to generate this wealth, from which then so-called wealth services can be consumed, like health care, education, sanitation, food, water and many more. The basis for this industrial activity is raw materials such as minerals and metals, which can be derived from the environment. “[T]hey form the backbone of modern economies and are key to providing wealth services to citizens around the globe such as housing, mobility and communications. Sustainability transitions such as the energy system transformation and megatrends such as digitization pose extra requirements on the world economy’s raw material supply” (Umweltbundesamt 2019). The raw materials industry and its downstream industry are therefore the backbone industrial sector of human wealth.

There is a specific interplay between *society and the economy*, *the economy and the environment* and *the environment and society* due to basic principles underlying each of these three “system stakeholders”.

To begin with society as system stakeholder, there are two concepts called **human development** and **human capacity** and there are indexes and indicators (the HDI - Human

Development Index and SWEIs - Social Wealth Economic Indicators) that measure this human development or human capacity. Human development is "is about expanding the richness of human life, rather than simply the richness of the economy in which human beings live. It is an approach that is focused on people and their opportunities and choices" (United Nations Development Programme UNDP 2020). Whereas GDP (gross domestic product) was invented to measure economic progress of a country it does not say anything about human well-being and development. Historically, the idea of "putting greater emphasis on employment, followed by redistribution with growth, and then whether people had their basic needs met" were the foundation for the human development approach and index (United Nations Development Programme UNDP 2020). Today, the "human status" in a society can be measured through the human development index HDI, which includes three indicators, namely life expectancy at birth (long life dimension), expected/ mean years of schooling (education dimension) and GNI (gross national income) per capita (standard of living dimension).

SWEIs similarly measure economic health but quality of life as interrelated factors, recognizing that both are prerequisites for robust businesses, economic competitiveness, and fulfilling lives. Human capacity in this sense is "the main ingredient for personal, business, and national success" (Gosh 2014: 19). The indicators are numerous, split in two groups (human capacity core indicators which measure human capacity/ input development and care investment core indicators which measure the national investment on all levels into care and the environment) and comprise dimensions such as caregiving (e.g.: time spent on unpaid care-work), education (educational attainment), health (e.g. maternal mortality rate), social equity (e.g. gender gap earnings), environment (e.g. carbon dioxide emissions) or government investment in care work (e.g. percentage of GDP for public funding for childcare and early education) as well as many more. "SWEIs provide building blocks for a more sustainable and caring economy. They demonstrate the substantial financial return from caring for people and nature - and the enormous costs of not doing so. They point the way to more effective government, business, and civil society investments." (Gosh 2014: 19)

Both of the measuring systems clearly derive human well-being from economic activity although clearly stating that by itself it does not yield the intended return. Therefore, the underlying basic principle for the social system stakeholder is that economic activity alone does not derive the desired minimum wealth alone but system relevant factors need to be leveraged correctly. The economy is the basis for being able to get to this leveraging point in the first place, however.

Concerning the economic system stakeholder, the gross definition of the economy comprises activities such as production, distribution and trade. Furthermore, consumption of goods and services by market participants as well as monetary transactions are part of the activity. "Economic activity is spurred by production which uses natural resources, labor and capital." (Brunner 2019). **Industrial activity** itself can thus be defined as the natural resources consuming part of the economic production activity, where the economy consumes the environment according to the illustrated model. In its broadest sense thus "the economy is defined as a **social domain** that emphasizes the practices, discourses and material expressions associated with the production, use and management of resources." (James, P. et al. 2015). Furthermore, there are three sectors of the economy: the primary sector is the extraction of raw materials, agriculture, mining, fishing and forestry or what can be called the extractives industry, the secondary sector with industrial production and construction and the tertiary sector with services, education and tourism (Fisher 1939). Even in this model the primary sector is defined as the one which first starts the economic chain by utilizing resources from the earth and all following sectors depend on it. It becomes clear that the economy system stakeholder relies on raw materials as underlying principle and that societal wealth thus depends on raw materials. It further becomes clear that the economy and as such society for wealth generation, which both rely on raw materials, thus completely rely on the environment.

Finally, the environmental system stakeholder provides something to society and the industry that is defined as **natural capital**. It "can be defined as the world's stocks of natural assets which include geology, soil, air, water and all living things. It is from this natural capital that humans derive a wide range of services, often called ecosystem services, which make human life possible" (The Biodiversity Consultancy 2017). There are four categories of ecosystem services and some may seem very obvious, such as for example the (1) *provisioning service*. It provides humans with food, clean water, fish, wood, fibers, minerals, raw materials for medicines and more and seems so obvious to society because its basic life and economic activity is based on these provisioning services. A less obvious ecosystem service but the one that creates the basis of all environmental existence is the (2) *supporting service*: It is responsible for soil formation, nutrient cycling, biodiversity, photosynthesis, habitat etc. Another one is the very important (3) *regulating service*: It regulates natural environmental dynamics and thus stabilizes the system by regulating and controlling temperatures, flooding, carbon, erosion, disease, biological decomposition, pollination and many others. The last service solely exists in relation to the human existence as "cultured beings" and it is called the (4) *cultural service*.

It provides society with services such as education about nature, room for recreation and leisure, aesthetic added-value, spiritual refuge and relaxation (World Forum on Natural Capital 2017).

Society and its interconnected industrial activity for wealth generation seemingly rely on the environment and at the same time consume the environment alike (Figure 1). The environment system stakeholder with its natural capital thus provides, supports and regulates and adds cultural value for societal and industrial existence. Without its services none of the societal and industrial activities would be possible. However, it also becomes clear that although, on the one hand, the two system stakeholders economy and society depend on and consume the environment, on the other hand, the environment is in no way dependent on the other two stakeholders.
The question now arises to which extent society with its industrial activities already consumes the environment? Is this consumption bearable for the environment?

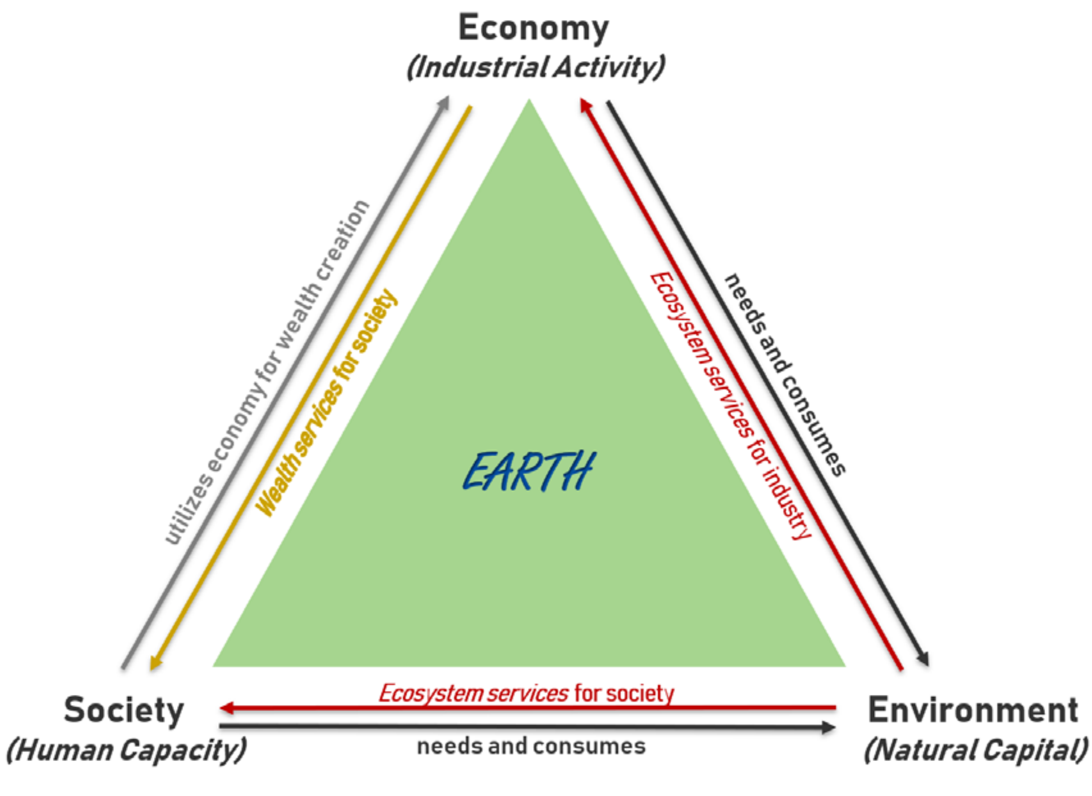


Figure 1 - Societal and environmental interactions

2.2 The societal and environmental status quo

Today's world is characterized by environmental pressures, to an extent, which humans have never been confronted with before due to a few very simple reasons. First of all, population growth has exploded over the past 120 years. When over the history of humankind population growth was modest, reaching a total of about 190 million people in the year 0 and slowly but a little bit faster continuing this trend by adding 410 million people over a period of 1.700 years to reach a total of 600 million, the growth somewhat accelerated between 1700 and 1800 when more than double of that amount was added to reach 990 million in 1800. In only another century the growth reached 1,65 billion people. Since then, in a really short 120-year period the population has increased by unbelievable 6,5 billion people. This stark increase becomes more tangible through Figure 2.

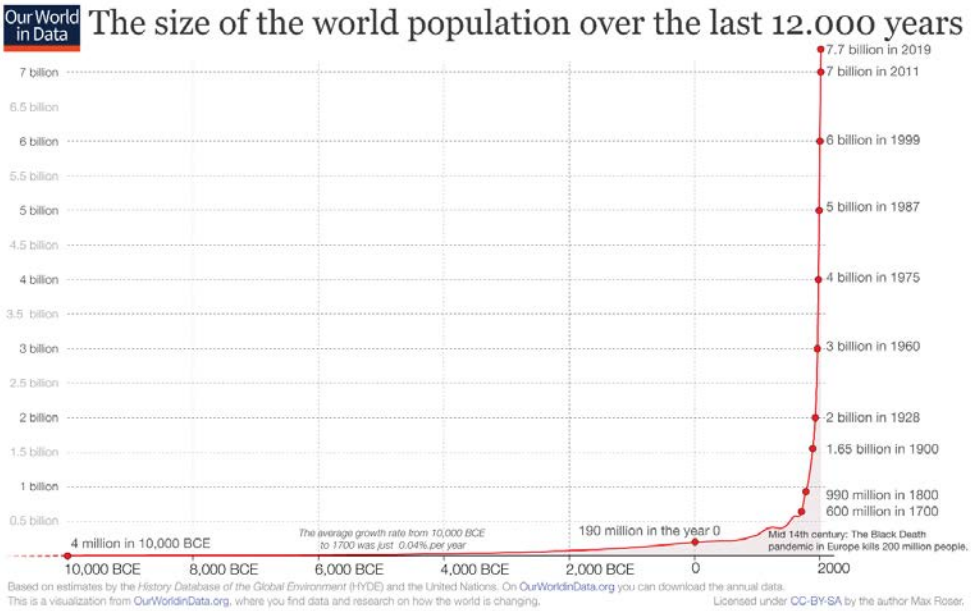


Figure 2 - World population growth (Roser 2013)

Humans went into the industrial revolution in 1900 with only a fraction of the people that live on the planet today when at the same time, however, industrial activity has been proportionately expanding. Close to 8 billion people live on the planet today, all of them striving for economic well-being for a better social life. The ecological reality of this is that human socio-economic activity cannot easily be absorbed by the environment anymore because it far exceeds its capacities. When the economic system was invented some 100 years ago (Raworth 2018) its industrial activities were insignificant to the planet (Daly 2015). They were minor compared to the existing large ecological reality and the environmental impacts were thus easily absorbed (Figure 3). Back then there was a total world population of 1,6 billion of which only a fraction were actually driving industrial activity. Today society still lives under the impression that it lives in such an empty world, that nature is endless, when in truth the world has become very full, with a human-nature ratio that does not leave much space. This leads not only to land use and land planning issues, but to unprecedented environmental pressures.

> In a little over two generations […] humanity […] has become a planetary-scale geological force. Hitherto human activities were insignificant compared with the biophysical Earth System, and the two could operate independently. However, it is now impossible to view one separate from the other. The Great Acceleration trends provide a dynamic view of the emergent, planetary-scale coupling between the socio-economic system and the biophysical Earth System. (Steffen et al. 2015a).

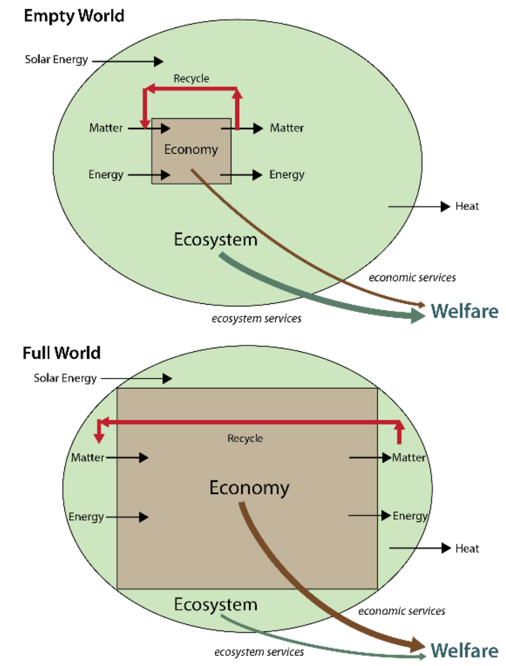


Figure 3 - Economics for a full world (Daly 2015)

The Great Acceleration describes the phenomenon connected to the rapid population growth in the last century, more specifically the period from the 1950s until today in which humanity has had an exceptionally high negative impact on the biosphere through human driven activities.

As can be seen in the most common socio-economic and earth system trends, everything has been increasing, not only GDPs and wealth, but CO_2, methane, ocean acidification, surface temperatures, domesticated land, water use, fertilizer consumption, international tourism etc. (Figure 4).

According to the last Intergovernmental Platform on Biodiversity and Ecosystem Services IPBES biodiversity report (Intergovernmental Platform on Biodiversity and Ecosystem Services 2019: 25) 75 % of all planetary terrestrial surface has been altered by humans already,

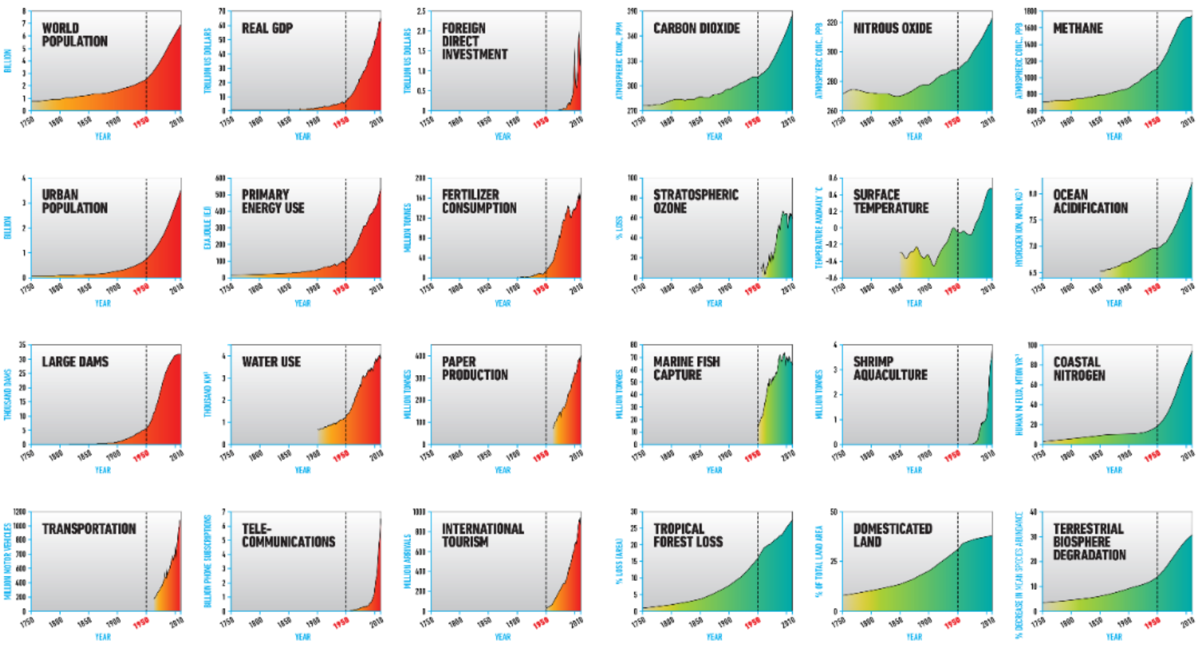


Figure 4 - The great acceleration trends (Steffen et al. 2015a in: White 2019)

85 % of all wetlands have been lost and 25 % of all species are endangered, with a risk of extinction within the next 10 years. This equals about 1 million species. The report states many other such uncomfortable truths, pointing out that most of these trends have started or accelerated since the 1900s.
This human driven impact and its implications even brought about a whole new geological age called the Anthropocene, an age in time in which human driven activity is mightier than geological force in driving ecological and planetary change. This age was preceded by the Holocene, an age which was incredibly favorable in terms of climate for all of human development and which probably was the reason humans developed so incredibly well throughout their history. All of this has been clearly monitored (Steffen et al. 2015a, United Nations Environmental Programme UNEP 2012) and nothing similar has ever happened in the history of the planet.

Since the start of these developments different groups of humans have been driving this development alternatingly in pursuit of social and economic development. According to Steffen et al. "in 2010 the OECD countries accounted for 74 % of global GDP but 18 % of the global population" (Steffen et al. 2015a). Inherent in this data is the fact that "most of the human imprint on the Earth System is coming from the OECD world." (Steffen et al. 2015a). This trend seems to be changing, however, as indicators start to stabilize in the OECD world and most of the increase of activity and imprint is now found in the fast-growing economies of the BRICS countries and the rest of the world. The human imprint, as it brings along negative effects for the planet, it results in positive dynamics for individual human lives, however:

> Since the mid-twentieth century, global economic development has already helped many millions of people worldwide escape deprivation. They have become the first generations in their families to lead long, healthy and educated lives, with enough food to eat, clean water to drink, electricity in their homes, and money in their pockets and for many, this transformation has been accompanied by greater equality between women and men, and a greater political voice. (Raworth, 2018: 45)

It must be welcomed that the social development of the world is heading in such a great direction as it is well known from the past that the world used to be a mostly unfavorable place for the majority of human realities. The utopia of Cockaigne has already become a reality for most people today (Bregman 2018).
In terms of enabling this social and economic trend and enabling this population growth, the environment has provided industrial activity an ever-increasing amount of raw materials to supply the population with biomaterials, fossil energy, metals and construction materials. Especially demand and supply for bio materials, for food and construction materials for shelter

have been strongly increasing. Raw materials demand directly corresponds to both, population growth (Figure 5) and gross national incomes (Figure 6).

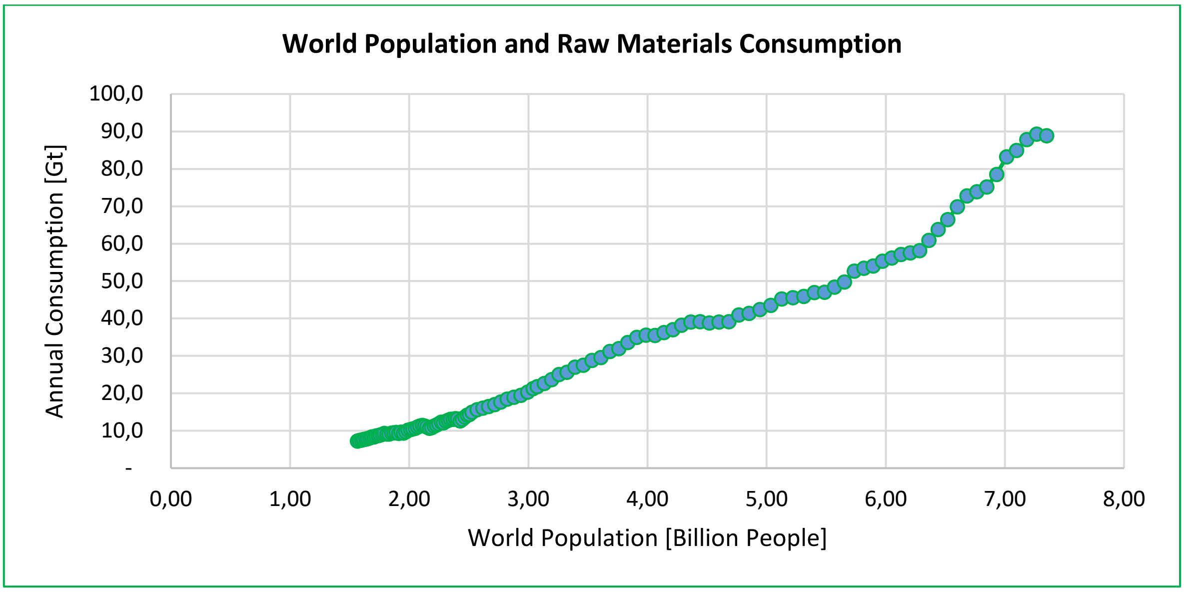


Figure 5 -World population and raw materials consumption (based on the data of Krausmann et al. 2018)

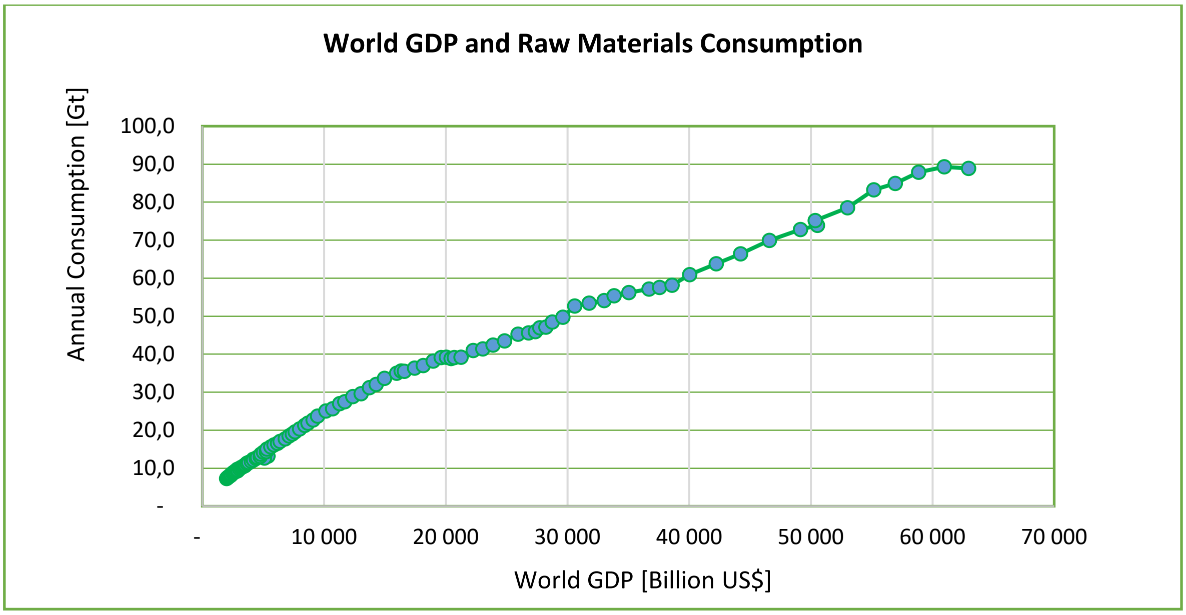


Figure 6 - World GDP and raw materials consumption (based on the data of Krausmann et al. 2018)

Regarding mineral raw materials, specifically metals, the types of elements that society has been extracting from the earth has also increased. When in 1700 merely 6 elements were used, more than 50 are being utilized today. The extractive industries are thus confronted with many challenges regarding sustainable production and supply of raw materials as demand for raw materials in amount and type is constantly increasing. However, the material available in the human environment for recycling is limited due to in-use stock and other constraints such as thermodynamics and required energy input as well as technological developments and complexity of product design. This causes ever changing supply patterns that need to be swiftly reacted to.

Whether considered to be good or bad, “[t]he dominant feature of socio-economic trends is that the economic activity of the human enterprise [overall still] continues to grow at a rapid rate” (Steffen et al. 2015a: 88) and there is no sign of a reversal (Burton 2016). Additionally, population growth is also still drastically increasing, projected to stabilize at around 10,9 billion only in 2100 (United Nations Department of Economic and Social Affairs, Population Division 2019). Furthermore, raw materials demand has strongly increased across all types leading to unprecedented extraction, supply and sustainability issues. As for the moment population and economic growth cannot be reversed, the question that seems to leave everyone pondering is how to relieve the environment despite these trends. Specific to this thesis is the question, how can we relieve environmental pressures in the primary economic sector that provides all economic and social development with its basic mineral raw materials?

3 SUSTAINABLE DEVELOPMENT THEORIES - THE ROAD TO SUSTAINABLE INDUSTRIAL DEVELOPMENT

> For an engineer who has been given the task to construct a machine, it is obvious that atoms will not be created or disappear. But in the planning of the industrial society, it seems that one expects value matter (resources) to be created out of nothing and unwanted matter (waste) to disappear into nothing. Furthermore, the industrial society still lives with the antiquated conception that society is small compared to nature. (Holmberg 1995)

In order to relive the environment of the given pressures and develop a strategy on how the mineral raw materials sector can develop more sustainably, the first obvious thing to do is to turn to general sustainability theory to find out what it can do for the endeavor.

3.1 General Sustainability Theory

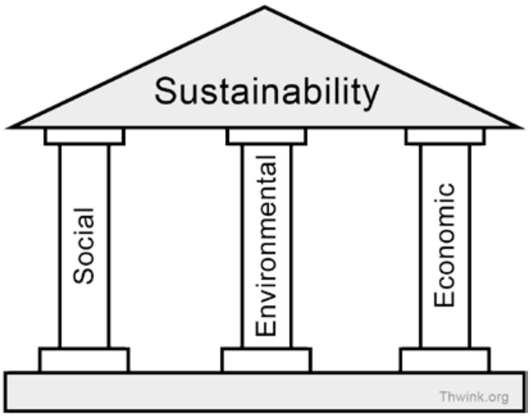


Figure 7 - The three pillars of sustainability (Chokshi 2017)

The one model of sustainability that everybody knows is the three-pillar model (Figure 7), sometimes also depicted as three intersecting equal circles. It seems like an omnipresent understanding of sustainability, placing ecology, economy and social matters at its core and as three equally valid foundations of the concept that are, unlike the model in Figure 1, seemingly not interdependent. It is not clear anymore where this model really comes from but according to Purvis (Purvis et al. 2018) the model evolved from the 1960's throughout to the 1980's out of several different schools of thought which were often competing with regards to a conceptualization of sustainability. What they all had in common, however, was the shared and "broad critique of the (then) economic status quo, both from ecological and social perspectives." In 1987, Purvis (Purvis et al. 2018: 692) concludes, the UN Brundtland report and the subsequent Rio process institutionalize "sustainable development" as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations Commission on Environment and Development 1987) and with it an "understanding placing economic growth as the solution to ecological and social problems" (Purvis 2018: 692). There is extensive discussion on the three-pillar model, its dimension and integration in the past and recently (Dixon and Fallon 1989, Giddings 2002, Dawe and Ryan 2003, Keiner 2005, Caradonna 2014, Petrişor 2014). However, it is further criticized that the framework is too empty and that “a consequence of the lack of rigor in the theoretical underpinnings of sustainability and the three-pillar paradigm is the difficulty in producing operational frameworks for the characterization of sustainability which remain rooted in theory. Such applications would necessarily have to be context specific, requiring both spatial and functional boundaries“ (Purvis et al. 2018: 692). Therefore, in a scenario in which the sustainable development or the sustainability quality of a certain process or technology has to be evaluated this model does not suffice. It could serve as the basis for developing a contextually specific framework guiding this framework in a suitable direction when populating it with specific functional and spatial boundaries as well as relevant indicators.

3.2 Weak versus Strong Sustainability

One thing the mentioned general sustainability model does not is to acknowledge that the environment is in fact the service provider for industrial and social activity as all three pillars are equally valid. In a similar manner, there is a discussion about weak and strong sustainability. According to weak sustainability theory, all three pillars of the model are equally important. The theory of weak sustainability rests upon the assumption that “we can purchase man-made capital (e.g. technological development, increments in income per capita etc.) with infinite Natural Capital” (Abreu 2020). There are three underlying assumptions (Neumayer 2003):

- Natural resources are and will remain abundant.
- Man-made resources can substitute natural resources.
- Technological development can overcome natural resource scarcity.

Weak sustainability thus believes that both natural capital and man-made capital can be equally valued. This theory allows for the depletion of natural resources as long as general production is maintained. In the context of discussions revolving around resource scarcity this concept seems little realistic.

Strong sustainability (Ayres 1998, Goodland and Daly 1996, Hediger 1999, Neumayer 2003, Dedeurwaerdere 2014, Pelenc et al. 2015, Cardoso de Oliveira Neto et al. 2018, Buriti 2019), on the other hand, is defined as having the environment as basis of economic and societal activity as a non-substitutable factor (Figure 8). Pelenc et al. summarize in their Brief for the Global Sustainable Development Report GSDR 2015 the key facts of why natural capital is not substitutable according to various strong sustainability proponents.

- „Firstly, there is a qualitative difference between manufactured capital and natural capital. Manufactured capital is reproducible and its destruction is reversible, whereas the consumption of natural capital is frequently irreversible (for instance species extinction).”

- Secondly, since manufactured capital requires natural capital for its production, it can never be a complete substitute for the biophysical structures of natural capital (Ekins et al. 2003).

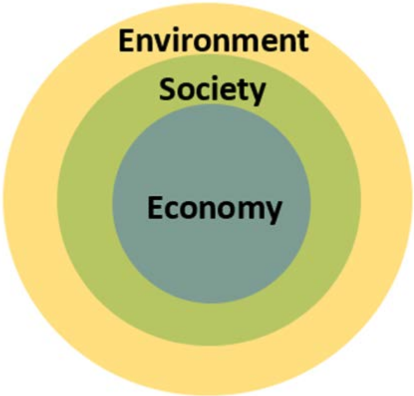


Figure 8 - The environment as basis of the strong sustainability concept

- Thirdly, an increase of future consumption is not an appropriate substitute for losses of natural capital (Dedeurwaerdere 2014). The following example helps to grasp the point: “Today’s generation cannot ask future generations to breathe polluted air in exchange for a greater capacity to produce goods and services. That would restrict the freedom of future generations to choose clean air over more goods and services” (United Nations Development Programme UNDP 2011: 17).”

Besides all discussions about whether or not economic growth may be good or bad and whether a new economic model should be established (Czech and Daly 2004, Kerschner 2010, Georgescu-Roegen in Bonaiuti 2011, Blauwhof 2012, Czech and Mastini 2020), it is a given fact that currently the established model is the one based on growth. In this growth model it should nevertheless be acknowledged that the environment is in fact the basis of human existence and industrial activity and that once the environment has reached its final capacity there is nothing more positive to gain for society.

3.3 The Planetary Boundaries

In fact, in recent scientific history a group of researchers of the Stockholm Resilience Center, (Rockström et al. 2009) has established a framework called *The Planetary Boundaries*. Within this framework a set of naturally existing limits were identified that are responsible for keeping up the ecosystem equilibrium (Figure 9). The planetary boundary framework “defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth System.” Overstepping them may lead […] to the beginning of global ecosystem imbalances, the results of which are unknown. Crossing these boundaries brings the risk of “irreversible and abrupt environmental change”, making our planet less habitable for humans (Steffen et al. 2015a, b). The current operating status is that indeed two of the boundaries have already been transgressed, namely genetic diversity inside the category biosphere integrity, as well as nitrogen and phosphorus accumulation in the category biochemical flows. Monitoring the boundaries over the last 10 years has shown that we are directed towards transgressing even more boundaries. These defined biophysical processes that have been identified to be responsible for keeping up the planetary environmental equilibrium should as such thus be guiding indicators in all industrial processes. No industrial process should contain any action that contributes to the increase towards transgression as it will destabilize our environmental basis for the future.

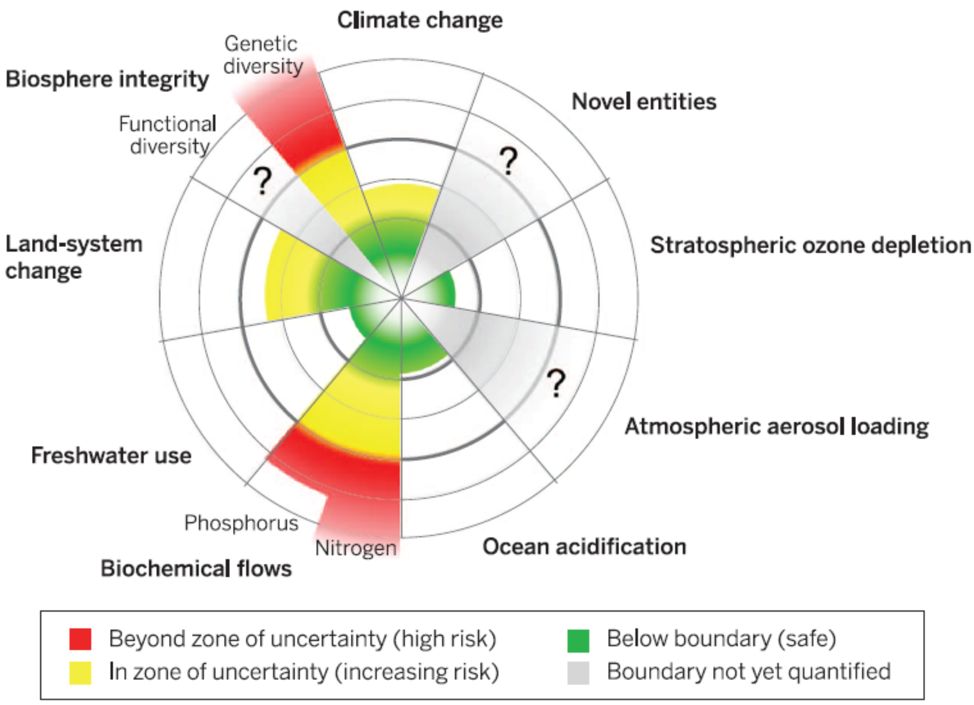


Figure 9 - The nine planetary boundaries (Rockström et al. 2009 in Steffen et al. 2015b)

3.4 The Sustainable Development Goals

In the search for suitable frameworks to define a process for sustainable raw materials supply a very prominent and not very old framework also comes to mind. On 25 September 2015, the 193 UN member countries adopted a set of integrated, indivisible and very ambitious goals to balance human prosperity while protecting the planet as part of a new sustainable development agenda, thus following the successful Millennium Development Goals of 2000 (United Nations General Assembly 2015). Within the resolution called “A/RES/70/1 - Transforming our world: the 2030 Agenda for Sustainable Development”, now colloquially called the Sustainable Development Goals (SDGs), of which there are 17, countries mobilize efforts to balance the environmental, social and economic dimensions of human development to ensure a sustainable future for all people by decoupling industry’s environmental impact from its economic activity.

This consists essentially of the "lasting protection of the planet and its resources", a "world free of poverty" and "shared prosperity" (United Nations General Assembly 2015: 3), but also "sustained, inclusive and sustainable economic growth", hence also reflecting the three pillars of sustainability on an equal level as an essential factor for the ability to achieve prosperity. As the three pillars are equally represented it seems as though the underlying notion of the SDGs is following a weak sustainability approach. After all, the agenda follows the original concept of the Brundtland report "Our common future" (United Nations World Commission on Environment and Development WCED 1987) in which economic growth is seen as the solution to achieve human well-being and solve environmental problems.

Within this proposed economic growth development of the SDG agenda, the promotion of policies for "(1) sustainable industrial development, (2) universal access to affordable, reliable, sustainable and modern energy services, (3) sustainable transport systems, and (4) quality and resilient infrastructure" is urged (United Nations General Assembly 2015: 8) which essentially reflects the environmental pressures defined by the UNEP (United Nations Environmental Programme UNEP 2012: 5), where it was stated that "population growth and economic development are seen as ubiquitous drivers of environmental change with particular facets exerting pressure: energy, transport, urbanization and globalization". The amounts of mineral resources needed for this proposed economic development will be enormous as they form the basis of all these mentioned systems, as has been established in chapter two already. "This [is] mostly […] driven by increasing demand in developing regions, where up to 3 billion people will move from low to middle class levels of consumption by 2030" (European Innovation Partnership on Raw Materials EIP 2018: 11). Supply of raw materials will have to match that demand. Statistics confirm this with raw materials demand having increased from 43 Gt in 1990, to 92 Gt in 2017 and with current trends and no concerted political action a projected growth to 180 Gt in 2050 (European Innovation Partnership on Raw Materials EIP 2018: 12).

> The outlook is for further growth in material use if countries successfully improve economic and human development, and are able to raise living standards and combat poverty. Assuming that the world will implement similar systems of production and systems of provision for major services – housing, mobility, food, energy and water supply – nine billion people will require 180 Gt of materials by 2050, almost three times today's amounts. (United Nations Environmental Programme UNEP 2016).

Without abrupt changes in technologies and behavior an increase in demand seems unavoidable. But not only the developing countries are in high demand of raw materials.

According to Krausmann a vast amount of the infrastructure and stocks that will be used in 2050 is not yet built as "The scenarios driven by economic activity are based on economic growth foreseen in the IPCC-SSP2 scenarios and result in strong growth of material stocks until 2050" (Krausmann et al. 2020: 5). The reasons for this apart from essential development in developing countries are that many developed countries are going through a rapid change in technologies which makes it necessary to exchange much of the existing infrastructure. Additionally, these technological improvements result in a higher complexity of materials in product compositions, which results in an increase of the variety of needed raw materials. Therefore, no matter if OECD, BRICS or developing nations, all of them will need increasing amounts of raw materials for development and to succeed in implementing the sustainable development goals.

Furthermore, population and GDP growth are not the sole contributors to an increase in raw materials demand in the future, also the shift to renewable clean energy technologies specifically will result in a so far underestimated mineral intensity. These technologies require much more materials than the fossil-fuel based electricity generation technologies. The World Bank Group has identified 17 specific minerals that will be in high demand until 2050 and has established various scenarios that all illustrate this. In their report it also becomes clear that it is impossible to cover the demand from recycling alone due to various factors such as for example lack of scrap availability versus increase in demand (World Bank Group 2020). All this will require a close scrutiny of the entire supply chains of these materials but also a thorough analysis of the production technologies and production and use life cycles of these materials (and others) in order to ascertain that society does not produce clean technologies in an irresponsible and dirty way thus cancelling out the well-intended climate friendly results.

3.5 Sustainable Development Goal 12

The Sustainable Development Goal 12 "Responsible consumption and production" with its target 12.2 - *by 2030 achieve sustainable management and efficient use of natural resources* is one of the SDGs. It seems to have a relevant incremental message and guiding quality with regards to the facts raised above. According to SDG 12, the principle of decoupling economic growth from resource use and environmental impact is the key to this seeming dilemma of environmental sustainability combined with economic growth. "Decoupling means two things: decoupling economic growth from resource consumption (**"resource decoupling"**) and from environmental impacts (**"impact decoupling"**)" (Figure 10) (United Nations Environmental

Programme UNEP 2015: 28). The SDG concept thus promises that less resources will be used and environmental impacts will be reduced despite economic growth.

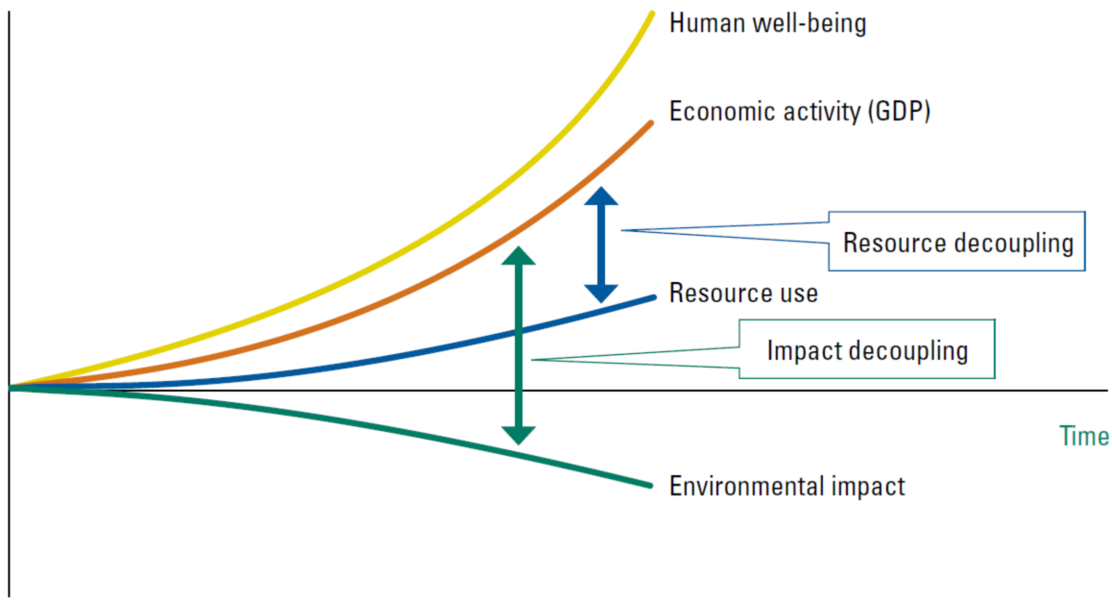


Figure 10- The two principles of decoupling (United Nations Environmental Programme UNEP 2011)

> One major challenge associated with moving towards sustainability in production and consumption activities is the high and rapidly growing use of natural resources (e.g., materials, energy or land) required in the process. Without dealing with this issue, sustainability cannot be attained, and neither can the relevant SDGs. (The World in 2050 2018: 58)

The UN states in its resolution that the concrete follow-up and review of the SDG implementation is voluntary and country-led. Methodologies, data sources, indicators etc. have yet to be developed on a national level as it is important to take into consideration the different national realities that exist and what these mean for goal implementation (United Nations General Assembly 2015: 31-32). In contrast to this, the goals address global problems and at a more in-depth glance. It seems that for some of them it may not be useful to solely be tackled on a national level, especially SDG 12. It is directly related to the underlying raw materials supply issue as mineral raw materials production supply chains are globally interconnected. This is due to the fact that today the system of mineral raw materials supply is not dependent on local downstream industries, as used to be the case in history when transport cost was an issue. Today mineral raw materials can be shipped cheaply to whichever location offers the cheapest refining and processing options. Transport at current cost is thus not a limiting factor in the economic value-adding chain and the chain of a single material is usually spread across the globe. Additionally, mineral raw material deposits are not evenly distributed across the planet, as some locations are more abundantly endowed with mineral raw materials than others and the types of mineral raw materials vary as well. This means that a single country cannot mine all its needed raw materials inside its own territory, which makes countries dependent on each other for supply. The challenge of such a globally spread und sustainably designed mineral raw materials supply chain is thus not a singularity to be treated solely on national levels by those countries who happen to address the challenge. Other countries may not do so in the same way or intensity or not at all. One single country can only improve so much in its small part of a global mineral raw materials value chain. Data show for example that although many countries are successful in lowering their CO_2 emissions nationally they are still large importers of CO_2 emissions through their raw materials and product imports (Steinbach et al. 2016: 81). This mechanism of avoiding non- sustainable practice inside the proper territory and yet still not being able to avoid the problem because of global supply chains perfectly illustrates the global interconnectedness and interdependency of trade flows. As a matter of fact, emissions do not stop at national borders and therefore this issue thus needs to be tackled on a globally integrated scale. If mineral raw material supply chains are to be made sustainable, they need to be tackled material chain by material chain from a holistic and integrated perspective. Furthermore, if decoupling is taken seriously it can only be realized either if there is a step change in existing environmental unfriendly technologies, processes or practices or if irresponsible materials by nature are abolished or substituted.

The questions thus arising are whether or not single materials are or can be produced in a manner that make global supply chains entirely sustainable and not just individual parts of those chains in countries or companies who care more than others? To which extent are current best available technology levels, supply chain management practices and sustainability standards implemented in the industry throughout the entire production chains of single materials? If all materials were produced sustainably throughout their cycle this would enable the industry to grow in a way that will in fact decouple its ecological impact from its economic activity.

The UN and EUROSTAT have developed indicators to measure the progress of implementation of SDG 12.2 inside the EU which are directly related to material consumption and production.

UN indicators (2) (United Nations Statistics Division 2019a)

- **Indicator 12.2.1:** Material footprint, material footprint per capita, and material footprint per GDP
- **Indicator 12.2.2:** Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP

Eurostat indicators (4) (Eurostat 2018: 219)

- **Ratio of resource use**
    1. materials to GDP
    2. energy to GDP
- **Harmful environmental impacts of**
    3. consumption of toxic chemicals
    4. emissions related to transport

These indicators, however, only measure quantitative outputs, therefore mirror the concept of "resource decoupling" in terms of quantities. The idea behind this seems to be growing the economy with less material input than before. There is a variety of approaches that try to measure the sustainability level of production at different stages and from various angles. There are e.g. also UN indicators that measure compliance with certain environmental frameworks (United Nations Statistics Division 2019b, European Commission 2019c). The World Bank Group tries to measure progress on SDG 12 annually but focuses very much on recycling of municipal waste (World Bank Group 2017, 2018). There are scientific approaches and projects for indicator development (Krajnc and Glavič 2003, Koltun 2010, Kim et al. 2012, European Environment Agency EEA 2016), however, they are all neither holistic in terms of encompassing the entire material cycle nor are they in any way easily accessible for decision makers or anyone else not scientifically involved in the subject matter.

These indicators do not in their nature reflect the concept of "impact decoupling", namely the environmentally relevant quality aspects of production technologies, processes or practices of globally spread raw materials value chains. Reduced output of a production process (less material) does not automatically result in a more sustainable process. Various other indicator literatures show as well that the main concern is always the amount of materials moved in terms of import and export which always results in *domestic material consumption* (DMC) or *material footprint (MF)* indicators (Calatayud and Mohkam 2018, Wiedmann 2013).

The question is thus how can this relevant SDG 12.2 be populated with a framework that allows for analysis of raw materials value chain production processes in terms of their environmental quality, thus their "impact decoupling" potential? Which qualities do these processes need to have and what are relevant indicators to measure these qualities? Another question is how can such indicators be easily comprehensible for everybody?

3.6 Circular Economy

One vision for sustainable production practices that has been evolving over the past few years is that of the circular economy (European Commission 2019a and 2019b, European Parliament 2018, Ellen McArthur Foundation 2017, Kirchherr et al. 2017, Korhonen 2018) in which the common understanding is that materials do not ever go to waste but move in circles through the system forever as they are recycled over and over again. Its basic approach breaks down production cycles for single materials. For proponents of the circular economy approach as a solution to the resource supply challenge a few misconceptions about it have to clarified, however, as this approach has so far only worked to a certain extent, unlike popular perceptions that it is a finished and functioning construct.

- "Modern and developing societies have an enormous amount of raw materials stored as **"in-stock use".** This creates a delay of up to 100 years for different materials before they are available for recycling. "As most resource flows end up in stocks, and much of the remainder is used dissipatively, e.g. for food and energy, the potential to close material loops or cycles is limited" (The World in 2050 TWI 2050: 59) Today's low recycling rates are not always an expression of our lacking will for recycling but a consequence of the rather long use of materials as well as the increasing overall consumption of products and services.
- Recycling and extraction of substances from waste requires **energy**, which increases with the percentage of recovery in an exponential way. If the extraction percentage is above a certain value then this results in the need for an enormous amount of additional energy. The production of this energy would require more raw materials than we extract from the waste.
- The recycling of raw materials from waste often produces fresh material slightly or very different from primary raw materials, not due to improper recycling technologies but because the laws of physics set natural limits. Following the circular economy concept, it is necessary, however, to merge the two raw material flow streams to provide raw materials sustainably with the needed **qualities** for the emerging technologies." (Moser and Feiel 2019)
- Any production process of a material, any consumption dynamic and any recycling method is connected to **material loss**. The most inevitable material loss is entropic dissipation, the "gradual erosion and dispersion of material components into the environment into a one-way flow of low entropy usefulness to high-entropy waste"

(Daly and Farley 2011: 39). Therefore, it is necessary to introduce primary materials into the circle to keep it the same size, as otherwise the material loss gradually decreases the total amounts of materials in the cycle. Furthermore, it is necessary to provide primary materials for the newly needed materials types that are not available in the human environment for recycling but are triggered by technological development as well as provide supply for the general demand increase. Generally, it must also be noted that the amounts of the materials leaving the system will rarely ever exactly correspond to the amounts needed for demand.

In addition, the Circular Economy approach neglects the facts that every step of material flow from the primary sources along processing, over production and finally the consumption of goods, has an impact on the economic, ecologic and societal pillar of sustainability. Even “ideal 100 % closed” material flow systems might create impacts that push the environment beyond the planetary boundaries. If material flow systems are too big, they cannot sustain on the long run.

Despite all these issues that need to be solved, one thing is certain: the circular economy approach has led science to look at materials in their individual production and consumption and reproduction and re-consumption path. This is a useful approach in order to determine how materials flow through the system, delineate the materials’ capacities and limits, functions and applications, its combination capacity with other materials in terms of application and their recyclability. Moreover, it shows the origins and final destinations of the materials, the directions of the primary and secondary material flow, how efficiently the materials flow through the system, where they are locked up for which periods of time and where they are lost.

In order to design future innovative, low impact material flow systems, research has to identify the sustainability impacts of every step of material flow from the sources over production to the use of products and develop a quantification system that allows the overall classification of materials in terms of their impacts. Such an analysis and material impact-based quantification approach would form the basis for a future selection of low impact materials and the design of material cycles that are sustainable on the long run and keep our environment within the planetary boundaries.

3.7 Ecological Economics

According to Ecological Economics (EE) the economy is an open subsystem of the closed “Earthsystem”. “This system is finite, nongrowing and materially closed, although open to solar energy.” (Daly and Farley 2011: 15) There is an optimum scale between the two. As opposed to regular economics it does not see the economy as the whole and closed system. Also, other than the SDGs, EE promotes development without growth as sustainability paradigm. Growth in this sense is defined as an increase in throughput through the open economic subsystem, throughput being “the flow of natural resources from the environment, through the economy, and back to the environment as waste” (Daly and Farley 2011: 6). Growth therefore cannot happen indefinitely due to the limited carrying capacity of the Earth. When economies grow, they do not only grow on paper and digital graphs on the stock market, they actually physically grow and take up more space, need more throughput and thus cause more and more impact. Hence, “physical growth encroaches on other parts of the non-growing finite whole, exacting a sacrifice of something – an opportunity cost, economists would call it” (Daly and Farley 2011: 16), which in this case is the environment. However, the end of growth does not imply the end of development according to Daly. It merely implies “qualitative improvement in the ability to satisfy wants (needs and desires)” which can be translated as efficiency. This approach seems reasonable for already developed economies, however, seems hard to put into the context of the growing population and developing economies, a question addressed by Kerschner who concludes that based on Daly’s theories and the history of the de-growth movement “economic degrowth in the global North (meaning the developed countries) provides a path for approximating the goal of a globally equitable [steady-state economy], by allowing some more economic growth in the South (developing countries)” (Kerschner 2010: 549). This addresses the question of distribution of resources among different individuals as a large portion of society is living in miserable poverty while other in overflowing wealth. Distribution in this sense is a question of sustainable consumption.

Concerning throughput EE argues that according to the second law of thermodynamics, the entropy law, it is possible to recycle materials but never to 100 % as energy, by this law, is not recyclable, at least it always takes more energy to do the recycling than the amount of energy that can be recycled. Recycling in general is thus “a little circular eddy in the linear flow of the throughput river” (Daly and Farley 2011: 31). It is argued that by implementing more efficient technologies as well as an improvement of human priorities throughput can be reduced. Therefore, efficiency and frugality together are the solution. It needs both because efficiency does not help if the effect of the higher efficiency of a product or service is annihilated through then buying more of the products or increasing the use of the service. To be frugal it is important to understand what price we have to pay or in other words which opportunity cost is inflicted on us for an increasing throughput through the system. Already humans have an “ecological footprint“ that is 30 % higher than the reproductive capacity of the planet (Daly and Farley 2011: 35).

3.8 Transformations to Achieve the SDGs

“Transformations to achieve the Sustainable Development Goals” is a report prepared by “The world in 2050 initiative” (The World in 2050 TWI 2050). It aims at pointing out the needed transformations of the societal systems to achieve the 2030 agenda. The authors see the extensive use of resources anchored in end use and consumption patterns of society and associated improvements in efficiency and reductions in waste offer the largest ‘upstream’ systems leverage effect (The World in 2050 2018: 59). In the report society is put at the core of the sustainability transformation and it is argued that only through changes in human mindsets, societal structures and human behavior change can be brought about (The World in 2050 2018: 37). This reflects the EE notion of frugality but omits the efficiency paradigm.

According to the report it is even crucial in consumption questions to “disentangle the resource efficiency of end-use and consumption patterns” (The World in 2050 2018: 81).

The resource (energy) needs (consumption)

- service level demand – a trip/ is a trip needed at all?
- individual service choice (which service is more efficient for customer) – car/ public transport
- service efficiency of usage (is service intrinsically efficient) – car/ car-pooling/ car sharing greater usage efficiency, is a car needed at all?
- technological (energy) efficiency of the service (e.g. a transport vehicle)
- energy source used for the service

These questions seem relevant in a strategic discussion around whether certain products are needed or not and how to design societal systems around them.

The authors do acknowledge though that dealing with the issue of increased natural resource use is without question necessary if sustainability and the SDGs are to be achieved (The World in 2050 2018: 58). It is certainly true, however, that the demand increase for resources happens at a much faster pace than the changes in societal behavior. Incorporating the production side of industrial processes is therefore a currently efficient way of implementing sustainability practices quickly. Additionally, it cannot be wrong to implement sustainable production methods as they will also serve a transformed society better, even with reduced material demand. Improvements of material efficiency, lower emissions, use and reuse of materials, such as carbon, recycling and urban mining are aspects that can be found in production systems and are priorities for transformation (The World in 2050 2018: 16).

With regards to the resource dimensions of SDG 12 the TWI authors point out that "[t]hese indicators currently, however, lack specificity […]" (The World in 2050 2018: 82). According to them the "appropriate resource flows for SDG 12 to be considered are those that […] are key in current models of service provision (e.g., energy, materials for housing, vehicles, appliances etc.), […]." They criticize, further, that "there exists not a single scenario illustrating an integrated SDG 12 pathway to 2050" (The World in 2050 2018: 84). There are some scattered studies that promote a specific approach and are deemed as SDG 12 relevant, however, they have a much too strong supply side bias for the authors. They further elaborate that "by looking at a resource matrix, including water, energy, land and materials it is possible to describe the interactions and interlinkages of responsible consumption and production [and] one could also include GHG emissions" (The World in 2050 2018: 84).

3.9 A Framework for Strategic Sustainable Development

The framework for strategic sustainable development (FSSD) has developed through a more than 25 year iterative process between scientists and practitioners to establish a "unifying and operational definition of sustainability, and a systematic approach to planning and acting for the fulfillment of it" (Broman and Robèrt 2017: 17). They have created a funnel metaphor for (un)sustainable development by which they are trying to illustrate the systematic decline of ecological and social systems' potential to fulfill human needs. This decreasing potential is represented by the inclining walls of the funnel that society has entered into. Through multi-annual dialogues with natural scientists they have concluded that the essential aspects that need to be sustained in the ecological system are assimilation capacity, purification capacity, food production capacity, climate regulating capacity and diversity (Steffen et al. 2004 and 2015 in Broman and Robèrt 2017). The FSSD provides simple first-order exclusion principles through the adherence of which a sustainable redesign of systems is possible. When designing processes or products the following criteria have to be applied:

In a sustainable society, <u>nature is **not** subject to systematically increasing</u>

a) concentrations of substances extracted from the Earth's crust
b) concentrations of substances produced by society
c) degradation by physical means

Through the application of these criteria in their design processes Electrolux for instance decided to phase out CFCs in a strategic manner (Broman and Robèrt 2017: 25). This framework can help any company to reflect their practices through "the use of 'not contributing' to unsustainability globally.

3.10 Life Cycle Assessment – LCA

Life cycle analysis is a methodology for holistically assessing sustainability implications of a product's entire life cycle. It has evolved out of early environmental impact analyses in the 1960s. Up until the 1990 it was a non-defined field with various approaches. In the 1990's standardization occurred and a holistic and internationally agreed upon uniform methods to perform such assessments and even an ISO standard (International Organisation for Standardisation) was introduced (Scientific Applications International Corporation SAIC 2006, Guinée et al. 2011, PRé 2019).

According to the ISO 14040 and 14044 there are **four phases** to life cycle assessment that are clearly defined as follows (International Organisation for Standardisation ISO 2006: 5):

1. **Goal and scope definition phase**
   This step ensures that LCAs are performed in a uniform manner. By defining the goals and the scope it is possible to delineate the aims and limitations of the analysis, which is essentially a model of a reality. Like every model it is subject to simplification which may blur the quality of the results.

2. **Life cycle inventory analysis phase (LCI phase)**
   Input /output with regard to the system being studied

3. **Life cycle impact assessment phase (LCIA phase)**
   Representation of LCI environmental significance for a more thorough understanding

4. **Interpretation phase**
   Discussion of LCI and LCIA for conclusions and recommendations for decision making.

The LCIA phase can be omitted if the LCI phase is sufficient for representing the scope of the study. It is referred to as an LCI study. Depending on their scope they can also be conducted partially, therefore not encompassing the entire life cycle of a product but only certain phases of the cycle, so-called cradle-to gate or gate to gate studies (International Organisation for Standardisation ISO 2006: 19). LCAs further do not encompass social or economic aspects of the product or service analyzed. However, the standard offered by ISO can be applied to these contexts.

Depending on the goal and scope, LCAs are always composed individually and hence with deviating system boundaries, depth and breadth. There is no single method for conducting an LCA according to ISO and it is always to be seen in the light of the intended application and requirements of the organization (International Organisation for Standardisation ISO 2006: 9). It is important to ascertain which entry and exit points as well as parameters and system components for analysis were chosen if for example LCAs are to be used as information source or several studies are to be compared. Also, it is important to be aware whether or not an LCA or an LCI study is analyzed. Comparing these two is according to ISO "only possible if the assumptions and context of each study are equivalent (International Organisation for Standardisation ISO 2006: 6)." ISO 14044 even states that in order for two studies to be compared they need to be compared "on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows (International Organisation for Standardisation ISO 2006: 8)." LCA is in any case an iterative approach and the scope may have to be adapted to the goal due to the data collected during the study (International Organisation for Standardisation ISO 2006: 11). Ayres (1995: 201) points out that a weakness of the LCA is that "[…] in many - perhaps most cases LCA can only expose the tradeoffs. It can only rarely point unambiguously at the 'best' technological choice."

3.11 Socio-Ecological Principles and Indicators for Sustainability

Holmberg's socio-ecological principles were defined as a basic understanding on which socio-ecological indicators for sustainability can be built and which they themselves actually defined. They are called socio-economic as the premise they are based upon essentially is that humans are the ones causing environmental impact through their resource use and resulting interactions with nature, reflecting "societal activities rather than the state of the environment" (Azar et al. 1996: 90). They are based upon four principles (Figure 11):

- The first principle deals with societal use of elements; from the lithosphere.
- The second principle deals with the necessary restrictions on emissions of anthropogenically produced substances.
- The third principle concerns the anthropogenic manipulation of nature.

- Finally, the fourth principle deals with the efficiency of the societal resource use (Azar 1996: 90).

The Earth system as such is divided into the following parts: The *lithosphere* from which humans derive their resources and which can be described as the Earth itself and its stable structure creating processes, the *ecosphere* which is the space between the lithosphere and the end of the atmosphere in which all of "active nature" (nutrient cycling, weather systems, biodiversity etc.) occur. A volcano eruption would be a flow from the lithosphere into the ecosphere and a sedimentation process a flow from the ecosphere to the lithosphere. Within the ecosphere there is also the *human sphere* in which our societal metabolism is taking place. The human sphere has created the *technosphere* that is also located in and also based on the ecosphere in which materials and substances are moved around to fuel the societal metabolism. The four developed principles focus on different parts of the interaction between the spheres. However, they are all concerned with the protection of the ecosphere, the seemingly most vulnerable sphere of all.

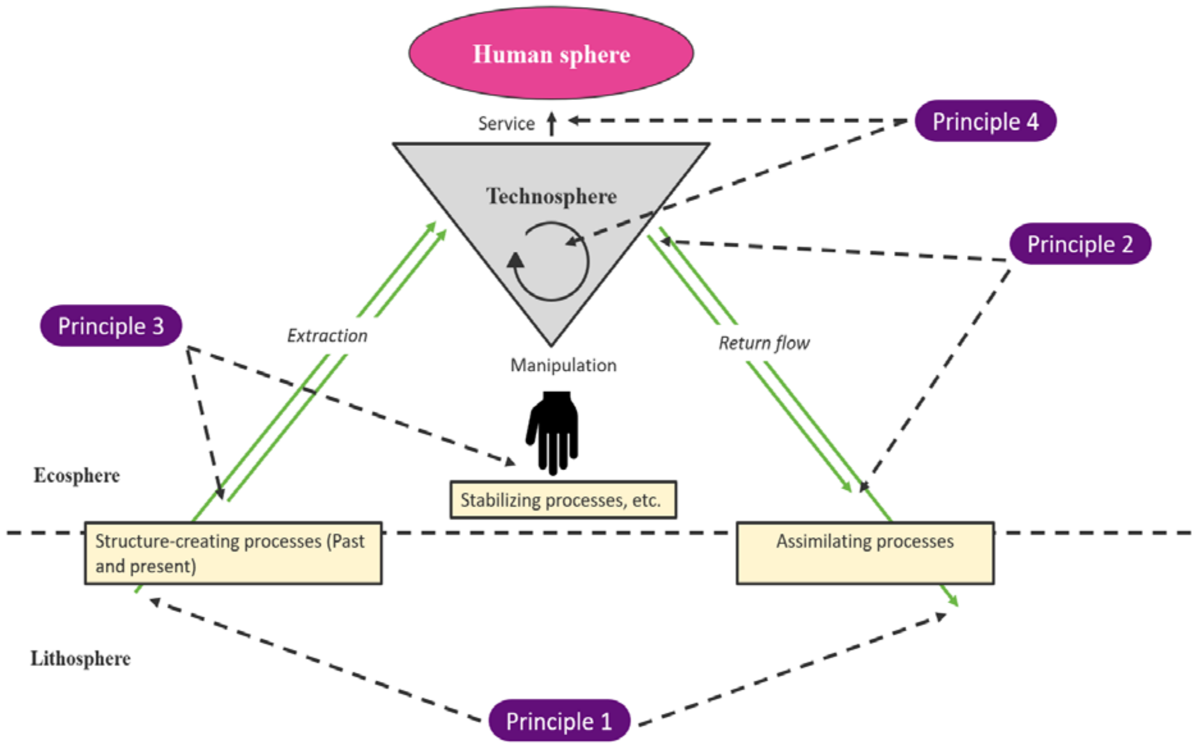


Figure 11- The Holmberg principles (Holmberg 1995)

The Holmberg Principles in more detail:

Principle 1

Substances extracted from the lithosphere must not systematically accumulate in the ecosphere. "Substances from the lithosphere must not be spread in the ecosphere faster than the sedimentation processes return them to the lithosphere" to avoid sedimentation in the ecosphere as "every substance has a limit (often unknown) above which it will cause damage in the ecosphere. In practical terms this means according to Holmberg: Radically decreased use of fossil fuels and materials from mining, especially of scarce metals" (Holmberg 1995: 33). The indicators developed around this principle are the *lithospheric extraction rate*, which is considered to be a flow of materials and the *accumulated lithospheric extraction rate* which is considered to be a state. In the case of the first indicator anthropogenic extraction should not exceed natural supply to the ecosphere through weathering. This threshold differentiates between different materials though. It is different with every metal for example as it strongly depends on the amount of the natural occurrence of a metal. If a metal is scarce in nature and intensively extracted then anthropogenic accumulation to the ecosphere is exceeding natural accumulation quickly. If a metal is abundant in nature then this is not the case. In the case of the accumulated lithospheric extraction rate a difference between total accumulation of the material in the technosphere and the ecosphere is made and comprises all material ever extracted since the industrial revolution.

Principle 2

Society-produced substances must not systematically accumulate in the ecosphere. This means that their production should not be faster than the rate at which they can be broken down into their molecules and resulting reintegration into biochemical cycles. In concrete terms a phasing out of such substances and a decrease in their intentional production is suggested. Indicators developed around this measure anthropogenic flows of substances versus natural flows, long-term implications of present emissions and long-term implications of emissions of substances that are foreign to nature. An indicator for substances foreign to nature in terms of their production versus their degradation time was not developed although suggested due to the complexity of the chemicals' environment. This refers to the number of chemicals used as well as their very individual degradation processes in terms of mechanism but also time frames. Holmberg suggests (in 1995 already) a monitoring system for the production volume of persistent chemicals should be introduced. With the EU chemicals regulation REACH No 1907/2006 (EUR-Lex 2006) that came in into force on 1 June 2007 a step into this direction was made. REACH stands for Registration, Evaluation, Authorization and Restriction of Chemicals. It has fundamentally harmonized and simplified the existing chemicals legislation for the industry (Wikipedia 2020). Another indicator suggested by Holmberg but not developed is one for the unintentional production of substances that are foreign to nature.

Principle 3

The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated. This specifically refers to the environment as the basis for society's production and thus wealth capacity. It is based on the idea that the environment takes time to regenerate what is takes from it. Therefore, society must not take more than can be regenerated as it depends on the long-term functions of the ecosystem. "Our health and prosperity depend on the capacity of nature to reconcentrate and restructure used materials into resources" (Holmberg 1995: 32). This is strongly linked to the idea of strong sustainability and the non-interchangeability of natural versus man-made capital. It is suggested to use more efficient planning and careful use of productive areas in agriculture, forestry and fishing as well as more careful planning of infrastructure. Interestingly, extraction is not mentioned in the overall perspective suggestion although before raw materials and fuel were brought in connection with the human existence base. It is also not included in the indicator development. Indicators that were developed around this are transformation of lands in terms of amounts of land transformed for societal purposes and due to its extensive impact one indicator solely focusing on agricultural practices and their influence on the land used in terms of reasons for changes in soil quality and marine and lake resources.

Principle 4

The use of resources must be efficient and just with respect to meeting human needs. This principle essentially reflects the fact that societal metabolism should be efficient and focus on meeting basic societal needs, avoid overconsumption and provide intragenerational justice through having as little environmental impact on the ecosphere as possible. Efficiency here also means social efficiency in that resources are distributed just. This has a strong correlation to ecological economics. This principle is actually the only really social principal of the four. Indicators developed around this are little surprisingly focused on measuring intragenerational justice and basic human needs.

According to Holmberg a systemic perspective is crucial as the simple nature of causality chains has become a blurry and complex one in today's global production and consumption world. When looking at a certain sustainability problem it is therefore important to also focus on the details and think further than just one-dimensional causal effects. Some aspects that he highlights are the following:

Local to global: "philosophy of dilution" transfers local problems to regional ones. Building higher chimneys and longer discharge pipes does not solve the problem but dilutes it (Holmberg 1995: 5). Today many substances pollute the global environment from various local sources. This affects also regions that do not actively participate in the pollution as pollutants are transported across boarders through winds and via waterways.

Specific to diffuse: In the past it was possible to assign pollution to a specific source. A chimney of a factory was assigned to the specific emission. Today a filter is used which is later landfilled and emits indirectly. Many diffuse emissions can be found in the consumption sector today and they come in the form of products often released into the environment by uninformed consumers such as emissions of micro plastic into the water streams through shower gels.

Short delay to long delay: The above-mentioned filter problem is also cause for long delay before the emitters caught in the filter reach the ground water after having been landfilled.

Low complexity to high complexity: In the past the casual chain was short e.g. factory poisons river. "Today the casual chains in the societal influence on nature look more like a brushy web"

Important questions to ask are thus: Where does the pollution really come from in terms of location, product, timeframe and interconnection to other factors.

Although the Holmberg principles are said to deduct socio-economic indicators, the principles themselves are at their core environmental principals that have at their center the value of strong sustainability. They focus on the human impact on the environment and are concerned for the environmental change this brings about in relation to the functioning of the socio-economic sphere. Their goal is clearly to save the environment. They acknowledge that as a society we need resources and that only by protecting nature we can function as a society, that society relies on nature for its functioning and they are thus similar to the underlying thought processes of the sustainable development goals. They also mirror the very essential planetary boundaries when in principle (1) Azar et al. talk about accumulation of carbon dioxide and phosphorus accumulation in the ecosphere or in principle (2) refer to human-made substance accumulation such as CFCs (Azar et al. 1996). In principle (3) land use and biodiversity are at the core and in principle (4) intergenerational justice mirrors the underlying principle of the Planetary Boundaries in that they are preserving the safe space also for future generations. Principle (1) and (2) also match two of the principles in the framework for strategic sustainable development, which is not surprising when taking into consideration that the former draws from the early principle work of Holmberg.

3.12 Conclusion

From the analysis of sustainability theories, it was shown that there are three important areas to be considered, namely ecology, economy and social properties. Therefore, a production and consumption process should consider all three of them. It should be socially and environmentally friendly but also yield an economic benefit. Through strong and weak sustainability, it became clear that the environmental sphere needs to be given the highest priority. Most of the above theories can be defined as strong approaches. If a process is not environmentally friendly, it should therefore be reconsidered. The planetary boundaries showed which biophysical properties are inherently responsible for the environmental system equilibrium and that these should to be considered in any process design. The SDGs represent economic growth as the solution for social development but propose environmental pressure relieve through decoupling resources use and environmental output. They want the economy to do more with less in an eco-friendlier way. Specifically, SDG 12 is concerned with this issue and one of its targets stands for sustainable natural resource use. The developed indicators by the UN and Eurostat can partially measure how much has been used in relation to the final output and in this way cover the resources use decoupling aspect.

They can also measure certain environmental outputs such as CO_2, however, they cannot measure the environmental quality of production outputs relating to the planetary boundaries and other sustainability scenarios. SDG 12 does not provide a coherent framework for the environmental analysis of

Table 1 - Summary of sustainability foci of various sustainability frameworks elaborated

Sustainability Framework	Environmental / Strong Sustainability	Environmental / Weak Sustainability	Social	Economic
Planetary Boundaries	x			
Sustainable Development Goals		x	x	x
Circular Economy		x		
Ecological Economics	x			
TWI 2050	x		x	
A framework for strategic sustainable development	x			
Life-cycle analysis	x	x	x	X
Socio-economic indicators for sustainability	x		x	

production systems, and subsequently does not provide guidance on “where” the desired decoupling effect can take place. Furthermore, through the circular economy approach and the LCA approach it became clear that it may be efficient to scrutinize single material chains more closely and that the design of the single material in products needs to be improved and more closely monitored for better material quality results and less energy input in recycling. CE, EE, the Holmberg principles and the FSSD have shown that it is important to design material throughput through the technosphere and human sphere in efficient ways, that minimize material loss or discharge into the ecosphere, that are tailored to demand scenarios but respect natural scarcity where necessary.

4 Objectives and Structure of the Thesis

The main aim of this chapter is to approximate the objectives of this thesis through carefully weighting and evaluating the main findings of chapter 2 and 3 on the question of what responsible production and consumption means and then deducting the research question and further work from it.

The illuminated context and sustainability theories in chapter 3 have led to an understanding that there are gaps in the practical application of Sustainable Development Goal 12 regarding its responsibility proposition. It has further led to an understanding that by reconciling the context of the world reality of an exploding resource consumption with the most prominent sustainability theories it is possible to create a new way forward that will permit to fill the SDG 12 framework with meaningful qualitative information. From the basic premises of the SDGs and SDG 12 and the findings in chapter 2 and 3 the research questions are deducted and sculpted.

4.1 Main findings and premises learned

Main finding 1: The basic premise of the SDGs and specifically SDG 12 is to work towards human well-being for everyone. To achieve this, it is necessary to uphold industrial production, if needed to increase it. This is because social welfare today and for the foreseeable future is based on industrial activity and thus environmental consumption for materials, also in a service economy. Materials should therefore be produced and consumed responsibly to decrease their impact on the environment.

Main finding 2: The concept of "resource and impact decoupling" is meant to generate more responsible industrial production to generate more well-being for everybody. The question is if and where this impact decoupling can take place in the system? Further, the question is whether successful decoupling is all that is required to consume and produce "responsibly", responsibility being the main tenor of SDG 12? Or does it take something else? As was illustrated above the indicators that have been established for the SDG target 12.2 are only quantitative and therefore not suitable to define whether or not something is produced responsibly. The issue with this is that less of something bad may be better but is still not good. A systemic qualitative analysis on the basis of existing quantitative indicators and additional existing information is needed. Firstly, this needs to be done to find out what exactly is environmentally not good about specific production processes of a holistic system and secondly, to establish a deeper understanding of what certain quantitative indicators, boundaries and data mean in a systemic environmental context and what they mean in relation to each other.

Main finding 3: The environment is the basis of everything, specifically all societal systems. This means that if the environment is overconsumed by humans the ecological safe-operating space for society will be destroyed. This is a fundamental problem for the future of our existence.

Within SDG 12 the decoupling proposition of the environmental impact implicates its importance. Furthermore, this significant environmental importance is part of the following sustainability theories:

- Strong Sustainability Theory: Natural capital is not substitutable
- Planetary Boundaries: Global environmental indicators for ecological equilibrium
- Ecological Economics: Full versus empty world and economy as subsystem of the Earth system
- Great Acceleration: Countering increase of negative Earth system trends
- Framework for strategic sustainable development: Countering the systematic substance increase and ecological degradation caused by humans
- Holmberg principles: Three of four have the environment as target for amelioration.

Main finding 4: There is a rapidly growing use of mineral resources and application of resulting materials. This is due to the extensive growth of the population, societal wealth around the world and the corresponding industrial activity. Mineral resources and materials are therefore system components that need to be produced responsibly due to the sheer volume and potential environmental impact their production might thus have.

Main finding 5: It is important to work within material and not product life-cycles and to try to close loops as much as possible (Circular Economy, Transformations to achieve the SDGs, LCAs, Ecological Economics). The old produce, use, waste mentality is no longer a valid concept associated with responsibility and society agrees that reducing, reusing, remanufacturing and recycling are integrated goals that should be strived for.

4.2 Overall objectives of the thesis

From the main findings above the following main research question for this thesis was deducted:

How can opportunities for the targeted environmental impact decoupling and responsibility proposition of SDG 12 be systematically identified in the extensive world of materials, *in a way that they are of significant relevance in todays' environmental and responsibility debate?*

In order to answer this question a **comprehensive responsibility assessment scheme** will be created. This scheme is based on the main findings of chapter 2 and 3 and on the resulting hypothesis that the environment is the boundary condition for all societal material systems. Therefore, the scheme will be premised on the following:

- systematic structure as assessment framework
- relevant and sound environmental indicators as assessment basis
- mineral resources or materials in our system as system components
- circularity of materials as system approach
- qualitative assessment factors that can assess the responsibility potential of a production process.

To structure an assessment scheme in a way that allows for **systematic identification of environmental decoupling potential** in the world of **materials** the following steps are taken:

- To cover the **systematic aspect** of the question, one material at a time should be scrutinized. Each material production system has its specificities and they can thus not be analyzed together. Therefore, one single material is scrutinized at a time.
- To cover the **environmental aspect** of the question, each of these materials should be scrutinized according to relevant environmental indicators. Therefore, in a first assessment trial one material is analyzed against sound and relevant environmental indicators.
- To cover the **circularity aspect,** the systemic framework around the one material to be analyzed takes into consideration its life-cycle properties.

At the end of this scrutiny it should be possible to answer the related questions

- *"Where in its life-cycle can a certain material be decoupled from its environmental impact?"*
- *"To which extent is a certain material a responsible material in our society?"*
- *"What needs to be done to make a certain material responsible in case there are deficiencies?" and*
- *"What should be done if there is no possibility to improve the materials environmental impact?"*

As an outcome of the thesis an **assessment scheme** will be developed that can be **transferred** to life cycles of various materials to assess their environmental sustainability and responsibility factor.

To find all this out, a **qualitative analysis** of a primary and secondary production cycle of a significant material **on the basis of quantitative data** will be done. The analysis will look at

a) the production methods (technologies, processes and practices) used in the production cycle and their respective environmental impact according to a specific indicator set
b) the context and set-up of relevant management mechanisms of the industry.

The production methods chosen for analysis will be "Best available technology (BAT)".

The (a) methods and (b) management mechanisms will be analyzed and assessed against relevant environmental indicators**,** that will be established beforehand the analysis according to the SDG 12 benchmarks "environmental impact decoupling" and "responsibility potential". The completed analysis will provide a current best practice scenario which will be evaluated, discussed and proposals for a future improved best practice scenario will be brought forward.

4.3 Structure of the thesis

In order to meet the anticipated objectives, the chapters are organized as outlined below:

Part one of the work (chapter 5) is concerned with discussing what responsibility means in connection to and as a motivation for an assessment scheme, narrowing down the sustainability theme covered in the assessment, outlining which indicators and systems and systems components are chosen.

In part two of the work (chapter 6, 7 and 8) the selected indicators are summarized and their possible individual meaning for the designated system chosen. Furthermore, the designated system component, its properties as well as its societal significance are highlighted. The component production system is outlined where appropriate.

Part three (chapter 9) deals with the assessment scheme which will be outlined and instructions given on how to use it. It will serve as basis for the subsequent case study.

Part four (chapter 10 and 11) will treat the case study "assessment" itself and an evaluation of and discussion around it.

5 Development of a Responsibility Assessment Scheme

> Decision making is usually based on economic documents. Their shortcomings with respect to sustainability are often not balanced with other kinds of documentary foundation covering aspects that are relevant for sustainability. (…) [T]here is a need for (decision makers to extract) the most relevant information on a form that is easily accessible, i.e. there is a need for indicators. (…) Such indicators must be based on a correct conception of the world (…), on a systematic and pedagogical description of what has to be fulfilled in a sustainable society. (Holmberg 1995)

5.1 Core motivation for a "responsibility" assessment scheme

We live in a society designed to generate wealth through industrial processes. In these industrial processes we produce and apply materials for which we consume the environment. The protection of our environment as basis for our human existence is the upper most priority if as a society we would further like to live in favorable environmental conditions. There are environmental stability limits with regards to our consumption of the environment regarding these conditions. As a **responsible society** it is our **duty to systematically evaluate systems and system components** with respect to their "responsibility potential" in the use in and for society. If we discover for example that a material or practice is utterly "irresponsible" and that this cannot be changed then it is necessary to replace this material or practice with a non-harmful practice or material (as e.g. done with chlorofluorocarbons).

But as "irresponsibility" is not always as obvious as with chlorofluorocarbons, a main question is therefore: What is responsibility? In order to be able to talk about responsibility and irresponsibility it is important to define what it means, a discussion seemingly absent in the SDG 12 context. Which qualities are designated to be responsible in the societal metabolism? The words "responsibility" and "sustainability" are currently found in all contexts and are often presented as equivalent. There are many attempts to define them, but they are all similar in essence (Industrie und Handelskammer Nürnberg 2019). Even in the UN context they are seemingly used interchangeably. The scientific theoretical discussion and reflection of these terms is clearly still in its infancy and it is urgently necessary to resolve their sponginess (Vogt 2019). According to Vogt, the normative content of "responsibility" is completely unclear, since everyone feels "responsible" in one way or another. One thing is clear however, responsibility is a purely human trait and therefore reliant on a human agent to be carried out (Goldberg 2017, Eshleman 2014). This means humans are to blame for irresponsible systems. Systems are not intrinsically irresponsible as they are human made. As is often tried in order to monitor sustainability in systems, quantitative indicators cannot yield any results, as CO_2 levels as such for example, have nothing to do with responsibility per se. They are merely a result of human agents' process and system designs, which makes it necessary to look at the system components that human agents have an influence on. Responsibility in this sense also means, as human agent or in this sense society, to have the courage to change unsustainable practices, processes and systems. This fact is a difficult concept as human action is mostly directed by the system dynamics that humans find themselves in. Responsible actions require humans to be brave enough to do them but they also require that human beings have the knowledge to be able to judge what the responsible option is.

Only after the fuzziness of this discussion is resolved it will be possible to derive concrete science from it, which will then also make it possible to formulate concrete measures for societal models. The SDGs are a good first step in this direction, but they also **need to be sharpened up in their individual thematic areas.** They are thus a good guideline and provide a direction for development, but how they are to be implemented and what synergies and trade-offs result from this can only be defined through an intensive work process. On the one hand, the achievement of individual SDG targets cannot take place in isolation, as the targets are interrelated and influence each other. On the other hand, it is also necessary to see the more concrete realization of the SDGs in connection to other sustainability approaches. It is therefore necessary to define even more clearly what a sustainably designed society should look like. What should the world look like in 2050? How are material life cycles designed in 2050? Only from this, concrete actions can be derived to achieve the SDGs and make responsible decisions that will lead society towards these goals.

In any case, it does not seem to make sense to bring about abrupt changes that could lead to systemic collapses but to work on the issues systematically and gradually. In this respect it is important to highlight or analyze single system components in a sort of systematic bottom-up approach with a top-down theory. But which system needs to be looked at in terms of responsible production and what are the system components? From what has been highlighted in chapter one, the problem society is facing is the increase in raw materials consumption and thus production and the associated environmental challenges that arise with this. In other words, this means that the production of materials has environmental impacts. Therefore, it seems reasonable to consider the material production system as 'the system' and 'the material' the single component of the system. The material should subsequently and in the spirit of the circular economy approach be scrutinized within the boundaries of its genesis, life profile and exodus from or ideally re-entry into the system at the end of its life-time. Considering the immense increase in material consumption in the future, this system and its components must be systematically captured if responsibility is a prerequisite for future societal actions. An ideal material life cycle in this sense does not systematically contribute to producing and accumulating harmful substances in the ecosphere.

In order to meet the responsibility-claim through and for sustainable material production systems, a tool is needed that can serve as an "easily accessible" source for responsible societal decision making. In this sense, an assessment scheme has to be developed that can provide a basis for defining if certain system components are sustainable and that can be an easy to apply tool for decision makers (be it on the political, policy or company level).

5.2 Narrowing the sustainability theme covered in assessment

It was learned in chapter two that sustainability comprises three pillars: ecological, social and economic sustainability. Additionally, it was learned that according to the concept of strong sustainability and the majority of the other prominent theories, the environment is considered to be the strongest pillar as it serves as the basis for all other systems. As a result, the research focus of this thesis is narrowed down as follows (Table 2):

The assessment scheme to be developed in *this thesis only covers environmental aspects* as a first attempt at defining the responsibility potential of the single system component 'material'. This also means that *a social and economic indicator set for the material production life cycle* still has to be developed if all three pillars of sustainability are to be considered in the future.

Furthermore, *this thesis only covers the production life cycle* of the system component 'material'. The consumption regarding the end consumer is not taken into consideration, neither are procurement processes within production. Therefore, environmental, social and economic indicator sets have to be developed for the consumption pillar in a separate work.

It is anticipated that the basic mechanism of the assessment scheme can be transferred to these other areas once completed.

Table 2 - Specific SDG 12 research focus of this thesis

		SUSTAINABLE DEVELOPMENT GOAL 12	
		Responsible Production	**Responsible Consumption**
3 PILLARS OF SUSTAINABILITY	Environment al	Environmental Indicators and Assessment Scheme	Environmental Indicators and Assessment Scheme
	Social	Social Indicators and Assessment Scheme	Social Indicators and Assessment Scheme
	Economic	Economic Indicators and Assessment Scheme	Economic Indicators and Assessment Scheme

COVERED	NOT COVERED

5.3 The systemic components of the assessment scheme

For a comprehensive assessment scheme that can define the responsibility factor of materials production and serve as decision making tool it is crucial to apply responsibility components that are (a) **highly relevant to society**, (b) **cover all important factors in terms of reflecting within them the majority of the outlined sustainability theories** and are (c) **scientifically proven to have systemic change potential**. The following 4 components were selected as they seem to fulfill the criteria: (1) environmental indicators, (2) a system framework, (3) assessment material and (4) an assessment framework.

*5.3.1 The nine Planetary Boundaries as **environmental indicators***

In this thesis and from the lessons learned from chapter 1 and 2, the Planetary Boundaries were selected to be the indicators of choice. They are, first of all, currently well known throughout and highly relevant for the scientific, societal and political world. Their core underlying principle is "a safe operating space for humanity with respect to the functioning of the Earth System" (Rockström et al. 2009). Scientifically deducted from this were all biophysical boundaries that are responsible for the ecological equilibrium on the planet. This renders them more than highly relevant for a healthy planetary environment and thus a healthy society. The PBs secondly not only cover all relevant environmental factors that need to be considered but with this also reflect within them the majority of sustainability theories that were outlined above. With its comprehensive environmental indicator set they cover the SDG 12 aspect of reducing environmental impact and thus decoupling. They adhere to the strong sustainability principle by making the environment the basis of all other systems and they are also compatible with ecological economics that see the economy as an open subsystem of the closed "Earth-system", with an optimum scale between the two. Additionally, the earth system trends illustrated in the great acceleration are in principle all mirrored in them and thus reversing PBs transgressions could contribute to their slowing. Furthermore, the PBs incorporate aspects that illustrate the systematic increase of concentrations of substances produced by society and ecological degradations as is outlined in the FSSD. They do not incorporate aspects that counter the systematic increase of concentrations of substances extracted from the Earth's crust, however. The SDGs themselves assume an increase in industrial activity and corresponding raw materials consumption. The PBs in that respect mirror what is 'globally unsustainable' thus defining the system boundaries of 'what not to contribute to' when companies try to design processes. The BPs are also mirrored in all four of the Holmberg principles, where accumulation of carbon dioxide and phosphorus in the ecosphere, human-made substance accumulation such as CFCs, land use and biodiversity as well as intergenerational justice are at the core (Azar et al. 1996).

The PBs systemic change potential is in the PB's nature. They are a scientific effort at identifying key Earth System processes and an attempt to quantify for each process the global accumulated boundary level that should not be transgressed if unacceptable global environmental change is to be avoided. (Rockström et al. 2009). So, the change they anticipate is in the worst case actually no more deleterious change and in the best case a reversal and amelioration of the deleterious changes and boundary transgressions that have already happened. It is important to understand that the boundaries are set in equilibrium to each other assuming that no other boundaries are transgressed (Rockström et al. 2009). It cannot be estimated how the boundaries change in relation to each other when a few are transgressed. Here the system reaches its limits.

The PBs are used as indicators to identify environmental impact decoupling opportunities as proposed by SDG 12 because they seem ideal for doing so. They point at really crucial boundaries that should not be reached. Decoupling should therefore happen first within the range of these indicators to be an efficient mechanism. Furthermore, decoupling can only be realized seriously if either there is a step change in existing environmental unfriendly technologies, processes or practices or if irresponsible materials by nature are abolished or substituted.

5.3.2 *The material life cycle as* ***a system framework***

The assessment scheme aims at assessing a single system component bottom-up. It was learned that one major sustainability challenge is the strong increase in material consumption and thus production and that without dealing with this issue sustainability and the relevant SDGs cannot be achieved (The World in 2050 TWI 2050: 58). It is important to have a systems perspective from which it is logically deducted that the whole system and its single components need to be considered (Holmberg 2015). Here the system is the *system of materials in production* and the *single system component a material*. Politically and scientifically the recent years have led to the promotion of the circular economic school of thought when it comes to analyzing material life spans. This is why the *life cycle of a single material* is the basic framework of the assessment scheme. **By combining the PBs with a material life cycle a comprehensive overview of each production step in the cycle can be given with regards to their PB compatibility and subsequently their responsibility potential (Figure 12).**

Within this life cycle, following the principles of LCA, system boundaries are defined. The life cycle is subdivided into several phases according to general LCA practices, namely:

- Phase 1: Cradle to entry gate
- Phase 2: Entry gate to exit gate
- Phase 3: Exit Gate to grave and/or entry gate

Within these phases single production steps (unit processes) are defined according to the individual production traits of the individual material. These unit processes can differ from material to material.

In phase 1 this can generically be described as deposit, mining and mineral processing; in phase 2 as raw materials conversion material production and manufacturing; in phase 3 the most important product categories that this material flows into and their recycling routes. A corresponding generic model is outlined below. As already mentioned the phase consumer usage of finished product is not considered because this phase needs its own set of indicators in all three sustainability pillars and subsequent analyses.

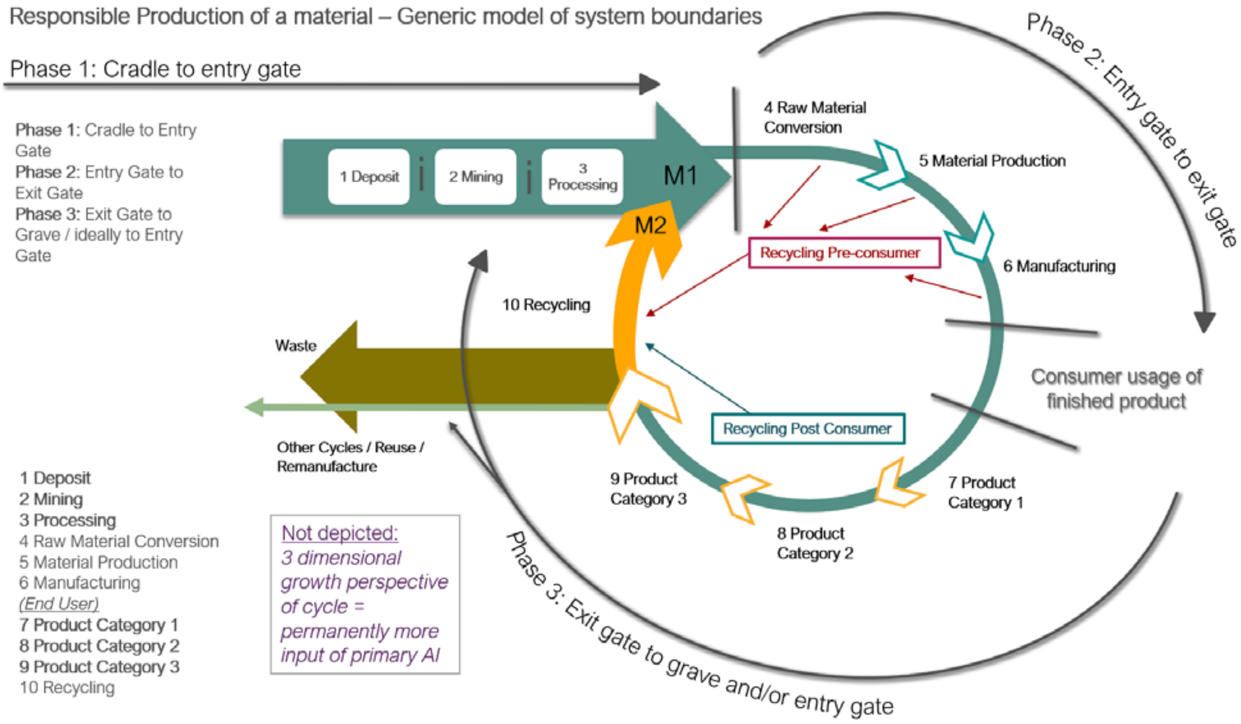


Figure 12- Generic life cycle as system framework

The difference between this assessment and a conventional LCA is that a conventional LCA analyzes the life cycle of a specific product within defined system boundaries whereas this assessment focuses on the systemic sustainable flow of a specific material, the inputs and outputs of all defined unit processes and the related technologies, processes or practices. The assessment thus covers the aspect of a best-available-technology (BAT) scenario (What is already technologically possible today?) and a best-available-practice (BAP) scenario (What is the reality in technology application today and why?). What would need to be done in order to change possible discrepancies? Once it becomes clear which inputs and outputs should be mitigated or replaced due to their incompatibility with the Planetary Boundaries, the respective technologies, processes or practices can be more closely studied to propose how this could be achieved.

In this sense, the framework will represent a generic LCA that discusses individual problematic components of the material production system in terms of contributions to environmental threshold transgressions and the corresponding technologies, processes or practices that lead to these transgression contributions.

*5.3.3 The non-ferrous metal Aluminium as a first **assessment material***

The material to be analyzed should be of significance and "**key in current models of service provision** (e.g. energy, materials for housing, vehicles, appliances etc.)" (The World in 2050

TWI 2050 2018), **common in terms of amount** in circulation in society and annual production so that a framework has the greatest possible impact already at the start and **important for society and future development**.

One material and its life cycle that is ideal to start with is Aluminium. It is a key metal because ”its applications span from everyday items like fuel-efficient vehicles, smart phones, zippers and foil to wiring power grid and housing the International Space Station” (The Aluminum Association 2020a). It is used vastly in all spheres of societal everyday life: transportation, electronics, electrical and electricity related-uses, applications, construction, consumer goods, household items, packaging, machinery, equipment etc. As it can be recycled very efficiently, it is very lightweight and has numerous other beneficial properties and is thus the material of choice for numerous new applications and future technologies as well as a critical cross-cutting material for a variety of highly important future energy technologies (World Bank Group 2020). Aluminium demand is significantly on the increase as it will play a major role in future societal developments. This renders it highly relevant in terms of impact on environmental systems. Therefore, the following work will scrutinize Aluminium’s entire primary and secondary production cycle in the sense of the established sustainability considerations and PBs to thus a more thorough framework for responsibility considerations inside SDG 12.

*5.3.4 The calibration matrix as an **assessment tool***

What leads to crossing Planetary Boundaries thresholds? How does the Aluminium life cycle add to transgressing these thresholds? The intersections where Aluminium production contributes to the pushing of PB transgression is exactly **the place where a systematic decoupling of environmental impact and industrial production can and needs to happen**.

The way the assessment scheme will be designed is to take the chosen environmental indicators – Planetary Boundaries – and cross-match (calibrate) them across each production step (unit process) of the life cycle of the material – in this case Aluminium (Table 3). These decoupling intersections are called calibration categories and they provide the room for finding decoupling solutions. Each calibration category is systematically numbered. The matrix allows a environmentally holistic and systematic systemic perspective on the production life cycle of a material and its role in the possible contribution to the transgression of planetary equilibrium boundaries.

Table 3 - Generic calibration matrix as assessment tool

CALIBRATION MATRIX			PLANETARY BOUNDARIES								
			PB1 Climate Change	PB2 Novel Entity	PB3 Stratos-pheric Ozone Depletion	PB4 Atmos-pheric Aerosol Loading	PB5 Ocean Acidi-fication	PB6 Biochemical Flows - Phosphorus and Nitrogen	PB7 Freshwater Use	PB8 Land-system Change	PB9 Biosphere Integrity [loss] of functional and genetic diversity
LIFE CYCLE UNIT PROCESSES	PHASE 1 - Cradle to Entry Gate	1 Deposit	PB1.1	PB2.1	PB3.1	PB4.1	PB5.1	PB6.1	PB7.1	PB8.1	PB9.1
		2 Mining	PB1.2	PB2.2	PB3.2	PB4.2	PB5.2	PB6.2	PB7.2	PB8.2	PB9.2
		3 Mineral Processing	PB1.3	PB2.3	PB3.3	PB4.3	PB5.3	PB6.3	PB7.3	PB8.3	PB9.3
	PHASE 2 - Entry Gate to Exit Gate	4 Raw Material Conversion	PB1.4	PB2.4	PB3.4	PB4.4	PB5.4	PB6.4	PB7.4	PB8.4	PB9.4
		5 Material Production	PB1.5	PB2.5	PB3.5	PB4.5	PB5.5	PB6.5	PB7.5	PB8.5	PB9.5
		6 Manufacturing	PB1.6	PB2.6	PB3.6	PB4.6	PB5.6	PB6.6	PB7.6	PB8.6	PB9.6
	PHASE 3 - Exit Gate to Grave or/ and Entry Gate	7 Product Category 1	PB1.7	PB2.7	PB3.7	PB4.7	PB5.7	PB6.7	PB7.7	PB8.7	PB9.7
		8 Product Category 2	PB1.8	PB2.8	PB3.8	PB4.8	PB5.8	PB6.8	PB7.8	PB8.8	PB9.8
		9 Recycling	PB1.9	PB2.9	PB3.9	PB4.9	PB5.9	PB6.9	PB7.9	PB8.9	PB9.9

5.3.5 Additional criteria

- The thesis is about Aluminium as metal in its production life cycle and no other forms of Aluminium such as Aluminium chemicals or salts, Aluminium hydroxides or Aluminium oxides.
- The thesis is concerned only with environmental impacts of Aluminium production. End-of-Life (EOL) consumption is not addressed and thus the end consumer is omitted in the scrutiny.
- Economic and social properties of the production cycle will only be taken into consideration when they are relevant for the failure of implementation of a sustainable environmental technology, process or practice.
- Transport and related emissions are not taken into consideration as they are not an intrinsic part of the production process as such and the shift to sustainable transport is a mobility research theme.
- The energy unit of choice used to describe the energy intensity of Al in production is always the embodied energy of the material, thus "the energy required to produce a material from its raw form, per unit mass of material produced (Gutowski et al. 2013: 3)." If embodied energy data is not available the most relevant data available will be taken and discussed. If embodied energy data is not relevant for the discussion of a specific system boundary the most relevant data for discussion will be used.

6 THE PLANETARY BOUNDARIES IN THE SPOTLIGHT

6.1 Planetary Boundary Number 1 – PB1: Climate Change

Climate change is caused in particular by the atmospheric gases called green-house gasses (GHGs) that trap the earth's heat radiating towards space in the atmosphere and thus cause the so-called "greenhouse gas effect". Some of them occur naturally (n) and some of them are human induced only (hi) and some of them are both. Some of them force the greenhouse gas effect (*for*) and some of them feedback to the effect (*fee*) (United States Environmental Protection Agency 2018a, European Commission 2020, NASA 2020a).

- **carbon dioxide** - CO_2 (n+hi, *for*) (64 %)*
- **methane** - CH_4 (n+hi, *for*) (17 %)*
- **nitrous oxide** - N_2O (hi, *for*) (6 %)*
- **fluorinated gases** - (hi, *for*) (23000 times higher warming effect than CO_2)
- **chlorofluorocarbons** - *CFCs* (hi, *for*)
- **water vapor** - H_2O (n, *fee*) (most important feedback greenhouse gas)

* share of global warming contribution (European Commission 2020)

Some of the GHGs occur naturally like CO_2 and methane but they are also caused by humans and their accumulation in the atmosphere is thus enforced. Other GHGs occur strictly from human industrial sources, such as N_2O, fluorinated gases and CFCs. "Long-lived gases that remain semi-permanently in the atmosphere and do not respond physically or chemically to changes in temperature are described as "forcing" climate change. Gases, such as water vapor, which respond physically or chemically to changes in temperature are seen as "feedbacks"" (NASA 2020a). That through higher temperatures more water evaporates and leads to an increase in precipitation can for example be described as feedback mechanism.

GHG levels in the atmosphere have been increasing in past decades. According to the International Panel on Climate Change IPCC alone in the years between 2000 and 2010 "[a]nnual anthropogenic GHG emissions have increased by 10 Gt CO_2 eq." and that this increase comes directly from energy supply (47 %), industry (30 %), transport (11 %) and buildings (3 %) sectors (International Panel on Climate Change IPCC 2014).

The control variable for climate change is atmospheric CO_2 concentration in ppm with a boundary value of 350 ppm (Rockström et al. 2009). The current situation comprises an increase of atmospheric CO_2 levels from 280 ppm to 412 ppm in the last 150 years (NASA 2020a), which is 40 % higher than it was when industrialization began (European Commission 2020) and clearly crosses the boundary already. The highest possible CO_2 reduction in all anthropogenically driven production and consumption of Aluminium is thus crucial. But also, methane is a crucial GHG as it is much stronger than CO_2. Dlugokencky leaves room for optimism though when he says that "[s]ince CH_4 has a relatively short lifetime and it is very close to a steady state, reductions in its emissions would quickly benefit climate" (Dlugokencky 2011).

Climate change will cause the earth to become warmer, which will lead to more evaporation and precipitation. Oceans will get warmer; ice and glaciers will melt and sea level will increase (NASA, 2020a). Around 1 °C of global warming can be attributed to anthropogenic activity on the planet with trends pointing upwards (International Panel on Climate Change IPCC 2014). "The contemporary climate is […] moving out of the envelope of Holocene variability, sharply increasing the risk of dangerous climate change" (Rockström et al. 2009). Data suggest that atmospheric CO_2 concentrations play a vital role in the ability of the planet to regulate temperature and that lower concentrations support the ability to form ice. With temperatures further on the increase the risk of triggering climate trends that could lead to unfavorable earth conditions and irreversible dynamics is high (Rockström et al. 2009, International Panel on Climate Change IPCC 2019). Global warming thus needs to be mitigated. The climate change boundary proposed aims at minimizing these risks and mitigating climate change. However, in contrast to the 5 gases that cause the greenhouse effect, the PBs only consider CO_2 as control variable. In this paper the other gases are added as control variable because although CO_2 is emitted in much higher quantities than the other gases which makes it seem more relevant, the other gases in fact "trap heat far more effectively than CO_2", especially fluorinated gases produce a warming effect that is 23.000 times higher than CO_2 (European Commission 2020). The significance of their contribution to global warming should therefore not be underestimated.

Boundary/ indicator to look for in Al production process: All GHGs

- CO_2
- methane
- nitrous oxide
- fluorinated gases
- chlorofluorocarbons

6.2 Planetary Boundary Number 2 – PB2: Novel Entity

The novel entity boundary refers to all types of human only induced and introduced substances onto the planet. Emissions of toxic and long-lived substances such as synthetic organic pollutants, heavy metal compounds and radioactive materials represent only a fragment of possible entities to be dealt with. The boundary was originally named chemical pollution but has been renamed to *Chemical pollution and the release of novel entities*. "Chemical pollution qualifies as planetary boundary in two ways in which it can influence Earth system functioning: (i) through a global, ubiquitous impact on the physiological development and demography of humans and other organisms with ultimate impacts on ecosystem functioning and structure and (ii) by acting as a slow variable that affects other planetary boundaries (effect on biodiversity or climate change)" (Rockström et al. 2009).

This boundary is closely linked to target 12.4 *Responsible management of chemicals and waste,* however in the case of Al life cycle again the SDG target does not offer any relevant indicators. As according to the makers of the PBs to current estimates there are 80.000 to 100.000 chemicals on the global market it is impossible to set one single boundary derived from the aggregated effects of tens of thousands of chemicals. Therefore, two approaches were developed to define a boundary. Either the focus is on persistent pollutants or on the effects they cause.

Boundary/ indicator to look for in Al production process:
Chemicals used in Al production process and their thresholds and effects

6.3 Planetary Boundary Number 3 – PB3: Stratospheric Ozone Depletion

Stratospheric ozone is a highly reactive colorless gas. It filters the sun's UV rays before they reach the troposphere. This is important because UV rays can have adverse effects on human health and marine organisms. Chlorofluorocarbons (CFCs) are chemicals that are human induced and cause the stratospheric ozone to deplete. Once released they attach to ice particles in the clouds in the polar zone. When the particles melt in the spring sun the CFCs are released and break the molecular bonds in the UV-radiation absorbing zone. Every year for the past few decades during the austral spring CFSs in the stratosphere destroy the ozone massively, also known as the ozone hole (Union of Concerned Scientists 2017; NASA 2020b, United States Environmental Protection Agency 2018b). The appearance of this ozone hole was a perfect example of a planetary threshold being crossed completely unexpectedly. It is unlikely that this can also happen for the entire global ozone. However, global warming in general causes more water to evaporate and thus more stratospheric clouds and the phenomenon of the ozone hole could thus happen elsewhere. This is the reason why the planetary boundary 3 is centered around "extra polar stratospheric ozone-depleting substances". Concerted human action was implemented through the 1985 *Vienna Convention for the Protection of the Ozone Layer* and the 1987 *Montreal Protocol on Substances that Deplete the Ozone Layer* to end production of halons by 1994 and CFCs by 1996 (with alterations in 1992 as the original terms were not effective enough) (United States Environmental Protection Agency 2018c). This has ultimately led to a halt of inducing CFCs into the atmosphere which has already resulted in a halt of stratospheric ozone decline and seems to be a good example of how to reverse transgression. However, there is a considerable time lag between the decrease of concentrations and the recovery of the ozone layer and it is expected that the ozone whole exists for many more decades (Rockström et al. 2019). Although there is a considerable real-time time lag, this process is considered a successful and quick example of concerted human reaction to an environmental problem.

Boundary/ indicator to look for in Al production process:

All ozone depleting substances (which include (Government of New Zealand, Ministry of the Environment 2019):

- chlorofluorocarbons (CFCs)
- hydrochlorofluorocarbons (HCFCs)
- hydrobromoflurocarbons (HBFCs)
- halons
- methyl bromide
- carbon tetrachloride
- methyl chloroform

6.4 Planetary Boundary Number 4 – PB4: Atmospheric Aerosol Loading

Aerosols are microscopic to nanoscopic solid or liquid particles suspended in the atmosphere. Due to their size they are invisible. They originate in natural sources such as desert dust or sea spray but also from human sources such as from burning fossil fuels. When these particles are sufficiently large, their presence can be noticed as they scatter and absorb sunlight. Their scattering of sunlight can reduce visibility (haze) and redden sunrises and sunsets. Aerosols play a very important role in the formation of clouds. Cooling water vapor in the air comes out of the gas phase and the water molecules form a liquid droplet on an aerosol particle which serve as cloud condensation nuclei. Once a droplet has formed more and more condensing molecules can attach to it. The more aerosols there are in the air the smaller the forming droplets are as molecules have many nuclei they can attach to. If aerosol density is scarce then many molecules have to condense on few aerosol particles, making the droplets heavy and the forming clouds will be rain raining the water off. Light clouds do not rain the water off. Extensive human aerosol production through burning fossil fuels results in a decrease of rain cloud formation which regionally can have severe drought effects. To the largest extent anthropogenic aerosols come in the form of smoke from burning tropical forests, the major component comes from the burning of coal and oil. The concentration of these sulfate aerosols has drastically increased since the beginning of human industrial activity and is highest in the northern hemisphere where industrial activity is the highest. The clouds with smaller droplet sizes through additional sulphate aerosols also reflect more sunlight than they would without their presence. Like this they reduce the amount of sunlight reaching the Earth's surface which can have regional cooling effects. They are believed to survive in the atmosphere for about 3-5 days (NASA 1996, Center for Aerosol Impacts on Chemistry of the Environment 2015). The cooling effect of aerosols and the warming effect of global warming do no simply cancel each other out, however as aerosols are distributed around the planet differently than greenhouse gases. The aerosol cooling effect is estimated to be less than half as much as the global warming effect (NASA 2010).

"Models estimate that aerosols have had a cooling effect that has counteracted about half of the warming caused by the build-up of greenhouse gases since the 1880s. However, unlike many greenhouse gases, aerosols are not distributed evenly around the planet, so their impacts are most strongly felt on a regional scale" (NASA 2010). Regional effects have been measured in Asia such as areal and time scale precipitation and monsoon shifts or reductions induced by areal cooling through aerosols. Other effects that have been found are crop damage from exposure to ozone, forest degradation and loss of freshwater fish due to acidic precipitation, changes in global precipitation patterns and in energy balance (Rockström et al. 2009).

Anthropogenic aerosols furthermore have a severe adverse effect on human health. Conditions such as adult cardiopulmonary disease, tracheal, bronchial, and lung cancer and acute respiratory infection in children in urban areas worldwide can be traced back to particulate pollution of the air. This pollution is responsible for "[…] about 800.000 premature deaths and an annual loss of 6,4 million life years, predominantly in developing Asian countries. Mortality due to exposure to indoor smoke from solid fuels is about double that of urban air pollution (roughly 1,6 million deaths), and exposure to occupational airborne particulates accounts for roughly 300.000 deaths per year, mainly in developing countries."

“Despite considerable advances in recent decades, estimating the direct climate impacts of aerosols remains an immature science. Of the 25 climate models considered by the Fourth IPCC (Intergovernmental Panel on Climate Change IPCC 2019), only a handful considered the direct effects of aerosol types other than sulphates” (NASA 2010). In any case, it seems that the vast heterogeneous composition of aerosols and their manifold behavioral properties still leave scientists pondering about their correlative effect on the climate and human health. This is why it has not been possible so far to identify a planetary boundary.

Boundary/ indicator to look for in Al production process:

- burning of fossil fuels that cause sulphate aerosols (environmental indicator)
- hints for generation of other aerosols in production process
- occupational airborne particulates (social indicator, not relevant to this thesis)

6.5 Planetary Boundary Number 5 – PB5: Ocean Acidification

Ocean acidification has the same cause as global rise in average temperatures, namely the increase of the CO_2 concentration in the atmosphere. This is due to the fact that the ocean absorbs CO_2 from the atmosphere. Scientist say that about half of the CO_2 generated from burning fossil fuels since the industrial revolution has been absorbed by the oceans (The Royal Society 2005). This rate is 100 times faster than it ever was before in the last 20 million years. (Rockström et al. 2009) and it leaves organisms in the ocean not enough time to adapt to these conditions. Studies “indicate that by the end of this century the surface waters of the ocean could be nearly 150 % more acidic, resulting in a pH that the oceans haven’t experienced for more than 20 million years” (National Oceanic and Atmospheric Administration of the U.S. Department of Commerce studies NOAA 2013).

The function is that once the [CO_2] is in the water it reacts with [H_2O] to form carbonic acid [H_2CO_3]. But this state is not steady and can quickly dissociate into bicarbonate [HCO_3^-] by releasing one [H^+]. This means that the more [H^+] ions are in solution, the lower the PH of the water is going to be, thus more acidic. The bicarbonate [HCO_3^-], however, can also further dissociate into carbonate [CO_3^{2-}]: [H_2CO_3] <=> [HCO_3^-] <=> [CO_3^{2-}]. The reaction can go into both directions. With the dissolution of CO_2 in seawater and the increase in [H^+] ions as the carbonic acid formed releases them, the reactions with [H^+] increase. This decreases the acidity of the water at least to some extent, but promoting the formation of bicarbonates.

$[CO_2] + [H_2O] => [H_2CO_3]$ - carbon dioxide and water form carbonic acid

$[H_2CO_3] => [H^+] + [HCO_3^-]$ - carbonic acid dissociates into $[H^+]$ hydrogen and $[HCO_3^-]$ bicarbonate

$[H^+] + [CO_3^{2-}] = [HCO_3^-]$ - the free $[H^+]$ hydrogen compounds with carbonate $[CO_3^{2-}]$ and also forms $[HCO_3^-]$ bicarbonate

In short this can be summarized as: $[CO_2] + [H_2O] + [CO_3^{2-}] => [2HCO_3^-]$) (The Royal Society 2005; National Oceanic and Atmospheric Administration NOAA 2020)

The lower the pH of the water the more difficult it is for marine life to sustain itself as a decrease in pH also decreases the metabolism and immune response of organisms and thus their behavior and abilities (International Union for Conservation of Nature IUCN 2020). The increase of CO_2 in the oceans "has led to a reduction of the pH of surface seawater of 0,1 units, equivalent to a 30 % increase in the concentration of hydrogen ion $[H^+]$" (The Royal Society 2005: iv). It is commonly understood that pH levels are very sensitive and that minor shifts can have immense consequences. With the seawater acidification as illustrated, this also demonstrably affects "the formation and dissolution of calcium carbonate shells and skeletons in a range of marine species, including corals, mollusks such as oysters and mussels, and many phytoplankton and zooplankton species that form the base of marine food webs" (International Union for Conservation of Nature IUCN 2020). This is because the compound $CaCO_3$, which is responsible for mineral formation, is impeded in formation, i.e. a prevention of calcination, or dissolved through the increasing number of carbonate ions $[CO_3^-]$ that react with the dissolved hydrogen $[H^+]$ thus forming bicarbonates $[HCO_3]$. The reason for this is that first of all, hydrogen ions $[H^+]$ tend to have a greater attraction to carbonate $[CO_3^-]$ than calcium $[Ca_2^+]$ (International Union for Conservation of Nature IUCN 2020) and second of all, "There is a critical concentration of carbonate ions in seawater (i.e. the saturation concentration) below which $CaCO_3$ will start to dissolve. […] Because added CO_2 decreases the carbonate ion $[CO_3^-]$ concentration, the saturation horizons will become shallower" (The Royal Society 2005: 44).

$[CaCO_3] \Leftrightarrow [Ca_2^+] + [CO_3^-]$ – this formula can go into both directions. Towards the left it means mineral formation and towards the left it means dissolution. (The Royal Society 2005: 43)

As the mineral calcite is less soluble than the mineral aragonite, both of which naturally occur in the ocean, the aragonite saturation level is lower (The Royal Society 2005: 44). The scientists of the Stockholm Resilience Center (Rockström et al. 2009) propose as a first estimate "a planetary boundary where oceanic aragonite saturation state is maintained at 80 % or higher of the average global pre-industrial surface seawater Ω_{arag} of 3,44". Since, however, it is very difficult and also seemingly counter-productive to actively influence ocean chemistry and aragonite saturation, the only reasonable way to try to stop ocean acidification and the subsequent calcium carbonate dissolution and calcination prevention trend is to reduce or best stop CO_2 emissions from entering the atmosphere. Only in this way the boundary conditions can be achieved and the acidification trend halted.

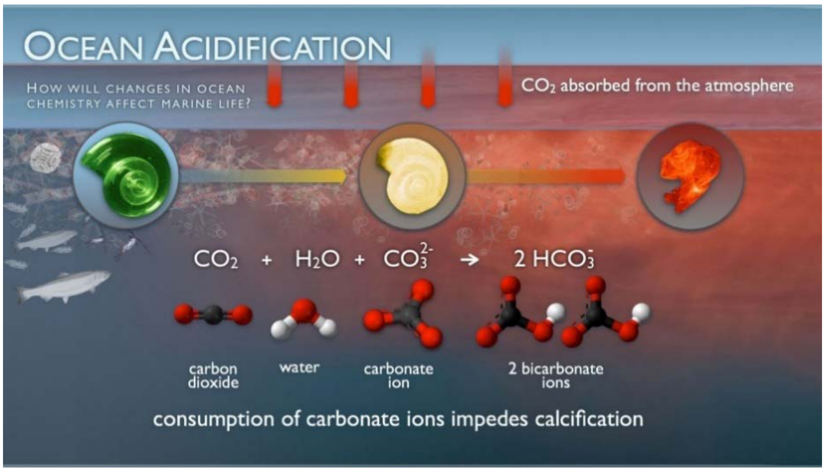


Figure 13 - Ocean acidification (National Oceanic and Atmospheric Administration of the U.S. Department of Commerce 2020

Boundary/ indicator to look for in Al production process:

- CO_2 emissions

6.6 Planetary Boundary Number 6 – PB6: Biochemical Flows (P and N)

The natural phosphorus (P) and nitrogen (N) cycle are important for nutrient supply in soil as they both play a crucial role in organism's energy transfer and the passage of genetic information (P) and the creation of amino acids, proteins as well as nucleic acids (N). They are in in close interaction with each other as key biological nutrients (Rockström et al. 2009). P and N can be found in nature on a large scale, i.e. they are very abundant, but rarely in a form that is easily biologically available. P is bound in "rock and sedimentary deposits and only released by weathering, leaching and mining" (Encyclopedia Britannica 2020a, 2020b). N, furthermore, even though one of the most abundant elements found in the atmosphere as gas, can only be converted into a biologically available form through nitrogen fixing bacteria in the ground that are able to break apart its triple covalent bond through the use of enzymes and symbiotic relationships with roots nodules of plants. Therefore, the natural P and N supply is not sufficient for human scale nutrient demand. For this reason, humans modify these cycles by synthetically fixing P and N on large scales.

This additionally introduced amount and thus increased circulation of P and N into the environment can have many adverse effects, especially on regional scales, such as eutrophication and other forms of pollution of aquatic and marine systems. Eutrophication leads to a decrease in biodiversity as organisms die in the water once it becomes anoxic. Aquatic systems may take long times to recover from this state (Rockström et al. 2009). "The flux of reactive (biologically available) nitrogen to the coasts and oceans increased by 80 % from 1860 to 1990, with […] more reactive (biologically available) nitrogen (produced by humans) than is produced by all natural pathways combined, and some projections suggest that this may increase by roughly a further two thirds by 2050" (World Resources Institute 2005).

Human-driven conversion occurs primarily through four processes: industrial fixation of atmospheric N_2 to ammonia (~80 Mt N a^{-1}); agricultural fixation of atmospheric N_2 via cultivation of leguminous crops (~40 Mt N a^{-1}); fossil-fuel combustion (~20 Mt N a^{-1}); and biomass burning (~10 Mt N a^{-1})" (Rockström et al. 2009). Also, N flows have been primarily regulated on local and regional scales but not on global one. Therefore, although also uncertain, as a first proposal it was simply chosen to set the planetary boundary of N flow as 25 % of the current anthropogenically induced N inflow into the environment, thus at about 35 Mt per year.

On a more global scale the inflow of phosphorus into the oceans is the same problem. In the past "the crossing of a critical threshold of P inflow to the oceans has been suggested as the key driver behind global-scale ocean anoxic events" (Rockström et al. 2009). It is proposed that P inflows into the ocean that exceed 20 % of the natural weathering can be the reason for such events. The inflow of reactive P from human activities into oceans is estimated to be around 9 Mt per year (of 20 Mt per year mined). It is noted, however, that there is a high uncertainty of and if anthropogenically induced P inflows can cause such anoxic events. However, it is argued as boundary that the "anthropogenic P inflow to the ocean is not allowed to exceed a human-induced level of ~10 times the natural background rate of ~1 Mt P yr^{-1}" (Rockström et al. 2009).

Boundary/ indicator to look for in Al production process:

- Phosphorus
- Nitrogen (fossil fuel combustion)

6.7 Planetary Boundary Number 7 – PB7: Global Freshwater Use

Global freshwater use is not only related to human induced use of fresh water but closely connected to the global climate dependent hydrological cycle. According to this planetary boundary there are two types of water use to be considered, **green water** (precipitation that adds to soil moisture and does not run off, eventually evaporating or transpiring) and **blue water** (freshwater in lakes, rivers, reservoirs and groundwater stores) (Gleeson et al. 2020: 1). A change in green water flows can have "impacts on climate regulation [...] affecting local and regional precipitation patterns" (Rockström et al. 2009). The reasons for such a change can result in land degradation and deforestation. For the boundary itself only blue water is considered as land use is a goal in itself and it is proposed that "[t]he close interactions between land and water, and between vapor flows and runoff, make it difficult to define an appropriate freshwater boundary that captures the complexity of rainfall partitioning across scales" (Rockström et al. 2009). It is estimated that there are accessible blue water resources in the range of ~12.500 km³ - 15.000 km³ per year (Postel 1998, DeFraiture et al. 2001 in Rockström et al. 2009). Currently there is a water withdrawal of ~4.000 km³ - (4 trillion m³ as shown in Figure 14) and it is estimated that physical water scarcity is reached at a threshold of 5.000 km³ - 6.000 km³ per year.

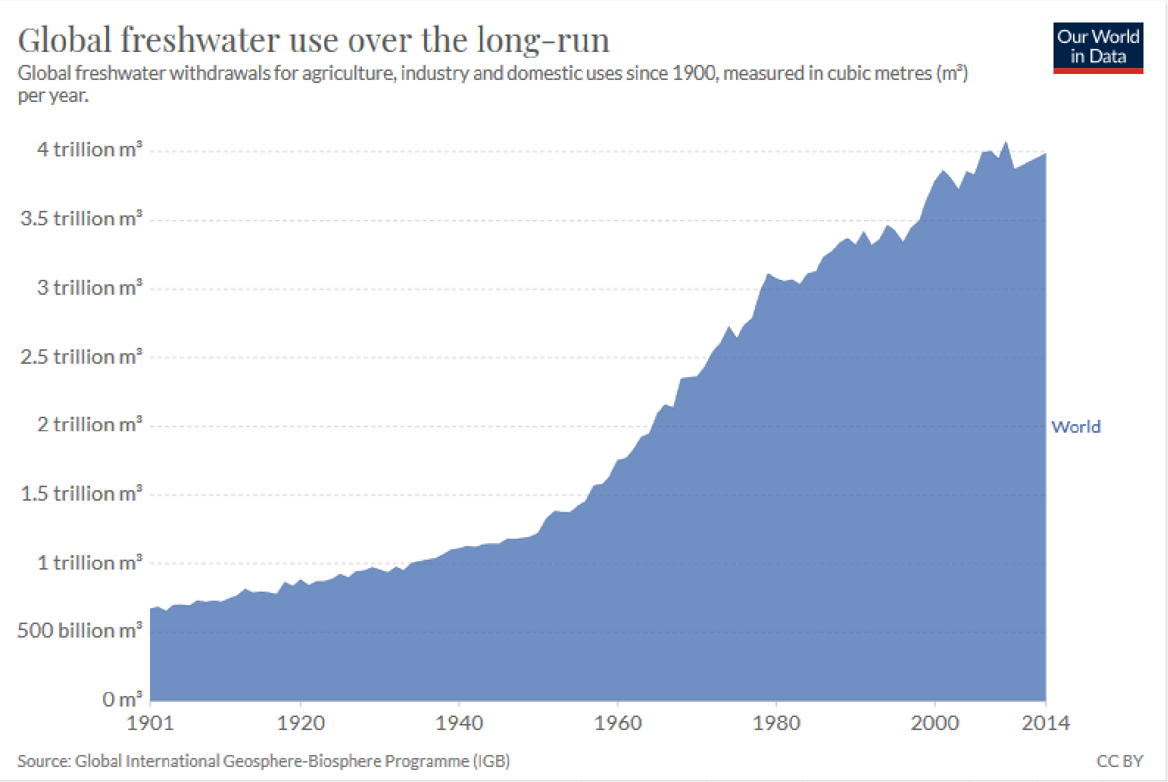


Figure 14 - Water Use and Stress (Ritchie and Roser 2017)

With growing demand of blue water in agriculture for irrigation corresponding to the increase in food production in coming years it seems as though the "remaining safe operating space for water may be largely committed already" (Rockström et al. 2009). Already 70 % of all freshwater withdrawal comes from agriculture as opposed to 20 % from industrial use (Ritchie and Roser 2017). Considering the increasing requirement for minerals in variety and amount to meet the future technologies and energy demand (World Bank Group 2020), it becomes clear that it is crucial to analyze and design water use in minerals production as efficiently and water scarce as possible.

Boundary/ indicator to look for in Al production process:

Freshwater usage

6.8 Planetary Boundary Number 8 – PB8: Land System Change

Land system change is societally driven conversion of land for socio-economic purposes. According to the last IPBES biodiversity report and Verburg 75 % of the ice-free land of the earth system has been altered by humans (Intergovernmental Platform on Biodiversity and Ecosystem Services 2019: 11, Verburg et al. 2013: 433). Further expansion of land use may seriously threaten the functioning of the ecosystem, biodiversity and the regulatory capacity of the earth (Rockström et al. 2009). "These changes affect the structure and function of ecosystems and alter their capacity to provide sustained ecosystem services for human well-being" (Verburg et al. 2013: 435). Thus, the over-altering of the earth's land to gain socio-economic benefit now fires back through inhibiting these benefits because of a loss of regulatory capacity of the earth system. The main driver of land conversion globally is agriculture which is also why the planetary boundary framework is mainly concerned with this and has only set a boundary for a maximum amount of agricultural global land usage. In terms of Aluminium production a driver of land system change is bauxite mining. It may not be an extensive driver in terms of size of land it uses, total global mining activity temporarily utilizes about 0,3 % of the global land system (Hooke and Martín-Duque 2012) but it should be looked at closer in terms of which type of land it uses. There are more and less sensitive land systems with tropical forests counting as the most sensitive as they have extensive global climate-buffering capacity (Pullen et al. 1996, Mackey et al. 2020). According to Tost the tropical biomes also have the highest ecosystem costs (Tost et al. 2020).

Boundary/ indicator to look for in Al production process:

Alteration of land through any production process

6.9 Planetary Boundary Number 9 – PB9: Biosphere Integrity (functional and genetic diversity)

There is growing evidence that biodiversity systems are crucial for sustaining ecosystems, their functioning and their services (Rockström et al. 2009). Their potential to respond and adapt to changes in physical and biotic conditions is affected as due to species loss the diversity of response mechanisms to these changes gets reduced. As a result, the biotic capacity of ecosystems is decreased. Since the start of the Anthropocene human influence has resulted in an increase of 100-1.000 times the extinction rates that were natural for thousands of years, currently ranging at around ≥100 extinctions per million species-years. Currently, 25 % of all species are threatened with extinction. "It remains very difficult to define a boundary level for the rate of biodiversity loss, that if transgressed for long periods of time, could result in undesired, non-linear Earth System change at regional to global scales." This is due to the fact that science does not yet have a clear boundary on the regulating role and mechanisms of biodiversity. However, the boundary is placed at 10 extinctions per million species-years to leave a safe room for uncertainty and to create a safe boundary (Rockström et al. 2009). Clearly, the boundary is being transgressed heavily. "Rates of habitat conversions, especially of forests, are higher in tropical regions than elsewhere on Earth" (Orians 2000). Interfering with these complex systems therefore generates high impact on their contained biodiversity as the complexity of interaction between species may be destroyed easily and may never be restored.

Boundary/ indicator to look for in Al production process:

Alteration of genetic or biodiversity through any production process

7 ALUMINIUM AS KEY MATERIAL IN OUR SOCIETY

As mentioned above Aluminium is the system component and material of choice for the following case study and it has been elaborated why this is so. However, to be able to develop a more in-depth understanding of the role and importance of the metal Aluminium in our society, its history, material properties and application areas are important to know and are described in more detail in the following passage.

7.1 The material Aluminium

With 8,3 % Aluminium is the third most abundant element in the earth's crust after oxygen (46 %) and silicon (28 %) (AZO materials 2005). "A pure form of the metal was first successfully extracted from ore in 1825 by the Danish chemist Hans-Christian Oersted." (The Aluminum Association 2020b). The reduction agent used back then to extract it was sodium (Na). It was first produced efficiently in 1886 through the invention of the Hall-Héroult electrolysis, which was only possible through the advent of electricity as the crucial cost factor for production (American Chemical Society 2020). Attempts to extract the material out of the ore before this were despite successful very labor intensive and inefficient with regards to the amounts that were won and the material was very costly. At this time Al had a higher price than gold. In 1852 the price for 1 kg of Al was $ 1.200 which dropped to $ 1 per kg around 1900 (Thompson 2016). From that time on the triumph of Al was unstoppable (Figure 15, Figure 16).

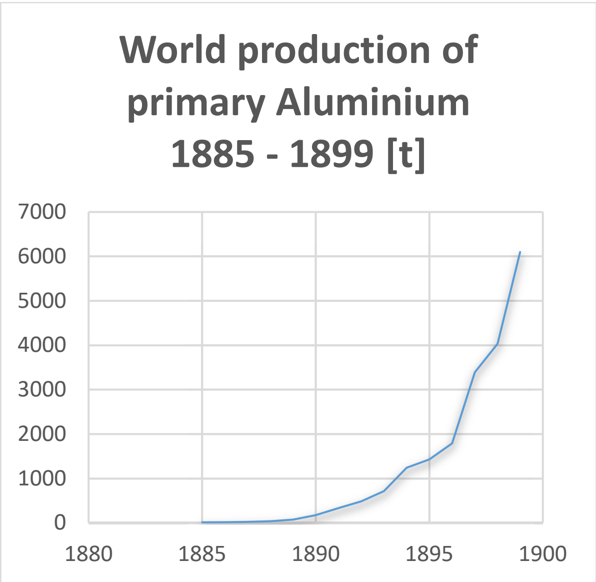


Figure 15 - Historic trend of primary Aluminium production 1885-1899 (Belli 2012)

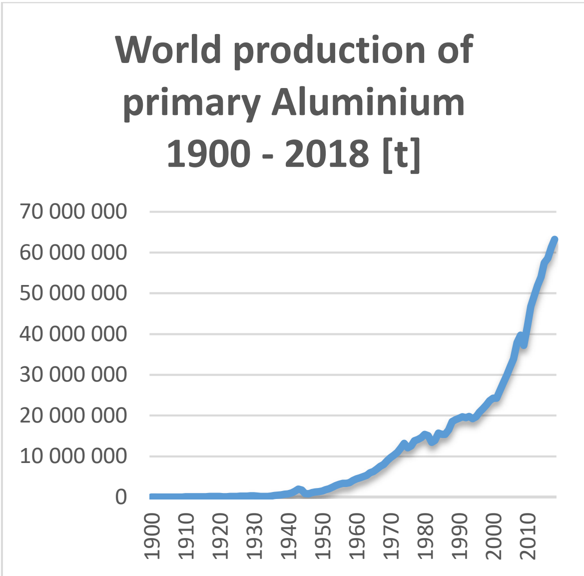


Figure 16 Historic trend of primary Aluminium production 1900 -2018 (Data 1900-2015: USGS 2015, Data 2016-2018: Reichl 2020)

The amount of Aluminium annually produced has since the industrial processing was invented only ever increased and seems to be skyrocketing since the middle of the 1990s when primary production has increased from roughly 20 Mt per year in 1995 to more than 60 Mt in 2020.

In 2018 the total primary production output was 63,2 Mt per year (Reichl 2020) and secondary production was 17 Mt per year (World Bureau of Metal Statistics 2018), which is a total of 80,2 Mt. According to Gutowski Aluminium demand is forecast to grow between a factor of 2,6 and 3,5 between 2005 and 2050 (Gutowski et al. 2013: 12) and the European Aluminium says that "[t]he global demand for primary Aluminium is expected to increase by 50 % by 2050, reaching 107,8 million tonnes" (European Aluminium 2019b). They attribute future demand to mainly mobility, construction and packaging whereas it is further pointed out that Aluminium will play a key role in any future technology-based mitigation scenario for both energy generation and storage technologies and hence the demand from 2018 production levels will increase significantly (World Bank Group 2020: 79).

Aluminium has evolved our society over the 20th century and enabled us to change mobility and mobilized modern life. It enabled the space age and moon landings. "It allowed airplanes to be built stronger and larger, it allowed buildings to be built higher, and it allowed power lines to be built further apart" (Thompson 2016). Furthermore, "[…] it became an essential ingredient in industrial and domestic products that ranged from airplanes and cars to designer chairs and artificial Christmas trees. It entered modern homes as packaging, foil, pots, cans and pans […]" (Sheller 2014). Aluminium has thus made available such an array of applications that today's consumer has functions fulfilled in everyday life that people 100 years ago could only dream of.

Due to the versatility of material properties countless applications have evolved in its 130-year history, as outlined below:

- **Construction, architecture** - roofs, winter gardens, window constructions, façades, office equipment etc.
- **Engineering constructions** - bridges, halls, telescopic platforms, tunnel formwork, scaffolding etc.
- **Mechanical engineering** - Al-profiles, casting parts, climate control technology etc.
- **Mobility technology** - air plane, ship, rail, vehicle construction etc.
- **Energy technology** - overhead line parts, Al alloyed steel wires etc.
- **Sporting goods** - skies, chain bikes, walking sticks, alpine sporting goods etc.

- **Household items** - foil, pans, ladders, buckets, baking pans, laundry racks, soap and toilet paper holders, sieves, jar lids, kettles etc.
- **Packaging** - drinks and food packaging, bottle lids, small load containers, tubes, medical packaging, foils etc.

"Packaging today responds to consumers' demands for choice and convenience as well as changed production and distribution conditions and systems" (AZO materials 2002a). Aluminium offers many advantages. It is corrosion resistant, an impermeable metal barrier to light, ultra-violet rays, water vapor, oils and fats, oxygen and micro-organisms. It is hygienic, non-toxic, non-tainting and retains the food's flavors and keeps contents fresh. This results in a long shelf-life. An Al thickness of 0,0006 mm is often enough for the needed barrier functions which further results in little material use per package and ultra-light weight (AZO Materials 2002a). It thus allows foods to be distributed over wider distances and thus makes it available for a wider population. According to World Aluminium the material packaging saves more resources than it needs in its production as it severely counteracts food loss in developing and developed countries, thus also the resources that go into the food production (World Aluminium 2018a). "Packaging is an essential part of a long-term incremental development process to reduce [food] losses" (Food and Agriculture Organization of the United Nations FAO 2014). However, a disadvantage of Al packaging for foods is that when used with acidic foods, the food ends up tasting like Aluminium.

7.2 Material properties, applications and functions

Aluminium's importance keeps on increasing in today's world. The main reason for the strong demand seems to be the material properties which render it a versatile, durable, "easy-to handle" and an affordable material as briefly summarized below (Davis 1999).

- **Low density (2,7 g/cm^3)/ Light weight**

Aluminium is a very light material with only one third the density of steel. One cubic decimeter of steel has a mass of around 8 kg and 1 cubic decimeter of Aluminium has a mass of around 2,7 kg. This results in less weight of Aluminium products which makes them for example easier to handle and more fuel efficient to transport. Packaging profits from the light weight of Aluminium in this way, for example in juice packaging where a 4,8 g flexible fruit pouch with Aluminium is many times lighter than a traditional glass bottle (AZO Materials 2002a).

- **High corrosion resistance through a natural Al_2O_3 protective layer**

When Aluminium is exposed to oxygen it immediately forms a thin oxide layer which acts as a protective layer against corrosion. Certain substances or conditions may destroy this protective oxide layer, such as alkalis but in general Aluminium is many times as corrosion resistant as other metals as the oxide layer is very stable. High corrosion resistance results in longevity of products.

- **Relatively low melting point (660 °C)**

Aluminium has a melting point between 570 °C and 660 °C. In alloyed form this may be even a little bit lower. A low melting point means e.g. considerably less energy input into the remelting of Aluminium for the casting of Aluminium semi-finished products. In comparison, copper has a melting point of 1.084 °C and pure iron 1.536 °C (Davis 1999).

- **High electric and thermo-conductivity**

Aluminium is used as electric conductor in power lines. Power lines are often made of Aluminium not Copper (Cu), although Cu conducts electricity better than Al. The power lines of Aluminium thus have to be thicker than Cu lines but they are still lighter. This means pylons can be built further apart and thus this saves money and material for building pylons (Thompson 2016). Further this means less land use.

Furthermore, Aluminium has a thermal conductivity at the top of the range for metallic alloys. “Aluminium’s high thermal conductivity can help minimize the time and energy taken to process, chill and reheat foodstuffs and to chill drinks in cans and pouches“ (World Aluminium 2018b). It is thus ideal for applications that minimize heating and chilling times.

- **No ferro-magnetic properties**

Aluminium is non-ferromagnetic which makes it ideal for any applications where magnetic properties create problems.

- **Reflectivity**

Aluminium has a very attractive appearance due to its shiny and glossy surface. However, this fact also has practical implications as Al hence reflects light with a more than 80 % range. This allows a much wider range of lighting in lighting fixtures. This reflectivity leads to Aluminium roofing reflecting a high percentage of the sun’s heat, promoting a cool interior atmosphere in summer, yet insulating against heat loss in winter. In fact, it is an excellent reflector of radiant energy through the entire range of wave lengths. “From ultra-violet through the visible spectrum to infra-red and heat waves, as well as electromagnetic waves such as radio and radar" (AMS 2020).

- **High material strength**

In relation to its low-density Al is much stronger than other metals. "This property permits design and construction of strong, lightweight structures that are particularly advantageous for anything that moves - space vehicles and aircrafts well as all types of land- and waterborne vehicles" (Davis 1999: 2). It does not lose its strength at low temperatures and is thus often used for cryogenic applications (Davis 1999: 1).

- **Bio- and eco-compatibility**

Aluminium as material is biocompatible and has unique properties such as moisture, oxygen and light resistance. This allows application in packaging. It is mostly used in food and medication packaging to increase longevity of products and does not have any influence on the packaged good, unless acidic. Existing alternatives are Gold (Au) or Copper (Cu) but they are economically not interesting. If after anthropogenic use Aluminium accumulates in the ecosphere it is non-toxic compared to other metals (Global Future Contamination Index FCI and median sink life in Azar 1996: 94) which is why it should be a light metal of choice (Holmberg 1995: 19).

- **Ductility**

Aluminium can be fabricated into any kind of shape known. There is almost no limit.

> It can be cast by any method known to foundry men; it can be rolled to any desired thickness down to foil thinner than paper; Aluminium sheets can be stamped, drawn, spun or roll-formed. The metal also may be hammered or forged. Aluminium wire, drawn from rolled rod, may be stranded into cable of any desired size and type (Davis 1999: 4).

In the same way the material can be machined easily, allowing most machines to operate at maximum speeds and thus making operations very cost efficient.

- **High alloying capacity**

In its original form Al has a tensile strength of about 70 MPa and is not as strong as when alloyed with small amounts of other metals that change the chemical structure of Aluminium. Through this and also cold working or heat treatment of the alloyed Al tensile strengths of up to 700 MPa can be obtained (Total Materia 2006). This fact however, also means more difficult recycling of Aluminium as it is practically difficult to separate alloyed Al into its constituent parts. However, through homogenous sorting it can be recycled according to type.

- **Good castability in the form of alloys**

"Castability is known as the ability of an alloy to be cast without formation of defects such as cracks, segregations, pores or misruns. Alloy dependent phenomena that determine castability are fluidity, macro segregation, hot tearing and porosity" (Di Sabatino and Arnberg 2009). Aluminium casting alloys, especially the near-eutectic ones, have excellent flow and mold filling properties. The good castability includes relatively high fluidity, a low melting point, short casting cycles, relatively low tendency for hot cracking, good as-cast surface finish and chemical stability (Otarawanna and Dahle 2011).

- **Recyclability**

Aluminium is a permanent material, which means that the metal we produce today does not just meet the current demand for the material in cars, packaging, buildings, and more, but over time accumulates to create a major economic resource for the future. Once Aluminium has been produced it is meant to stay in use as long as possible and it can be recycled easily (European Aluminium 2019a).

Aluminium can be recycled multiple times without losing its original properties, for at least 20-30 recycling trips or more (European Aluminium 2019a: 22). It falls under the category of permanent materials (vs. non-permanent materials) which not only means that it is meant to stay in use as long as possible but that recycling does not downgrade the material properties as is the case with other materials that after a few cycles become unusable or suffer major material loss. It further means, that once it goes out of use it remains and is not lost as such "[…] metals such as Aluminium (Al) and Iron (Fe) are elements and so cannot be destroyed. In fact, planet earth has not suffered any loss of metal elements; they merely move location and appear in different forms" (Metal Packaging Europe 2020). They move from the lithosphere into the technosphere and eventually to the ecosphere from where they will be slowly reintroduced into the lithosphere (Holmberg 1995). Its material and recyclability properties make Aluminium highly interesting for future energy technologies that enable the green transition within the EU Green Deal.

7.3 Embodied energy of Aluminium production

Aluminium is a very energy and thus CO_2 intensive metal in its primary production. Per ton of Al, 20-40 GJ of energy input are required in the Bayer process, 150-160 GJ in the Fused-salt Electrolysis. This means an energy balance of approximately 200 GJ in primary production excluding the mining energy requirement. In contrary to that the energy embodied in recycled aluminium is much lower: 14-18 GJ if the Aluminium comes from the refining phase and/ or

7-9 GJ from the remelting phase (Low-Tech Magazine 2020, Norgate and Jahanshahi 2011, Antrekowitsch 2019).

It is an agreed upon fact, that in the life cycle of primary Aluminium production it is the chemical reduction steps that are responsible for the large energy footprint of Al production (Gutowski et al. 2013) and not like in gold production where the ore is highly dilute and the mining step and thus the amount of "ground/soil" moved is the perpetrator for energy consumption. However, there has been a constant trend in smelter energy decrease over the past years due to technology improvements (International Energy Agency IEA 2020a)

BAT and thermodynamic limits

In an attempt to estimate "the possibility of reducing absolute material production energy by half, while doubling production from the present to 2050 (1)," Gutowski suggests that the two core steps to reduce energy intensity of [Aluminium] production would be for all production to use the existing best available technology (BAT) and to move towards the theoretical minimum of energy reduction (Gutowski et al. 2013: 5). In terms of BAT they have found that the Al smelting operations using current BAT by far outdo the ones that use older technologies in terms of energy efficiency. Against common expectation "[…] some of the least energy-efficient facilities for Aluminium production are actually operated in the developed world where the installations are older […] (Gutowski et al. 2013: 5)" which is due to the investment realities of such industrial facilities. Once in operation they have to stay in operation for as long as possible to pay off. The authors estimate "that a worldwide move from today's average towards BAT would result in an overall energy reduction of about 18 % (Gutowski et al. 2013: 6)." As far as the second option of moving towards the theoretical minimum energy in Al production is concerned Choate et al. generally state that the theoretical minimum energy needed for the transformation of a material is "simplistic, thermodynamically ideal and require[s] and infinite time to complete [… but] provide[s] benchmarks [for R&D] that no process will do better" (Choate et al. 2003). It is thus a benchmark that should be moved towards. It also highlights the range of R&D opportunities. If this range in an overall evaluation is not sufficient then more drastic strategies may have to be deployed. An overall reduction of around 37 % energy input could be achieved if both strategies were deployed, with an 80 % efficiency towards the theoretical limit (Gutowski et al. 2013: 7) (Figure 17).

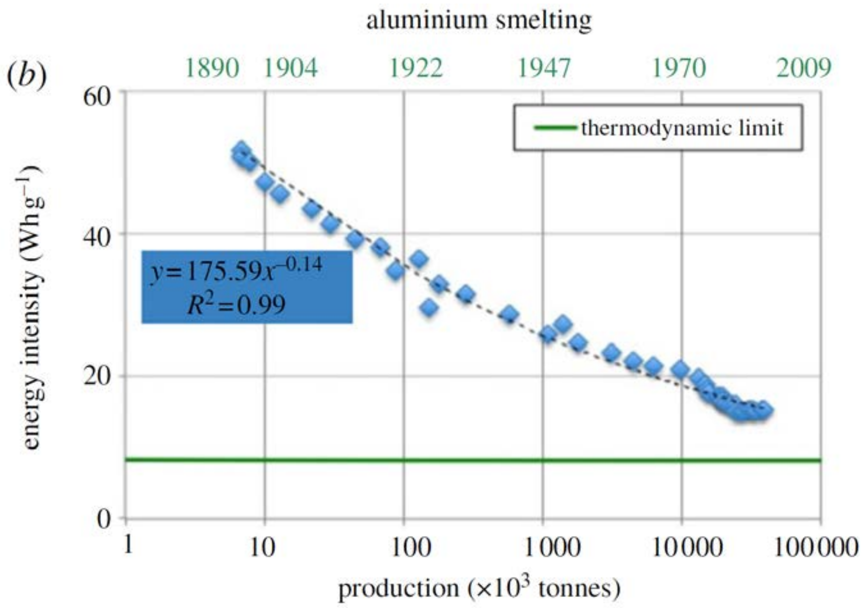


Figure 17 - Thermodynamic limit of Aluminium smelting energy efficiency (Gutowski et al. 2013)

All in all, the principle of decoupling, namely reduction of production impact with increasing or stable output, is met to a certain extent in Gutowski et al.'s as well as Choate et al.'s approach. However, according to the authors, energy intensity could not be reduced by 75 %, which would be necessary if the goal of halving material production energy while doubling production until 2050 should be met. Therefore, BATs are still limited, and the solution may only be a technology improvement, a new technology or a process improvement within the proposed R&D space that this approach offers.

The production methods of primary Al production have not changed since the beginning of production in 1886, however, they have become much more efficient. "There has been an impressive reduction [in the energy intensity/ the electricity used in the smelting of Aluminium] over about a century. The average annual improvements for the energy intensity for these technologies have been in the range of 1,0 % - 1,5 % (Gutowski et al. 2013: 5)" which corresponds to the IEA information of annual overall reductions in energy intensity in Aluminium production (including bauxite production and recycling) of 1,2 % in 2018 and an average decline of 1,2 % in the timeframe 2010-2017 (in Alumina refining 3,0 % in the timeframe 2010-2017, decreasing only by 1,8 % in 2018 and in Aluminium smelting an energy intensity reduction of on average 0,6 % for the timeframe 2010-2017 and 0,4 % in 2018) (International Energy Agency IEA 2020a) (Figure 18). Nevertheless, Aluminium smelting makes up 75 % of all Aluminium production energy requirement (Gutowski et al. 2013: 6).

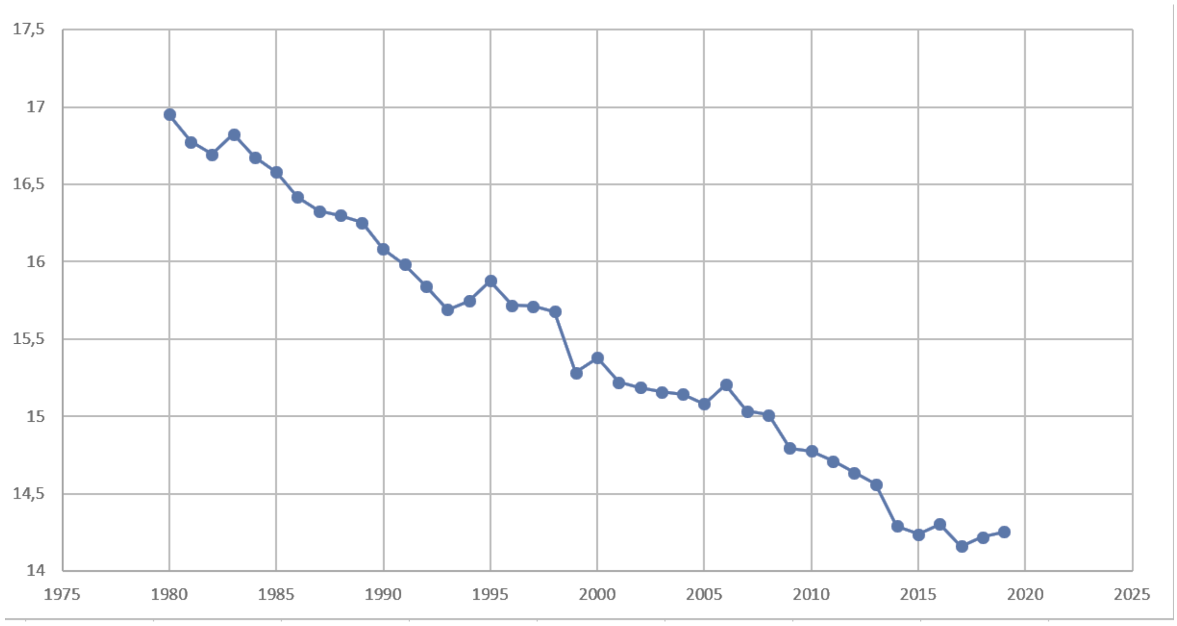


Figure 18 - Historic trend for energy intensity of Al production (kWh/t) 1980-2019 (World Aluminium Statistics 2020)

According to the IEA more than half of the Aluminium production in 2018 was in China (International Energy Agency IEA 2020a). It was also China that is responsible for the drop in production energy intensity as they are leading smelting performance with BAT since 2014 (Figure 19).

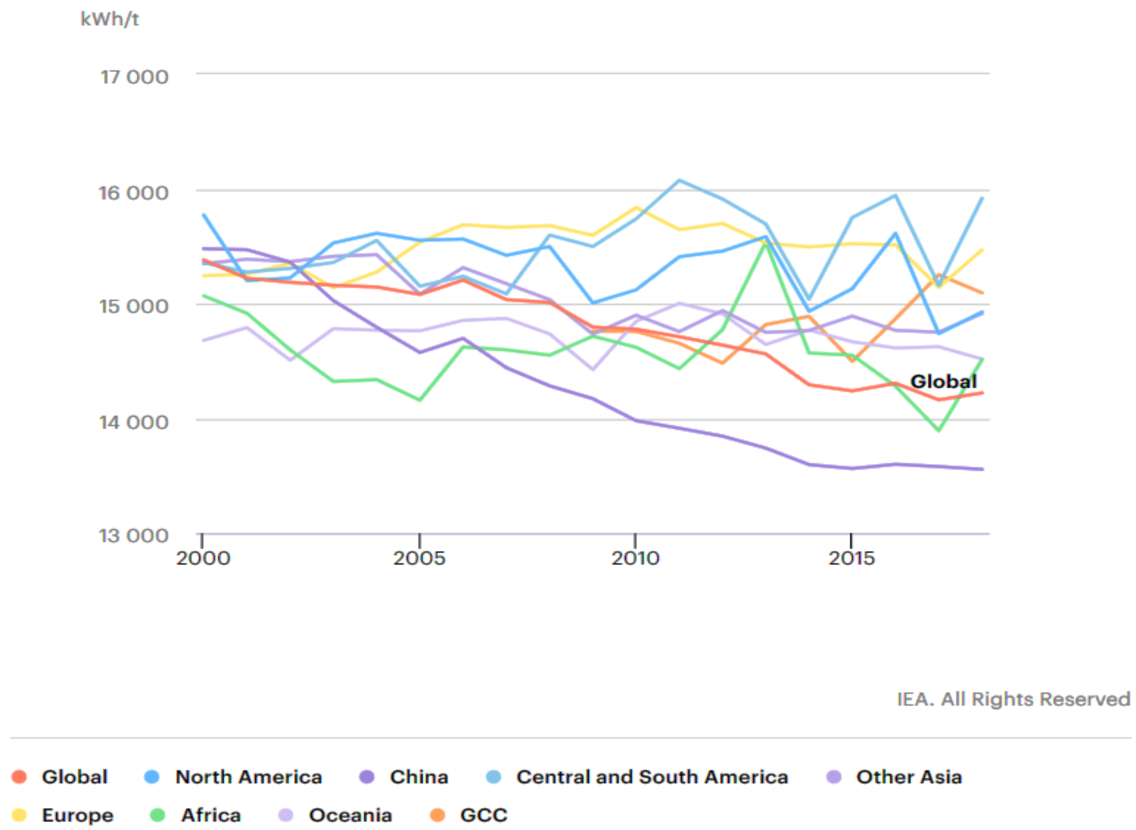


Figure 19- Electricity intensity of primary Aluminium smelting by region 2000-2018 (International Energy Agency IEA 2020a)

8 The Aluminium Production System

Best available technology and best practice standards of the Aluminium life cycle will be scrutinized according to the structure illustrated in Figure 20. The unit processes (UPs) and system boundaries that were isolated for analysis are clearly depicted and defined. The individual unit processes are explained and where possible brought into relation with the PB indicator framework. This chapter serves as basis for the case study in chapter 8.

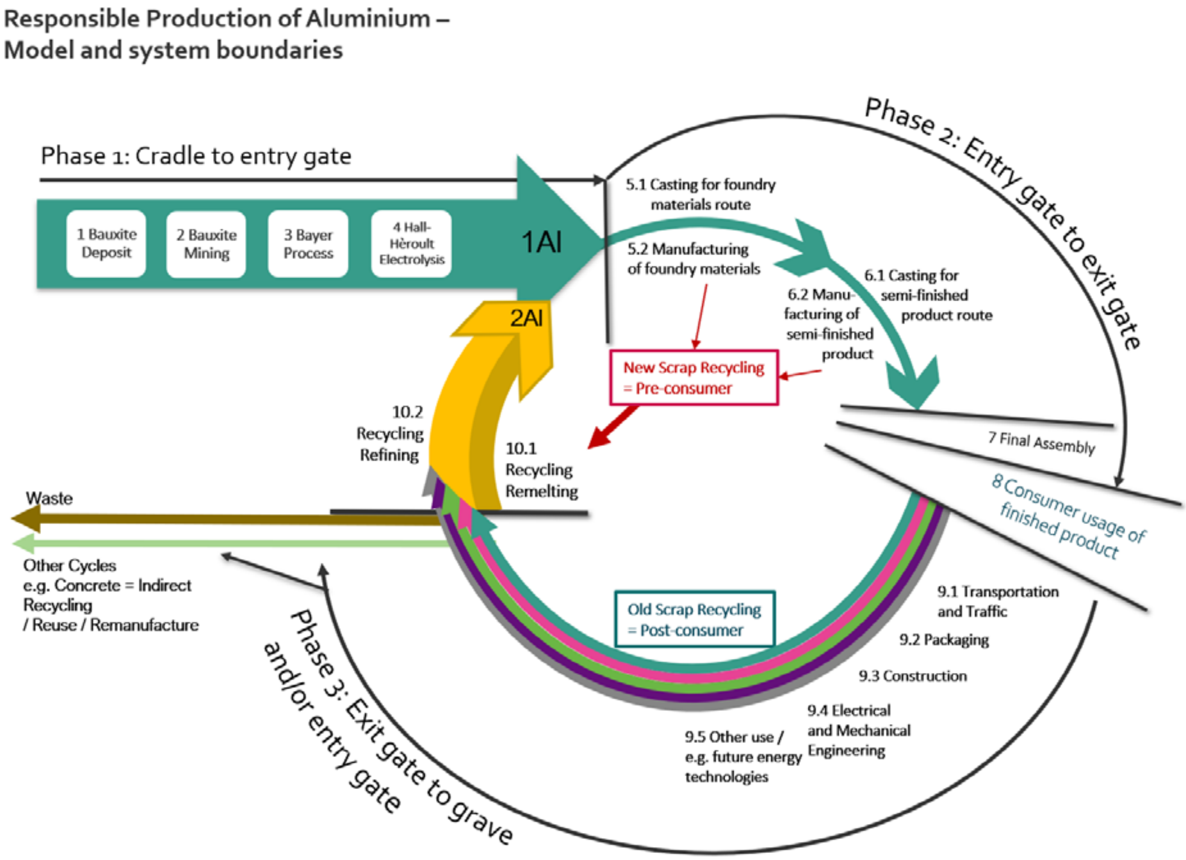


Figure 20- Aluminium cycle system boundaries and unit processes

8.1 Phase 1 of the Aluminium production process – Cradle to entry gate

All of the primary Aluminium production is composed of three production steps as follows (Figure 20): (1) Bauxite deposits are explored and then (2) Bauxite is extracted and send to a plant with little or no processing (3) In a plant in a first step Alumina is produced through a wet-chemical leaching of the bauxite in the Bayer process followed by (4) Aluminium production through fused-salt electrolysis (Hall-Héroult process). The rough material input is 5 t of bauxite for 2 t of Alumina for 1 t of pure Aluminium - 5:2:1(Balomenos et al. 2011).

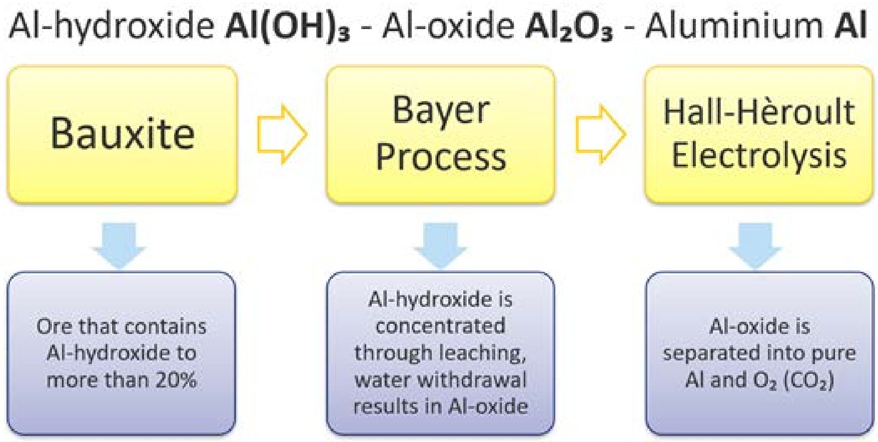


Figure 21 - Simplified overview of primary Al production process

8.1.1 UP1: The bauxite deposit and pre-mining activities

Characteristics of bauxite deposits: Bauxite, which is named after the place it was first found, in Les-Baux-de-Provence in France, is a heterogeneous material, mainly composed of one or more Al-oxides and Al-hydroxides. Furthermore, it contains changing mixtures of silica, iron oxide, titanium oxide, Alumina-silicate and other impurities (Mineralienatlas 2020). There are two differentiations of bauxite deposits according to the underlying rock types: First, there is silicate or laterite bauxite, which is, weathered residual material formed in subsoil on any Aluminium rich rock and with little iron content. This type mainly appears in tropical and sub-tropical regions as warm and moist climate conditions with dry periods and varying ground water levels are a prerequisite for its formation (United States Geological Survey USGS 2020, Mineralienatlas 2019). Deposits of laterite bauxite are mainly found in Australia, India, Guinea, Brazil and Jamaica (United States Geological Survey USGS 2020). The second type is karst type bauxite, mainly formed on carbonate rocks or karstic depressions. It is transported material such as felsic volcanic ash or any aluminous sediments washed into the basin of deposition. Deposits of karst bauxite are mainly found in Europe, Turkey, Russia and China. Karst bauxite is economically not as important as laterite bauxite (United States Geological Survey USGS 2020, Mineralienatlas 2019). Bauxite from laterite type deposits contain around 20 % to 25 % of Al or 40 % to 50 % of Al_2O_3. The mining cut-off grade is usually around 20 % Al.

The general geometry of bauxite deposits can be characterised as tabular shaped layers of bauxite material with a thickness in the range of meters up to 10 m, sometimes even more. Bauxite deposits stretch out typically over quite large areas. Most of the bauxite deposits occur close to the surface with a waste rock coverage of some meters only.

Prospection and exploration of bauxite deposits is therefore typically based on geological investigations and the geo-chemical properties of the earth. Due to the rather continuous nature of bauxite deposits, **exploration** for them is typically based on a wide network of core drilling: e.g. in a grid of 200 m x 200 m. Once a pre-feasibility study for a bauxite deposit based on core drilling is done, a second exploration step as input into a feasibility study might be based on trenching with a more detailed analysis of the quality and quantity of the bauxite deposit.

Environmental impact of prospection and exploration of Bauxite deposits

Due to the nature of bauxite deposits, the efforts for their prospection and exploration are quite low. As explained above exploration through core drilling is typically done on a very large grid of around 200 m by 200 m. Taking an average value of 1m for soil coverage and 5 m for the overburden and 5 m for the thickness of a bauxite deposit, around 50 m of core drilling are sufficient to explore around 2,4 Mt of bauxite. Therefore, the exploration efforts are around 20 m core drilling per Mt of bauxite. Therefore, the exploration efforts are around 20 m core drilling per Mt of bauxite, a comparatively low value. In terms of core drilling costs these amount to around 5.000 € to 10.000 € per 1 Mt of bauxite with an estimated time of at most 2 3 days of drilling, resulting in 1 t of CO_2 emissions (200 kW drill rig, 1 m core/ hour, 0,2 l diesel/ kWh, 2,65 kg CO_2/ litre of diesel), 2 m^3 of water consumption (water recycling during drilling) and based on BAT exploration technology negligible land disturbance. No other areal emissions than CO_2 and water use are expected from exploration drilling on the basis of the BAT procedure.

8.1.2 UP2: Bauxite mining and processing

According to World Mining Data, Bauxite production in 2018 was around 335 Mt (Reichl 2020). 95 % of the bauxite production is used to produce Aluminium. The rest of the bauxite goes into other applications as e.g. cement production. The total primary Aluminium production in 2018 was 63 Mt. Thus from 5 t of bauxite around 1 t of primary metallic Aluminium can be extracted. The biggest bauxite production countries in 2018 were Australia, China, Guinea, Brazil, India, Indonesia and Jamaica (Figure 22, Table 4). With respect to global production distribution and company concentration the supply risk of bauxite/ Aluminium is low with a Herfindahl-Hirschmann-Index of 812 (low) (Bundesanstalt für Geologie und Rohstoffe BGR 2013). Current global known bauxite reserves are around 70 Gt (BGR 2020). Thus, the supply based on the current amount of reserves and current production rates will last for more than several centuries.

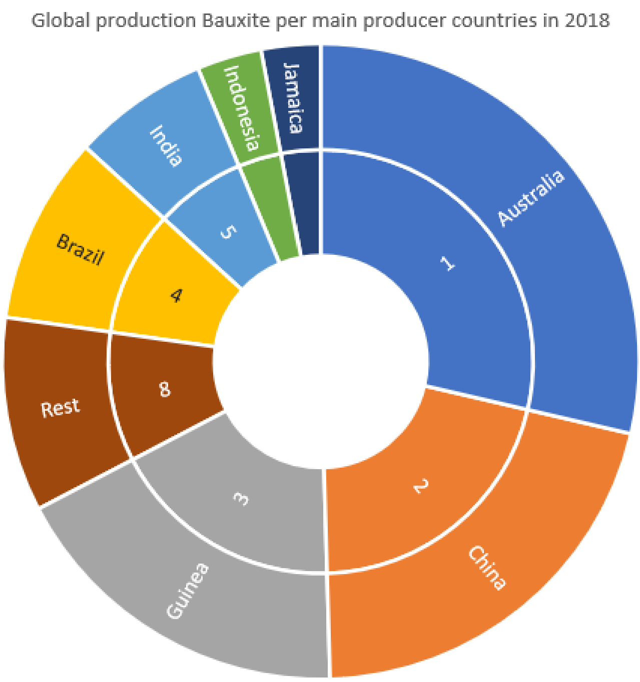


Figure 22- World production of Bauxite in 2018 per main producer countries (Reichl 2020), exact data cf. Table 4

Table 4 - Bauxite producer countries 2018 with more than 10 Mt per year

	Top (source: Reichl 2020, World Mining Data)		
	unit: metric tons		
1	Australia	*29%*	*95.947.593*
2	China	*21%*	*70.000.000*
3	Guinea	*18%*	*59.573.707*
4	Brazil	*9%*	*32.000.000*
5	India	*7%*	*23.193.680*
6	Indonesia	*3%*	*11.023.850*
7	Jamaica	*3%*	*10.058.228*
	Top 7	**90%**	**301.797.058**
	World Rest	**10%**	**33.165.327**
World production in Mt		**100%**	**334.962.385**

Bauxite is mainly mined in tropical and subtropical areas and is mined in open pit mines as the bauxite usually appears in relatively thin tabular layers close to the surface. The typical steps involved in bauxite mining are summarized in Figure 23.

Bauxite mining and processing steps (9): (based on Australian Aluminium Council 2020, World Aluminium 2018c)

(1) Land clearing: The first step is to clear the surface from (typically) rain forest trees and vegetation. Useful timber is collected. If an average bauxite thickness of around 5 m and an ore density of 3 t/ m^3 is taken into account, around 6 to 7 ha of direct land are used for 1 Mt of bauxite. Of course, this may vary significantly with the geometry and coverage of bauxite deposits, with several "extra" needed for the mining and processing infrastructure (access roads, repair shops, mining and processing building, stock pile areas etc.) it is estimated that around 15 ha of land per 1 Mt of bauxite produced are temporarily used.

(2) Collection of rehabilitation material: In a second step, seeds, seedlings and cutting are collected for rehabilitation.

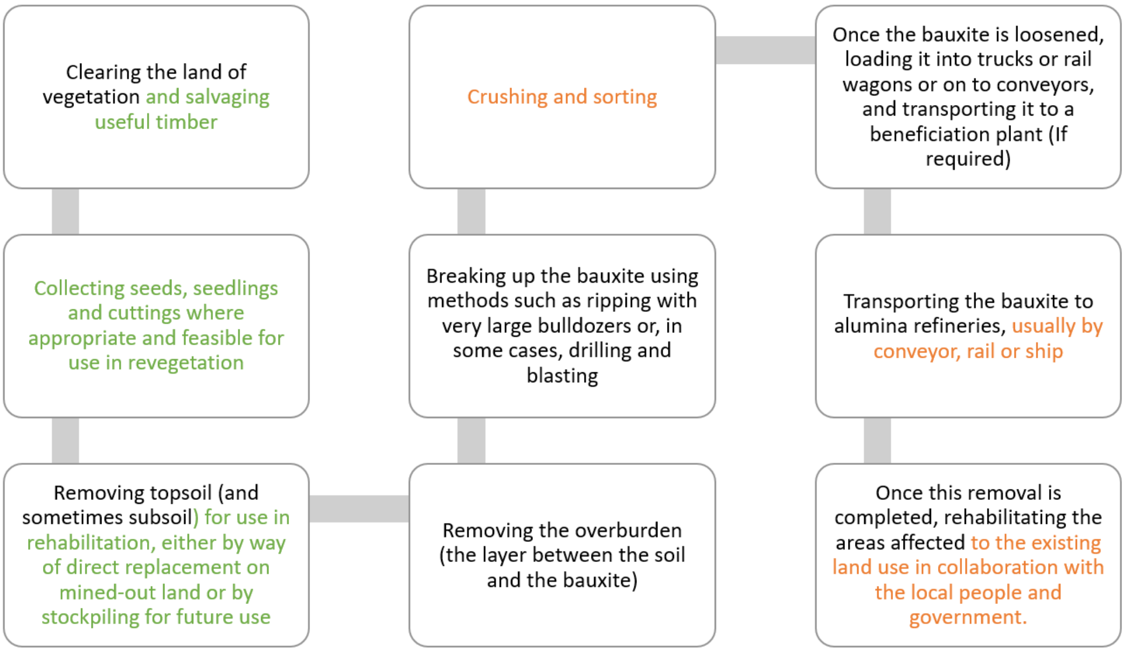
(3) Storage of soil: The humus soil is removed and stored for later rehabilitation or directly used on mined out areas. The amount of soil can be calculated with an average of 1 m soil in thickness and therefore a soil volume of around 60.000 m^3 to 70.000 m^3 per 1 Mt of bauxite (at a soil density of 1,3 t/m^3 this amounts to 80.000 t to 100.000 t of soil per Mt of bauxite)

(4) Overburden removal: In the next step the overburden is removed. Different methods are used for the excavation of the overburden: depending on the strength of the overburden rock mass, either drilling and blasting or ripping is used. The broken overburden material is usually loaded onto trucks and hauled to dump sites, which frequently are already mined out areas that are then re-filled and subsequently rehabilitated. Loading is typically done with hydraulic excavators. In case the overburden is soft it might be excavated with dozers/ rippers and scrapers, which would haul the material directly to dump sites.

If an overburden coverage of 5 m thickness and a deposit thickness of 5 m, both with a comparable density, is considered (which is a rough estimation), then roughly 1 t of overburden has to be removed for 1 t of bauxite.

(5) Extraction: In the next step bauxite is extracted, either with drilling and blasting or with ripping, depending on the strength of the bauxite. The extraction energy effort increases with the strength of the material, but not significantly.

(6) Crushing and sorting: After the excavation/ breakage of the bauxite, it is loaded onto trucks with hydraulic excavators which then haul the material to crushers where the bauxite is brought to a homogenous and suitable size ready for transport. In case the bauxite is soft it might be excavated with dozers/ rippers or scrapers, which would haul the material directly to the crusher. Another option for the bauxite extraction would be a continuous operation with rock breakage by drilling and blasting, loading the bauxite with hydraulic excavators into mobile crushers and transportation to either transport stockpiles or the processing plant by belt conveyors.



Green = World Aluminium 2018, Sustainable Bauxite Mining Guidelines
Orange = Lee et al. 2017, Environmental and Occupational Health Impact of Bauxite Mining in Malaysia
Black = Overlap

Figure 23 - Typical processes involved in surface mining of bauxite deposits also considering sustainability aspects, Lee et al. (2017) and World Aluminium (2018) consolidated

(7) Beneficiation: An optional step called beneficiation may be needed. This process may improve the ore quality through the removal of waste materials through screening, washing and dewatering. Tailings (mainly clays and fine sands) are a by-product of this beneficiation. Usually, no enrichment to a "bauxite concentrate" is done. A recovery in the bauxite processing plants is therefore estimated to be around 95 %.

(8) Transport: As a next step, the processed bauxite is transported to Alumina refineries for the Bayer process (Australian Aluminium Council 2020).

(9) Rehabilitation: Once the ore is exhausted in a certain part of the mine the land is rehabilitated. This is usually done continuously throughout the life of a mine.

Environmental impacts of Bauxite mining and processing

(1) Material efficiency: Based on the explanation of the mining process steps above, and the rather continuous nature of bauxite deposits the following **“material efficiency”** estimations are done for a surface mine on bauxite:

- In-situ bauxite (mineable resources): 100 %
- Mining recovery in surface bauxite operations: 80 % of the mineable resources (= reserves)
- Waste rock: 1 t waste rock handled/ t of bauxite mined
- Soil: 0,1 t soil/ t of bauxite mined
- Processing plant recovery: 95 %

For 1 t of bauxite sent to the Alumina refinery, therefore, a total 2,15 t of material (0,1 t soil, 1 t waste rock, 0,05 t processing waste, 1 t of bauxite product) has to be moved and processed.

Based on a BAT approach it is estimated that,

- the waste rock and processing waste is used to refill the mined-out area.
- the soil is used to rehabilitate and revegetate the refilled mining area.

(2) Land use and residue management: As explained above, around 15 ha of land are used for the production of 1 Mt of bauxite. At a production of 335 Mt of bauxite in 2018 this results in a land use of 5.025 ha. This mining land is used during the operation period of a mine and based on a BAT approach, the land is restored and rehabilitated to the original status. Overburden from new areas to be mined is usually used as filling material for the rehabilitation of mined out areas. Rehabilitation to the original “nature” is a big challenge, as shown in Figure 24 “bauxite mining is mainly concentrated in three biomes, “Tropical & Subtropical Moist Broadleaf Forests” (e.g. countries such as Brazil, India and Jamaica), “Tropical & Subtropical Grasslands, Savannas & Shrublands” (Australia and Guinea) and “Mediterranean Forests, Woodlands & Scrub” (Australia and Greece), which account for over 90 % of production. This has geological reasons, as bauxite occurs where intense

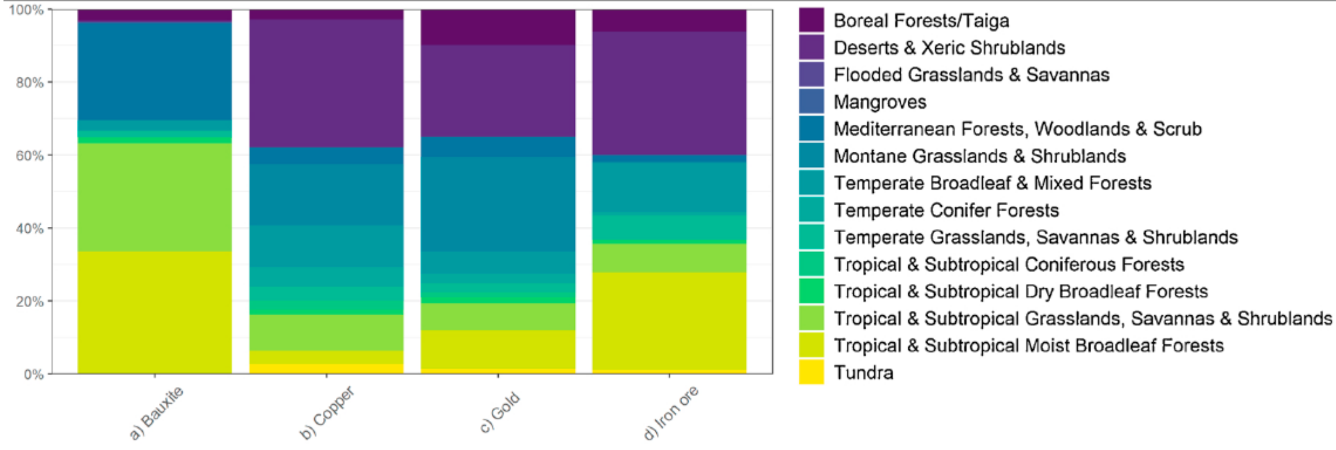


Figure 24 - Primary bauxite biomes compared to other minerals (Tost et al. 2020)

weathering and drainage of the source rock is happening, which is in the tropics." (Tost et al. 2020). "Tropical ecosystems are characterized by both high richness of species in many taxa and complex biotic interactions among component species" (Orians 2000). Unfortunately, bauxite "deposits often overlap, or are adjacent to, areas of high conservation value" (World Aluminium 2018c: 6).

Bauxite being mainly in tropical and subtropical forests and savannahs renders it a highly sensitive ore where rehabilitation processes matter proportionately more than with other minerals. But "all [bauxite mining] operations reporting to the International Aluminium Institute have clearly defined rehabilitation objectives, fully integrated rehabilitation programmes, and written rehabilitation procedures. Most have made considerable [] provisions [of all sorts]:" (World Aluminium 2018d). Rehabilitation thus includes reapplication of the topsoil-layers after operation which is carefully removed and stored before and during the mining process. Seedlings, sapling, rock formations and timber structures are saved and re-introduced (Figure 25). Results of a survey conducted by Atkins et al. have shown that the rehabilitation performance of the bauxite industry is permanently becoming better, "with rehabilitated areas increasing faster than mined areas, and that it is dedicated to minimizing the environmental impacts of its actions" (Atkins et al. 2016). As a further step towards the reduction of land use, disturbance of rain forest areas and bio-diversity reduction, innovative rehabilitation methods have to be developed. In case successful this could basically eliminate Bauxite mining's impact on land use and biodiversity reduction.

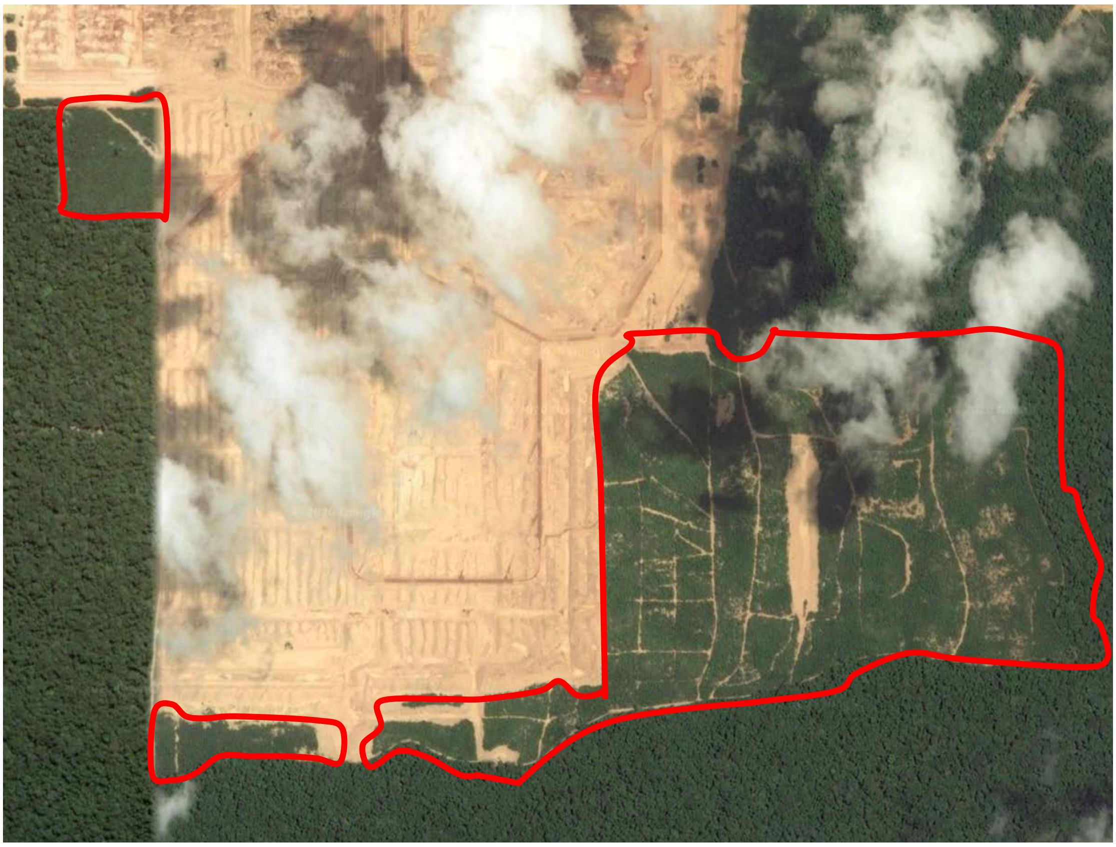


Figure 25 - Ongoing rehabilitiation, Mineração Rio do Norte, Porto Trombetas Brazil, Google Maps screenshot (access: 2020-06-04)

(3) Water use: On average water withdrawal from bauxite mining can be estimated at 0,404 m^3/ t per year (Tost et al. 2018), although there is no comprehensive literature on this.

(4) CO_2 emissions and energy use: Norgate and Haque carried out an LCA study to "determine the life-cycle-based energy requirement and associated greenhouse gas emissions of selected mining and mineral processing operations to assist the Australian minerals industry in identifying potential areas for improvement of their environmental performance (…)" (Norgate and Haque 2010). In the study the analysis focused on the cradle-to gate phase of metal production of iron, Aluminium (bauxite) and copper. In case of bauxite, open pit bauxite mines in Australia were taken into consideration. Since, according to Norgate and Haque, there is little published inventory data concerning single indicators in the cradle to exit gate phase, the inventory data that was used derives "from a number of published sources for bauxite (…)" and the study is thus to be considered a "preliminary (…) investigation to assess the relative contributions of the various stages to the energy and greenhouse gas footprints of the selected mining and mineral processing operations" (Norgate and Haque 2010). In the study, bauxite is analyzed with the functional unit 1 t of ore ready for ship loading.

According to the results (Figure 26), greenhouse gas emissions directly related to mining and processing are 4,9 kg CO_2 per t of ore, where loading and hauling in the mine are the largest contributors to CO_2 emissions.

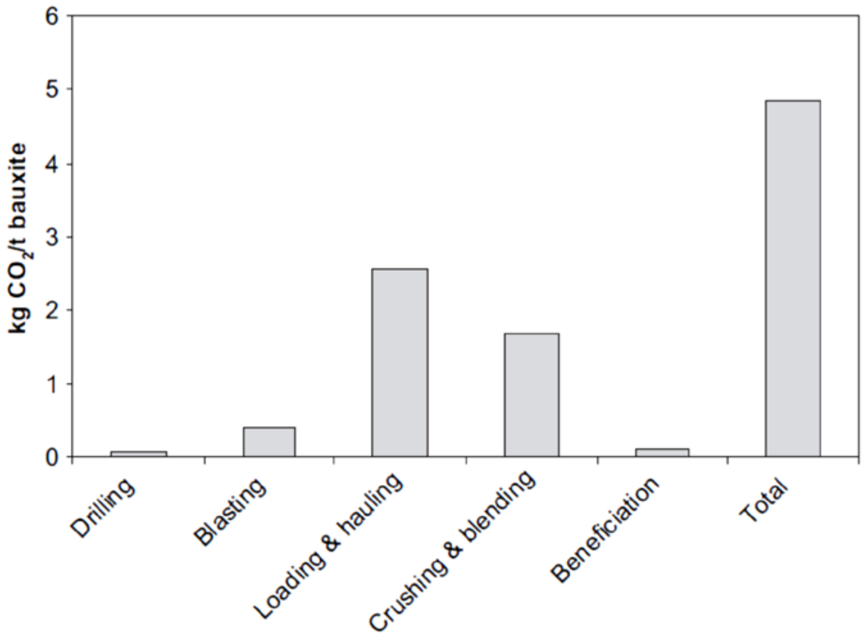


Figure 26 - Stage contributions to GWP for bauxite production (Norgate and Haque 2010)

In comparison to iron ore with 11,9 kg CO_2, copper 38,8 kg CO_2 (628 kg CO_2 per t of concentrate) and base metals in general with 32 kg CO_2 per t of ore this is relatively low. This is mainly due to the fact, that the amount of waste rock (overburden) above bauxite deposits is quite low (1:1 as explained above) and that the Aluminium grade in the bauxite deposit equals the one in the final product sent to the smelter. In bauxite processing no enrichment is taking place.

With around 335 Mt of total global bauxite produced in 2018 (Reichl 2020), the total global CO_2 emission from bauxite mines is around 1,6 Mt of CO_2 and is thus comparatively much lower than CO_2 emissions for iron or copper (Figure 27).

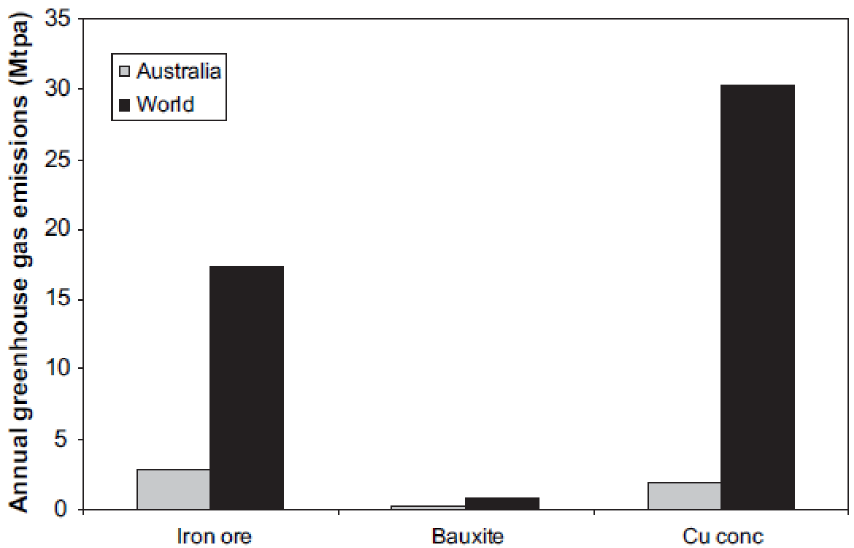


Figure 27- Annual greenhouse gas emissions from iron ore, bauxite and copper concentrate production (Norgate and Haque 2010)

(5) Chemicals and pollutants:

For every t of bauxite 0,1 kg particulates are emitted (The Aluminium Association 2013).

8.1.3 UP3: Bayer process

In the Bayer process, developed at the end of the 19th century, Alumina is extracted from bauxite with a sodium hydroxide solution under pressure and elevated temperature in digesters (Balomenos et al. 2011).

Bayer process steps (7):

(1) (2) Crushing and grinding: In most cases, bauxite is delivered directly from the mines without further treatment. It is pre-crushed with roller or cone crushers to a grain size of 20-30 mm. For digestion, fine grinding of the bauxite to < 0,1 mm is required. Today almost exclusively wet grinding is done, as it saves great amounts of energy and also dissolves part of the Aluminium hydroxide. Gangue solids (such as other minerals) are physically separated from the sodium Aluminate slurry, usually by filtration or settling.

(3) Digestion: The extraction of Alumina from bauxite is based on the solubility of $Al(OH)_3$ in hot concentrated NaOH as sodium Aluminate. Higher Na_2O concentrations and higher temperatures improve the digestion. The chemical reaction underlying the Bayer process is given as follows:

$NaOH + Al(OH)_3 \leftrightarrow Na^+ + Al(OH)^{4-}$

It must be noted that bauxites with a mass ratio of Alumina to silica above 9 are digested through the Bayer process and bauxites with a mass ratio of Alumina to silica below 7, i.e. most of the bauxites of Russian and Chinese origin, are digested through a sintering process (those containing the hydroxides Boehmite and Diaspore). These ores are difficult to process and processing energy required is much higher as shown in Table 5.

Table 5 - Hydroxides in bauxite and associated origin (hydroxide contents: VCH 1996, origin: Tabereaux and Peterson 2014)

Type	Digestion temperature in C°	Concentration of NaOH in g/l	Concentration of Na_2O_3 in g/l	Origin of ore
Gibbsite γ-$Al(OH)_3$	100-140	105-260	90-165	Brazil, Guinea, Guyana, India, Jamaica, Surinam, and Venezuela
Boehmite γ-AlOOH	200-240	105-250	90-160	Russia, China
Diaspore α-AlOOH	206	150-250	100-150	Russia, China

There is also a discontinuous process with an autoclave, however, the continuous process has advantages with regard to digestion as Table 6 shows.

Table 6 - Bauxite digestion process technology (according to data in Antrekowitsch 2019, Krone 2000 and Pawlek 1983)

Properties	Autoclave	Tube reactor
Reaction temperatures	140-250 °C	Up to 300 °C
Na_2O in NaOH solution	200-350 g/ l	140 g/ l
Al_2O_3 in NaOH solution	110-140 g/ l	110-140 g/ l
Unit engineering effort	High	Low
Pressure in unit	40 bar	Up to 200 bar
Digestion time	6-8 hours	A few minutes
Heat source		vapors from the flash tanks, leach from the digestion, high pressure steam

(4) Separation of red mud: The suspension coming from the autoclave or tube reactor which has cooled down to 100 °C must be separated from the residue which has not dissolved, the red mud. This is done via gravity separation in the thickener. Flocculants are used to accelerate the settling of the red mud. It cannot be avoided that NaOH and Alumina are lost with the red mud through the reduction of the temperature. In order to keep the losses within limits (up to 25 %), the red mud is washed in a series of downstream washing thickeners in countercurrent. Afterwards it is filtered and landfilled.

(5) Precipitation of the hydroxide: The $Al(OH)_3$ crystallizes from the clarified, diluted and cooled-down to approx. 50 °- 80 °C supersaturated leaching solution. Cooling brings the solution into a metastable state but despite super saturation there is no spontaneous precipitation. To improve the reaction kinetics, inoculation with solid $Al(OH)_3$ from production is performed. The cooled leaching solution is now transferred to large cylindrical container stirring tanks. Through classification in hydro separators a fine fraction is obtained, which serves as hydrate seed, and a coarse fraction which goes to calcination. The Al-hydroxide is washed and filtered after classification.

(6) Treatment of the Aluminate leaching solution: The thin leaching solution resulting from the filtration of the Al-hydroxide usually still contains fine hydroxide, which can be separated in special thickeners and subsequent vacuum evaporators.

(7) Calcination: The filter-moist $Al(OH)_3$ still has a residual moisture of 10 % - 16 % and is either sold as hydroxide with 65 % $Al(OH)_3$ after drying at 110 °C or converted into Aluminium oxide by calcination in rotary kilns at 1.300 °C. This brings with it very high energy consumption, dust discharge and poor modification of the powder. It can also be converted in fluidized bed furnaces at 1.100 °C.

$2Al(OH)_3 \leftrightarrow Al_2O_3 + 3H_20$

Environmental Impacts of the Bayer process (including calcination of the produced Alumina)

The top part of Figure 28 shows the mass & energy balances of the Bayer Process.

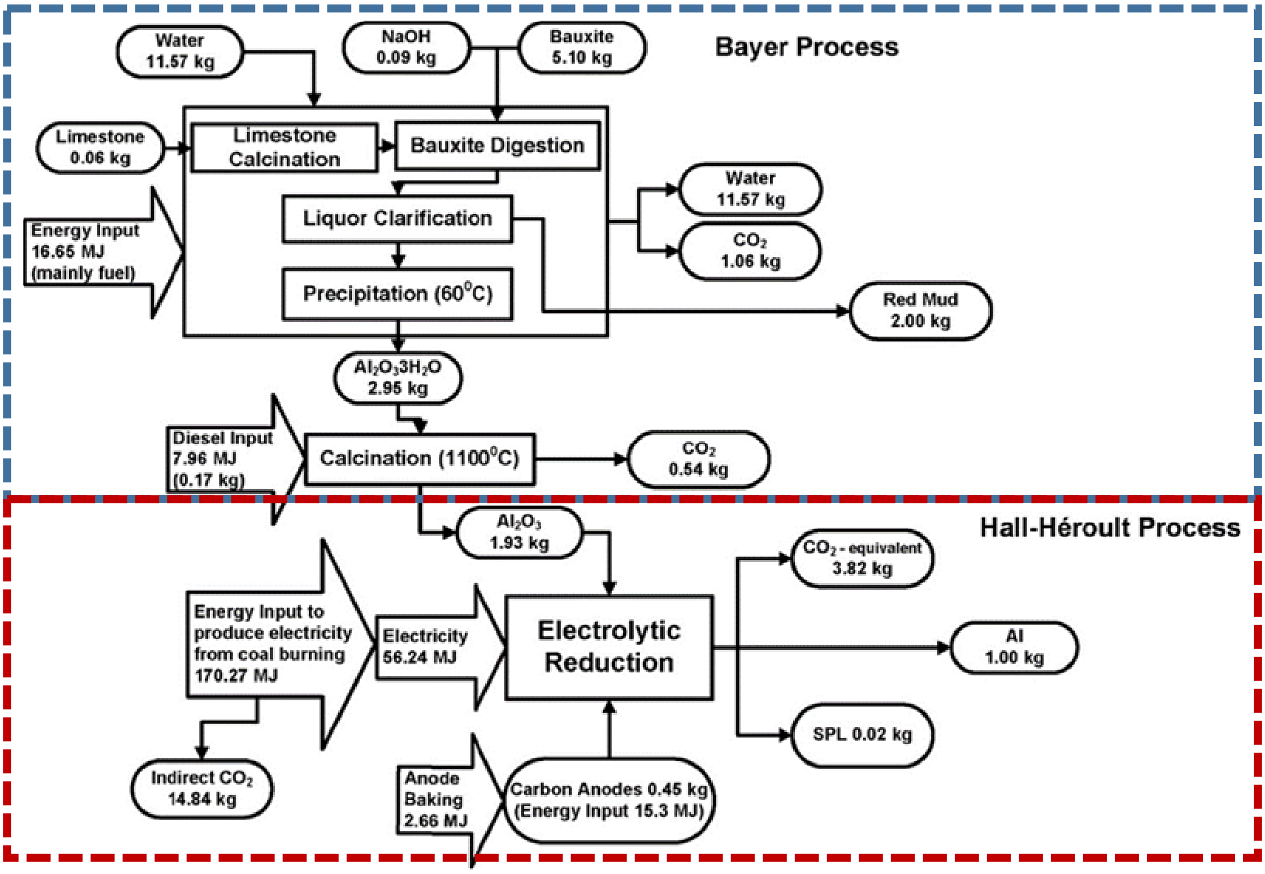


Figure 28 - Mass & energy balances in current industrial process of primary Aluminium production (Balomenos et al. 2011).

In the Bayer process from 5 t of Bauxite, around 2 t calcined Alumina are produced. As waste 2 t of red mud are generated and around 1,6 t of CO_2 are emitted. This relates to around 0,8 t of CO_2/ t of Alumina or around 1,6 t of CO_2/ t of Aluminium. The energy input is around 12,5 GJ/ t of calcined Alumina or around 25 GJ/ t of Aluminium (Balomenos et al. 2011). Water in and output are balanced, at around 6 t/ t calcined Alumina.

(1) Material efficiency: Based on Balomenos et al. 2011, the material efficiency of the Bayer process is as follows:

Bauxite feed: 100 %

Precipitated Alumina: 58 %

Calcined Alumina: 38 %

Red Mud: 39 %

Alumina recovery: 85 %

So, for every ton of calcined Alumina out of the Bayer process around 2,5 t of Bauxite have to be processed. In terms of Alumina recovery, the Bayer process is with 85 % (estimated 45 % of Alumina in the Bauxite feed) recovery reasonably good.

A big material efficiency issue of the Bayer process is the high amount of red mud produced, which does not only contain 15 % of the Alumina but a high amount of other valuable materials, as shown in Table 7. Apart from iron and Titanium the global amount of red mud contains more Gallium than the annual world production of this metal.

(2) Land use and bauxite residue management: Almost all of the red mud is landfilled and not further used due to the lack of economic possibilities for preparation and further processing.

Table 7 - Chemical composition of red mud from different and regions (translated from Hanel and Doppelhofer 2011 based on data of Sushil and Batra 2008 and Stroh et al. 1994)

Country	Fe_2O_3	Al_2O_3	$TiOa_2$	SiO_2	Na_2O
Australia	40.5	27.7	3.5	19.9	1-2
USA	30.4 55.6	16.2 12.2	10.1 4.5	11.1 4.5	2 1.5-5
India	20.3 35.46 52.4	19.6 23 14.7	28 17.2 3.3	6.7 5 8.4	8.1 4.8 4
China	6.85	7.3	2.45	13.9	2.73
Hungary	38.5	15.2	4.6	10.2	8.1
Jamaica	50.9	14.2	6.9	3.4	3.2
Suriname	24.8	19	12.2	11.9	9.3
Germany	38.8	20	5.5	13	8.2
Bandwidth	**24 - 50**	**12 - 30**	**2 - 18**	**4 - 20**	**1 - 8**

It is stored in special landfills because of the contained water-soluble alkalis. With 1 t of Al_2O_3 produced, around 1 ton of red mud are produced, thus, close to 150 Mt of red mud from bauxite production are approximately landfilled each year. It is noted in the *Metal stocks in society* report (United Nations Environmental Programme UNEP 2010: 22) that "[m]odern mines measure the metals concentrations in tailings discards, but the information is generally proprietary. [They] know of no stock estimates at levels higher than individual processing facilities." With all Aluminium ever produced a calculated estimation of about 4 billion tons of red mud has been produced, the gross of which is still present in tailings ponds around the world. Various chemical constituents (Table 8) in variable values can still be found in them but are usually not extracted (Pawlek 1983, Hanel and Doppelhofer 2017, Antrekowitsch 2019). The biggest problem about red mud utilization is the high content of Na_2O in solution (up to 8 % as illustrated in Table 7. The resulting pH-value of 10-12,5 makes red mud highly alkaline (Sushil and Batra 2008, Wang et al. 2008). This concentration causes problems in the further processing in many ways, e.g. with regards to extracting the contained Fe. In addition to the listed elements and minerals, up to 3 % of other accompanying elements, for example Sb, As, Be, Cd and some others can be found (Hanel, M. und Doppelhofer, B. 2011). A challenge is not only the management of the red mud itself in terms of holistic usage of all remaining constituent metals but also the usage of the residue constituent Aluminium which is associated

Table 8 - Summary of red mud properties (Hanel and Doppelhofer 2017)

Properties		Unit	Cause	Impact/Problem
Fe_2O_3-content	24 - 50	weight.-%	caused by content in Bauxite	Quantity of red mud increases, aluminium output is reduced
Al_2O_3-content	12 - 30			
TiO_2-content	2 - 18			
SiO_2-content	4 - 20			
Na_2O-content	1 - 8			leads to increas of pH-value
grain size	< 75	µm		Difficult handling due to almost fluid formation of the red mud
pH-value	10 - 12,5	---	result of the acidic digestion in the Bayer process	Strongly acidic, to a high degree environmentally hazardous due to possible washout of alkalis, requires post-treatment before further processing
alkali content	~10 000	mg/l		
surface	10 - 30	m^2/g		Can be used specifically, for example catalysts
heavy metal content-radioactivity	Uran 50 - 70 Thorium 20 - 30	g/t	caused by content in Bauxite	Can be environmentally harmful and hazardous to health

with Aluminium loss currently. There are various other problems associated with red mud such as for example problems with landfilling it due to varying grain sizes and thixotropic behavior of the material or the content of heavy metals and radioactive materials which have significant environmental impacts. A summary of red mud properties and associated impacts was summarized by Doppelhofer and Hanel in 2011 (Table 8).

Red mud is unsuitable for pig iron production and the recovery of TiO_2 and Na_2O is not economic. Possible usable areas would be the cement industry and brick production. The unfavorable properties of the material (pH value, alkaline content, fine grain fraction) and the low landfilling cost currently mainly lead to landfilling the material.

(3) Water use: According to Balomenos et al. 2011 around 6 t of fresh water are used per ton of calcined Alumina. All the water is recycled and thus the Bayer process with respect to water use can be considered as neutral.

(4) CO_2 emissions and energy use: Generally, the Bayer process is an energy-intensive process. The energy requirement is around 12,5 GJ/ t of calcined Alumina. Around 8,5 GJ/ t is used in the digestion steps and around 4 GJ/ t in the calcination process. The total CO_2 emission from the Bayer process is around 0,8 t CO_2/ t of calcined Alumina. Currently there is no other method to digest Bauxite than the Bayer process. Ideally regarding BAT, ores containing Gibbsite are used to produce Alumina as they require the least digestion temperature, by means of continuous processes with a tube reactor as it operates on low temperatures and high pressure, therefore lower NaOH concentrations. This has to be considered as BAT.

(5) Chemicals and pollutants: Apart from the red mud residues (see (2) Land use and Bauxite residue management in this section above) the following chemical emissions and pollutants result from the Bayer process (The Aluminium Association 2013):

Table 9 - Chemical emissions from the Bayer process (Aluminium Association 2013)

Emissions to air	
Type	**[kg/ t of Alumina]**
Unspecified particles	0,56
SO_2	2,4
NO_x (as of NO_2)	0,68
Heavy metals to air	0,0002
Emissions to water	
Type	**[kg/ t of Alumina]**
Suspended solids	0,015
Oil and grease	0,767
Heavy metals to fresh water	$7*10^{-8}$

8.1.4 UP4: Fused-salt electrolysis - Hall-Héroult Process

Metallic Aluminium is produced in the Hall-Héroult process by the electrolytic reduction of Alumina, which is dissolved in a molten bath consisting of cryolite (Na_3AlF_6) at a temperature of around 960 °C. The process was developed almost simultaneously and independently of each other by Héroult and Hall in 1886 and has, except for efficiency and environmental aspects, not changed much in principle ever since (Balomenos et al.2011).

Consumable carbon anodes carrying electrical current are immersed into the electrolyte. The current flows through it and breaks the chemical bond between Aluminium and oxygen. The pure Aluminium metal deposits in molten form at the cathode at the bottom of the cell, while the oxygen formed at the anode reacts exothermically with the carbon of the anode to form a mixture of CO and CO_2 bubbles (Kammer 2002). The composition of the electrolyte is shown in Table 10. The practical Al_2O_3 content is between 3 % and 6 %. The most important additives for the melting point reduction of the electrolytes are AlF_3, CaF_2 and LiF because of which the melting point remains at 950 °C (Antrekowitsch 2019, Aluminium Production.Com 2009).

Table 10 - Composition of the electrolyte (Antrekowitsch 2019)

Contents	Share in %
Na_3AlF_6	> 75
Al_2O_3	1–9
CaF_2	4–8
AlF_3	5–15
LiF, MgF_2	1-4

Figure 29 shows the simplified basic diagram of an electrolytic cell. The electrolysis is carried out in steel tanks usually referred to as pot shells as they contain all other elements of the cell. The pot shell is clad with some layers of refractory bricks on the bottom to insulate the cell and avoid heat loss. On top of those there is a carbon lining which also represents the cathode. It is usually made of anthracite and is consumed at a ratio of around 20-40 kg/ t of Aluminium (Antrekowitsch 2019). Rails underneath the cathode serve as the cathodic current supply. The cell contains the electrolyte, the molten Aluminium and a crust of solidified electrolyte on top. From above, the carbon anode with its current supply hangs into the bath. The Al-oxide in the bath is depleted on a regular basis as the electrolysis is carried-out and needs to be replenished on a regular basis. This is done through a so-called feeder (Kammer 2002, Antrekowitsch 2019, Aluminium Production.Com 2009).

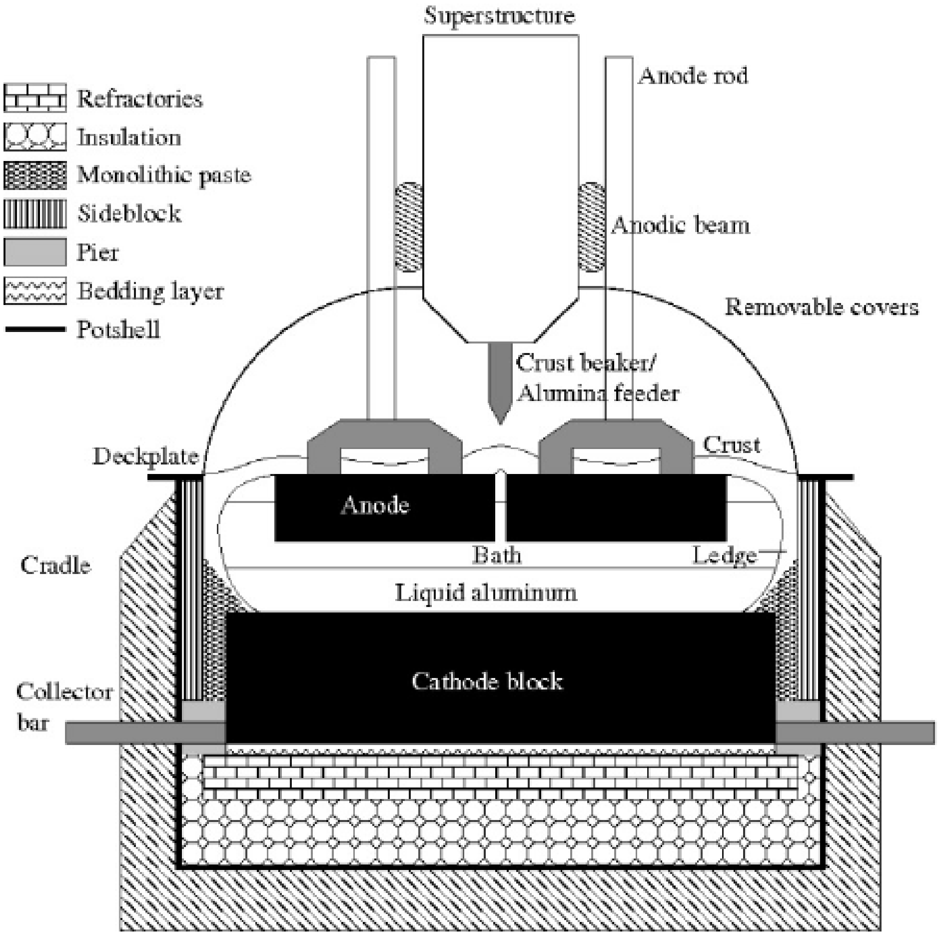


Figure 29 - Design of a fused-salt electrolysis cell (diagram of the Hall-Héroult electrolysis cell - (from Richard 2004)

The development of electrolysis cells is moving in the direction of point-operated, fully enclosed furnaces with pre-baked anodes and higher current ratings, with the furnaces being monitored and controlled by process computers. The cleaning of electrolysis exhaust gases has dry adsorption, i.e. gaseous fluorine is adsorbed onto Alumina and fed back into the cells. This not only avoids that fluorine gas escapes into the environment but also means that less virgin fluorine has to be fed into the electrolyte. Furthermore, the coarser sandy oxide, which has high adsorption properties, can be used which requires lower calcination temperatures at the end of the Bayer process.

The Hall-Héroult process is very energy intensive. Approximately 50 GJ/ t of Aluminium is consumed directly in the electrolytic reduction of Alumina (Balomenos et al. 2011).

While the current Hall-Héroult process is a single polar process, new research points in the direction of a multipolar cell with bipolar electrodes or multiple cathode-anode pairs. This could yield energy savings of up to 40 % due to the lower electrolyte temperatures and thus higher current density. However, for the multipolar cell to work, first inert anodes need to be introduced. Research stagnates at a TRL level of 5 an has not gone beyond pilot testing of a few initiatives, key challenges constituting the improvement of improving cell configuration as well as anode, cathode and bath chemistries (International Energy Agency IEA 2020b).

Environmental impact of Hall-Héroult electrolysis

Mass & energy balances in current industrial process of primary Aluminium production (Balomenos et al. 2011, also see Figure 28).

(1) Material efficiency: In the Hall-Héroult process close to 100 % of the Aluminium from the Alumina are recovered.

(2) Land use and bauxite residue management: The electrolytic cells used in the process need to be periodically replaced, producing a carbon-based solid waste of around 20kg/ t of Aluminium, known as Spent Pot Lining (SPLs), which is classified as a hazardous waste (EUR-Lex 2000), due to its chemical content (Balomenos et al. 2011). The SPL material is typically landfilled. Because of the amount of material, the size of the land used for the fill is negligible. It is more the toxic nature of the fill that is problematic. Also, the land used for the set-up of the plant itself is marginal and has no relevance.

(3) Water use: Apart from cooling of the electrolysis cell, no process water is used. The cooling process does not pollute or consume the water. Therefore, the water impact is neutral.

(4) CO_2 emissions and energy use: Energy input in the electrolysis process is extensive. The specific energy consumption is between 50 GJ and 60 GJ/ t of Aluminium (Balomenos et al. 2011). This energy is the energy directly used in the electrolytic reduction of Alumina. Even if the energy is sourced from renewable energy sources (typically hydro power), the amount needed still is extensive and has to be lowered in the future, as also renewable energy sources rely on resource intensive infrastructure to be built. Thus, the less energy needed the less energy infrastructure needs to be built. To give an idea on the amount of energy in the production of Aluminium, a comparison with other metals is shown in Figure 30. There the gross energy Requirement (and not only the energy needed in the Hall-Héroult process), also referred to as embodied energy or cumulative energy demand, which is the cumulative amount of primary energy consumed in all stages of a metal's production life cycle, is shown (Norgate et al. 2007, Norgate and Jahanshahi 2011).

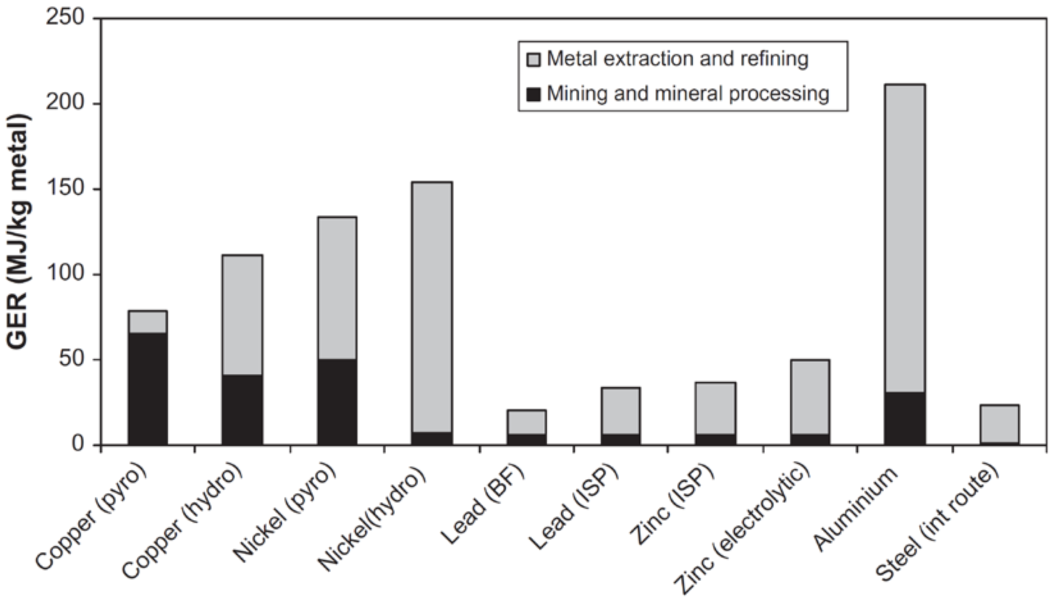


Figure 30 - Cumulative energy consumption for the production of 1 t of metal (Norgate and Jahanshahi 2011)

The total amount of energy consumed in the production of 1 t of Aluminium, for the cradle to entry gate part, is 211 GJ/ t of Aluminium (Norgate et al. 2007). As can be seen from Figure 30 the specific energy requirement for the production of Aluminium is the largest for all the metals compared.

The anodes used in the electrolysis are not inert and are consumed by combustion. Around 1,53 t CO_2/ t Al are released. Another 0,12 t CO_2/ t Al are released during the anode baking and around 2,18 t CO_2/ t Al, equivalent of hazardous perfluorocarbons result from the process upset knowns as anode effect (Balomenos et al. 2011). So, in total around 3,82 t of CO_2 equivalent gasses per t of Aluminium are released in the Hall-Héroult process, only from the consumption of the anodes. The application of inert anodes in the electrolysis of Al would substantially reduce carbon related process emissions. Further, the anode has to be exchanged every two weeks because it gets consumed by the electrolysis which poses a stability, productivity and energy efficiency risk to the electrolysis cell. Ideal would be an inert anode. Choate et al. estimate that "in conjunction with a drained cathode, […] an inert anode may save up to 22 % of the energy required for reducing Aluminium" (Choate et al. 2003). Until the industrial readiness of inert anodes, there are still some improvement measures that can be taken regarding the anodes in the electrolysis. There are currently two different anodes in use, the Prebake and the Soderberg anode. Prebake, discontinuous or continuous anodes are produced from high purity petroleum coke with pitch binder (Prebake Consumption 400-500 kg/ t Al). Self-burning

Soderberg anodes are hardly used any more due to the environmental pollution caused by hydrocarbons and fluorides. Most new operations use the more energy efficient Prebake anode.

Choate et al. suggest that possible future carbon taxes may hasten the development of inert anodes (Choate et al. 2003). This was in 2003 and up to date the anode has not been implemented on an industrial scale. According to "industries and research organizations believe that inert anodes can be prepared and used in the nearest future" (Padamata et al. 2018: 28). According to the IEA the current TRL of the inert anode is 5 and small-scale tests have been conducted in the past several years, the key challenge being the affordability of the materials used and finding a material that does not corrode in the process (International Energy Agency 2020b). There are leading scale-up initiatives by Alcoa and Rio Tinto in a joint-venture named Elysis, which aims at implementing a low-carbon Al production technology by 2024 (International Energy Agency IEA: 2019). Further, RUSAL in Russia and INFINIUM in the US have been developing and testing inert anode technologies. If these initiatives succeed this could potentially enormously change the carbon footprint of Al production.

In terms of the total CO_2 emission of the Halt-Héroult process, much depends of course on the source of energy used in the electrolysis plant. For electrolysis plants powered with hydro-electricity, the CO_2 emissions are largely limited to the 4 t CO_2 from the anode's consumption (provided the CO_2 from the construction and operation of hydro power electricity and its transport is neglected). For electricity from coal fired power plants, the specific CO_2 emissions out of the Hall-Héroult process for the production of 1 t of Aluminium are around 18 t of CO_2. This is one of the highest of all metals produced from primary sources (compare to Figure 31) where the total specific equivalent CO_2 emissions are shown (22,4 kg CO_2/ kg Al))

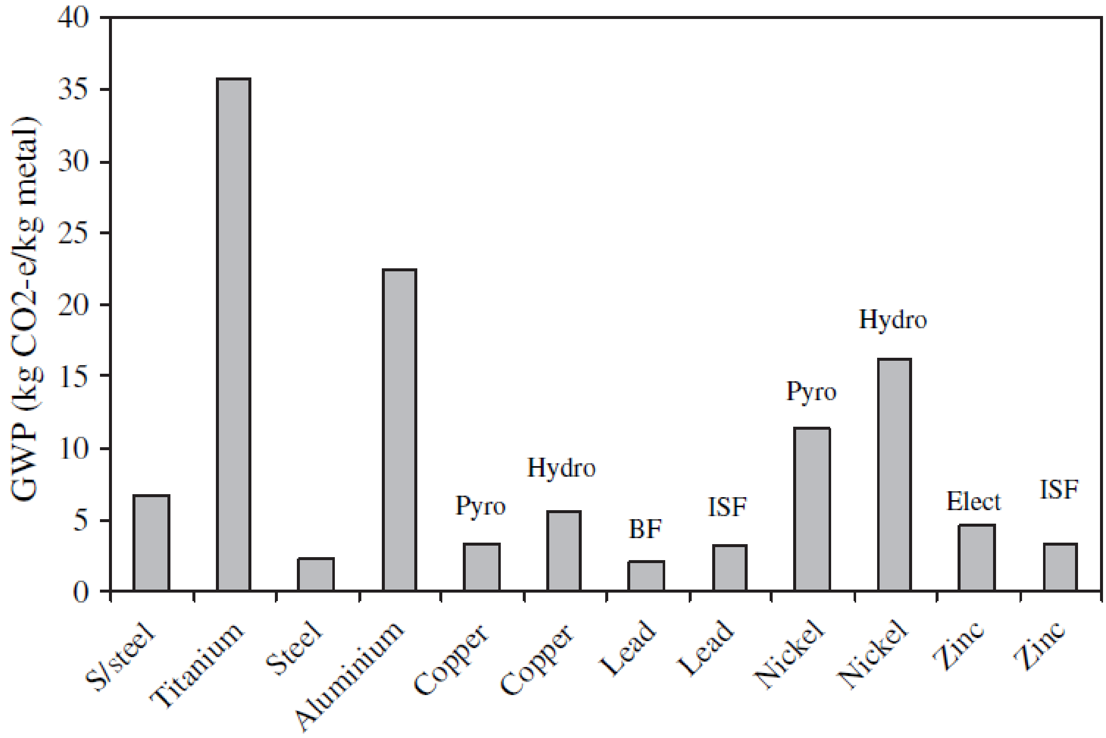


Figure 31 - Specific CO_2 emissions for the production of 1 t of metal (Norgate et al. 2007)

(5) Chemicals and pollutants: The carbon cathode lining in an Aluminium smelting pot needs to be replaced regularly. Up to this day, no efficient technology has been developed for the recycling of the spent pot lining of an electrolysis cell. This spent hazardous carbon refractory waste is a mix of graphite and refractory cladding, with a high content of cyanides and fluorides. Most of the SPL waste is incinerated or landfilled at an amount of around 20 kg of waste per 1 t of Aluminium (at 60 Mt annually this results in 1,2 Mt SPL). Some of the producers keep this waste at the production site. The Slovenian National Building and Civil Engineering Institute (ZAG) together with other partners is currently working on such a recycling technology. This SPL-CYCLE technology represents a new circular economy business model, with the complete elimination of waste landfilling and incineration costs (Mladenovic 2017).

The collection of the exhaust gases by fully encapsulating the furnaces with subsequent exhaust gas purification allows operation that complies with the latest environmental protection legislation. In dry adsorption, 98 % - 99 % of the gaseous and powdery fluorides are adsorbed by the Alumina and returned to the electrolysis cell. Accordingly, the need for electrolyte additives is reduced. The amount of fluorine emitted per t of Aluminium is on average about 0,9 kg (Antrekowitsch 2019, Aluminium Production.Com 2009).

8.2 Phase 2 of the Aluminium production process – Entry gate to exit gate

In phase two of the Aluminium production process the material undergoes two basic fabrication routes, namely the foundry material route and the semi-finished product route (Figure 32) to afterwards end-up in more specific product categories. In most cases the Aluminium is alloyed, which is necessary because in its pure form it is very ductile but to obtain the material strength needed in some applications the addition of other elements is necessary. The following chapter briefly illustrates the basic fabrication route unit processes for Aluminium.

Primary smelter / elektroysis	Product route	Material	Raw product	Processing	Final products e.g.
Aluminium extraction from electrolyte with subsequent specific alloying and casting to send off to fabrication route	foundry material route →	foundry alloy	ingots for remelting	casting	cylinder heads, engine blocks, housings, wheels
	semi-finished product route →	wrought alloy	rolling ingots/ slabs	rolling	sheets, plates, foils, cans
			extrusion ingots/ billets	extrusion	facade claddings, tubes, profiles, wires
			ingots or billets	machining	tubes, infinte custom-made parts (handles, knobs, racks)

Figure 32 - Summary and overview of Aluminium fabrication routes, alloys and processes

8.2.1 UP5.1 Casting of Aluminium for the foundry material production route

The raw product for the *foundry material production route* of Aluminium are foundry alloys in the form of ingots. Foundry alloys are materials that are used to cast complex geometrical shapes as final products. After the extraction of the molten pure Aluminium from the electrolysis cell, it is transported to a reverberatory holding furnace where, according to the material properties needed, it is alloyed accordingly. Alloys have to be composed in a way that they are beneficial for castability but also for the final product requirements. The molten Aluminium is further degassed to remove impurities. When Aluminium "comes in contact with moist air the water vapor decomposes and releases hydrogen into the melt. […] this dissolved gas has a detrimental effect on the mechanical properties of Aluminium castings" (Sigworth 2016). Purging gas treatment is therefore necessary to achieve high quality castings. It is also filtered to remove possible traces of oxygen and other inclusions dissolved in the molten Aluminium (UACJ 2020). Once the Aluminium alloy mixture is correct (=foundry alloy) and all impurities are removed, it is cast into ingots (Figure 33) for remelting. The standard ingot size is nominally (2 cm - 3 cm) x (3 cm - 8 cm) x (6 cm - 12 cm) (American Elements 2020). They are then stacked and sent to an Aluminium fabrication plant. If this plant is close to the primary smelter it is also possible to transport the material in liquid state to save the energy for remelting the ingots.

Figure 33 - Aluminium ingot for remelting (BCT Metals 2020)

8.2.2 UP5.2 Manufacturing of foundry materials

The manufacturing of foundry materials happens through casting foundry alloys into a desired shape to receive a final product. This is a very flexible and inexpensive way of shaping Aluminium into any number of forms desired and is the most widely used one. Casting applications can be found throughout society (e.g. household items such as cookware or garden tools), in fact, the very first Aluminium products were castings. However, castings are especially numerous in the automotive industry. "[It] is the largest market for Aluminium casting. Cast products make up more than half of the Aluminium used in cars. Cast Aluminium transmission housings and pistons have been commonly used in cars and trucks since the early 1900s" (The Aluminum Association 2020d). The process is simple in principle and has despite technical advances not changed over the years. Casting involves pouring molten Aluminium into a mold to produce a specified shape. There are three methods that can be considered the most important: *die*, *sand* and *permanent mold* casting.

For all casting processes to consider is that if not possible to remove inside parts of a cast then a semi-permanent technique has to be applied. Furthermore, it is important to include into the molds a part-removal design so that the pattern can be removed after casting. Casting is a very efficient process to use Aluminium's material strength and light weight properties to produce complex products.

8.2.3 UP6.1 Casting of Aluminium for the semi-finished product route

This unit process functions much the same as the above casting process. There are two exceptions, however, the alloying of the molten Aluminium differs in terms of composition of the alloys and the final form of the cast product may vary. First of all, the composition of the alloys is specifically adjusted to receive a wrought alloy at the end and not a foundry alloy as the products of the semi-finished product route are meant to undergo mechanical processes like rolling, extrusion or machining. The composition of the material is therefore different, as its material behavior requirements differ. Secondly, the form of the final product of this stage varies as after the molten Aluminium is alloyed, has undergone purging gas treatment and filtration it may be cast into ingots for remelting the same way as foundry alloys in casting furnaces or it may already be cast into bigger ingots (called slabs) (Figure 34) or billets (Figure 35) in continuous casting plants, ready for mechanical processing and thus saving the remelting step. If they are cast into wrought alloy ingots with the purpose to be remelted the ingots are small like above. They are sent off to a fabrication plant where only then they are remelted and shaped into their final raw product (slab, billet).

Figure 34 - Aluminium ingot for remelting (BCT Metals 2020)

Figure 35 - Extrusion billets (AluminiumGuide.com 2020)

8.2.4 UP6.2 Manufacturing of semi-finished products

The manufacturing of semi-finished products through wrought-Aluminium alloys splits into several downstream roads, three of which are the most important ones, namely rolling, extrusion and machining.

The rolling process of Aluminium (Figure 36) is the basic process for the production of *plate* (thickness more than 6,35 mm usually used in heavy duty applications), *sheet* (thickness: 0,2 mm to less than 6,35 mm, most widely used application) and *foil* (thickness: less than 0,2 mm) which are the basic semi-finished products for final products applied in sectors such as aerospace (e.g. plane skins), transportation (e.g. auto body sheets), packaging (e.g. cans) and construction (e.g. façades). In a fabrication plant this process starts with either the remelting of Aluminium wrought alloy ingots to create slabs (which can weigh more than 20 t) for rolling or the slabs themselves are already available as they were procured as such from the primary smelter. In the process, first of all the slab is heated and introduced into a breakdown mill where it is rolled to a certain thickness of only a few centimeters. Then further rolling begins, which is either done hot, in which case the slab is preheated before it is passed through the rolls, or it is done cold, in which case the Aluminium has room temperature. Rolling temperature influences the final look and structure of the product. The slab is thus rolled between two rolls, between which the gap is variable, and pressure is applied. Through this the slab is continuously flattened to the thickness of the size between the rolls and is thus stretched i.e. prolonged. Each time the sheet is passed through the rolls, it is flattened slightly more. Either the sheet is rolled between the same rolls and the gap is continuously narrowed or it is passed through a series of different rolls with progressively smaller rolls. Depending on whether plate, sheet or foil is the final product, once the raw slabs have been rolled out to a desired thinness, these three final products undergo different finishing processes, sheets e.g. through solution-heat treating to make it stronger or plate through a second-hot rolling to make it thinner. Afterwards coiled sheets are run through slitters that trim the uneven edges off and also often divide it into numerous narrower coils. Plate remains uncoiled throughout the process. The recycling properties of sheet and plate are excellent as they can be recycled without loss of properties (The Aluminum Association 2020e, 1999/2007).

<u>The extrusion process</u> of Aluminium (Figure 37) fabricates products that are widely used, e.g. in automotive (frames and mounts), construction (structural support and profiles) and everyday-life (chairs and shelves). Extrusion is a fundamentally easy-to-understand process and is applied in many areas of life, such as making pasta, play-dough presses for children or pressing toothpaste out of a tube. In principle, a s soft material (in this case an Aluminium billet) gets pressed through a desired smaller profile shape (extrusion die) and is plastically deformed, coming out at the other side of the profile in rams of various lengths looking exactly like the profile. The extrusion process undergoes the following steps: Preparation of the extrusion die and transport to the press, preheating of the Aluminium billet and transfer to the press, pushing of the billet through the press with a ram, emerging of the extruded material at the other end of the die, quenching of extrusions on run-out table, shearing of extrusions to table length, cooling of extrusions to room temperature, stretching of extrusions into alignment, cutting of extrusion to finish length. In the Aluminium processing this technique offers almost unlimited options for the design of products. Hollow, semi-hollow or solid shapes, from complex to simple can be

created. The process is low-cost and offers the opportunity for fast product development due to speedy prototype development and testing phases (The Aluminum Association 2020f, Gabrian 2020).

The machining process of Aluminium (Figure 38) can consist of various machining techniques, e.g. cutting, drilling, milling, boring, lathing, bending, punching, turning or sandblasting). The material composition strongly influences the castability of the Aluminium. Most frequently, machining is carried out with high-precision electro-mechanical CNC machines (computer numerically controlled machines). These machines can manipulate the material across a varying number of axes, usually three to five. Machining Aluminium parts opens up the opportunity for producing high-precision engineering parts that can be found in numerous sectors such as aerospace, automotive, construction and electrical (Concerning Reality 2018).

Figure 36 - Aluminium rolling (UACJ 2020)

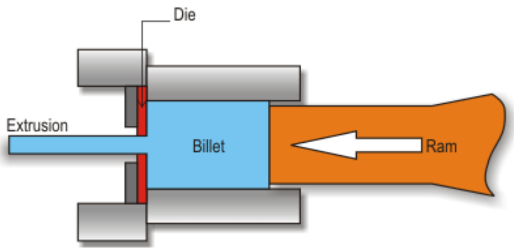


Figure 37 - Aluminium extrusion (AZO Materials 2002b)

Figure 38 - Aluminium machining (Alumill 2020)

8.3 Phase 3 of the Aluminium production process – Exit gate to grave or entry gate

In 2018 80,2 Mt of Aluminium were produced, 63,2 Mt of which were produced in primary production and 17 Mt came out of secondary material. Since 1885 a total amount of 1.394.733.288 Mt of Al has been produced (calculated based on data of Belli 2012, Reichl 2020 and USGS 2015). 75 % of this amount is still in use (The Aluminum Association: 2020c) and has therefore been recycled several times and been re-introduced into use. Energy demand for the production of 1 t of primary Aluminium equals the energy demand for 20 t of Aluminium from secondary sources (1:20) (Antrekowitsch 2019). In relation to the total production Aluminium recycling is increasing in tonnage but decreasing in percentage as Figure 39 and Figure 40 well illustrate (Reichl 2020, United States Geological Survey USGS 2015, World Bureau of Metal Statistics 2018). Aluminium recycling is strongly on the increase in absolute terms, however, this is not mirrored as percentage in the total amount produced.

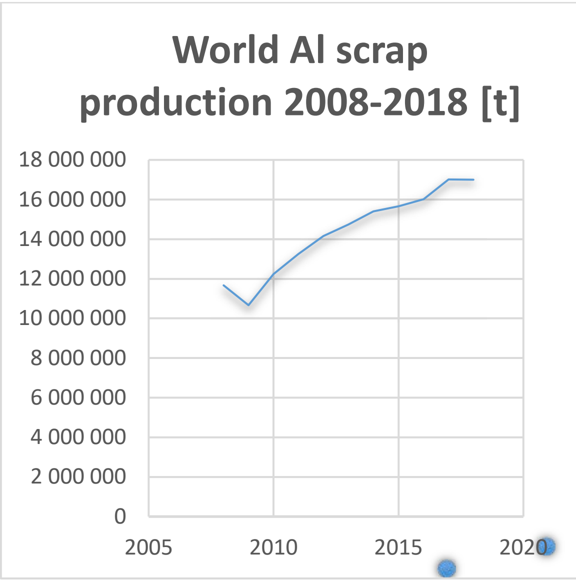


Figure 39 - Total global secondary Al production (based on data of World Bureau of Metal Statistics 2018)

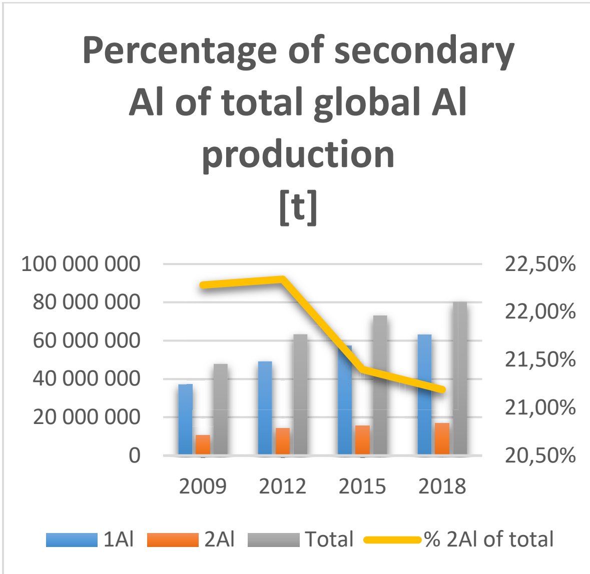


Figure 40 - Secondary Aluminium percentage share of total global Aluminium production (based on data of World Bureau of Metal Statistics 2018, Reichl 2020 and United States Geological Survey USGS 2015)

Although secondary Aluminium production in the form of scrap recovery has increased from 11,7 Mt in 2008 to 17 Mt in 2018 in absolute terms (World Bureau of Metal Statistics 2018), the significantly increasing production of primary Aluminium each year has led to a decrease of the secondary Aluminium percentage share of total production, namely a decrease from 22,7 % to 21,1 % secondary Aluminium in total world production. This can be considered a downward trend as every year since 2008 the share has decreased slightly, although increasing in absolute terms. Increasing recycling at the pace of demand increase seems to be the challenge.

One of the delimitating factors for the increase in secondary production is the availability, i.e. non-availability, of scrap (Buchner 2015: 1, International Energy Agency IEA 2020a). Krausmann conformingly find in a study about in-use stock of metals generally that "77 % of end-of-life outputs of metals are recycled, but the share of secondary materials in total metal inputs to stock is only 27 %" (Krausmann et al. 2017: 1882). One reason for this is that in-use stock of Al is very high with a global average of 80 kg/ capita (United Nations Environmental Programme UNEP 2010: 17), industrialized nations have a much higher in-use stock; e.g. Austria with 360 kg/ capita in 2012 (Buchner 2015: 29). In combination with a mean residence/ lifetime of 23-30 years, depending on the product categories the material flows into, (Krausmann 2017, Gerst and Graedel 2008) this results in little Al output compared to the demand. It locks Al old scrap generation for an exceptionally long time before it is available

Metal	Reservoir	Predominant Metal-containing Final Goods	End-use Fraction (%)	Ref.	Estimated Residence Time (years)	Ref.
Al	Building & construction	Siding, window frames	25	*(1)*	30-50	*(2, 3)*
Al	Infrastructure	Cable used by power utilities	18	*(1)*	30-40	*(2, 3)*
Al	Transportation	Automotive equipment, railway equipment, aviation	28	*(1)*	15-40	*(2, 3)*
Al	Packaging	Beverage cans, foil	13	*(1)*	0.3-0.8	*(2, 3)*
Al	Other		16	*(1)*	10-15	*(2, 3)*

Figure 41 - In-use stocks of Aluminium (Gerst and Graedel 2008)

for recycling Figure 41. In principle the longevity of products is a desired effect, however, in the case of Aluminium where demand increase is immense due to all socio-economic factors elaborated on in chapter 2, this results in higher and higher primary production.

Aluminium is ideal for recycling and recyclable more than any other material in its pure form. However, most of the Aluminium in use is alloyed which makes recycling somewhat tricky. In anticipation of closing product group loops, Aluminium scrap should be sorted according to its alloy composition and then recycled separately (Figure 42), therefore foundry alloys should become cast Aluminium products and wrought alloys should become extruded and rolled products again (European Aluminium 2019a). Apart from internal scrap (which does not appear in any statistics because if clean and sorted it is remelted on the spot in the primary smelter, i.e. processed directly together with electrolysis metal) recycling happens via two different routes, namely the remelting or the refining route.

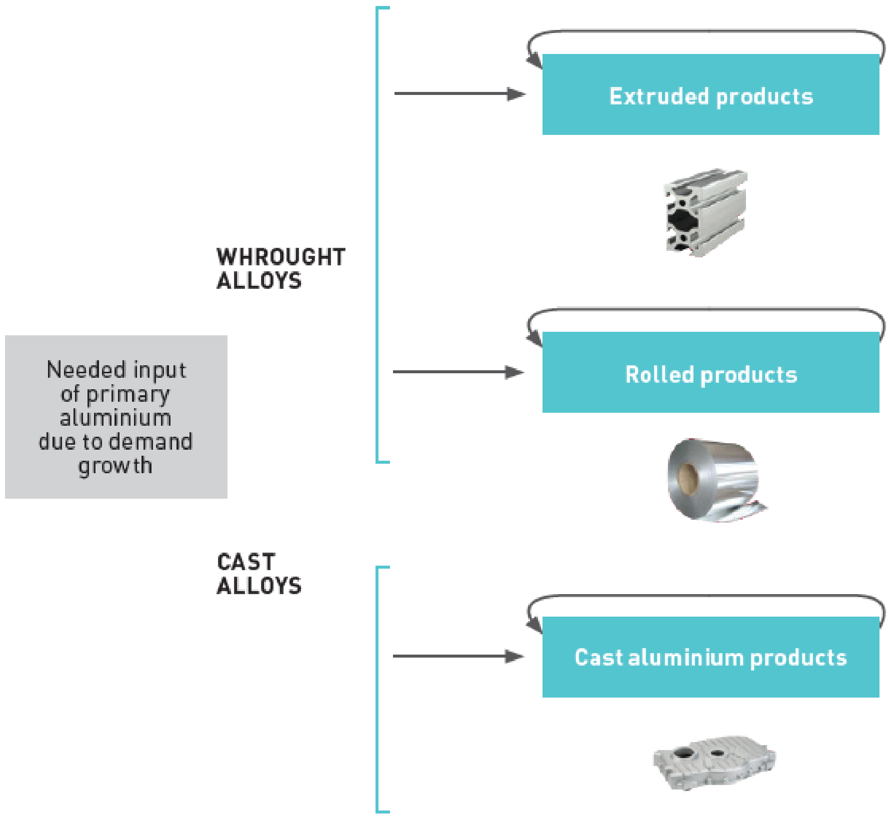


Figure 42 - Ideal sorting of Aluminium scrap of different alloys (European Aluminium 2019a)

8.3.1 UP10.1 Remelting (new scrap/pre-consumer scrap/pure scrap)

Processing of pure grade scrap, so-called new scrap is increasingly important for closing loops. The remelting plants (remelters) mainly process low-contaminated, low-alloy wrought alloy scrap. Often the processing of these materials is carried out on behalf of the scrap supplier in return for a smelting fee. They are also sometimes directly purchased from scrap yards or directly from the place where the scrap was produced in the production process (Krone 2000).

In many unit processes of Aluminium production scrap is generated, for example stamping skeletons, machine turnings, chips or scrapped pieces during fabrication (up to 35 %). If semi-finished product or casting producers have in-house furnaces they can directly return the internal scrap to their own melting operations. The processing of the raw materials consists only of making these materials chargeable by cutting or, if necessary, compacting. It is then melted down in fuel-heated multi-chamber furnaces. Rotary drum furnaces and crucible induction furnaces, more rarely channel-type induction furnaces, are also used. The melts are fed into fuel-heated holding furnaces via channels or by ladle transport, which also function as pouring furnaces. The purging gas treatment and filtration takes place, just like in the case of metallurgical and semi-finished product plants, either in the holding furnaces and/ or in systems which are arranged "in-line" between the casting furnace and the continuous casting plant. Then the melt is usually cast in vertical continuous casting or even delivered in liquid form. Wrought alloys in the form of rolling ingots, extrusion billets for further production are the final product (Krone 2000).

Due to its known origin this material has the highest value of all scrap materials. Downgrading of the recycled material is largely avoided as it is generated during manufacturing of semi-finished or final good before it is in consumer use, it is therefore pre-consumer scrap and is always immediately returned to a smelting process (World Aluminium 2021, Tabereaux and Peterson 2014).

8.3.2 UP10.2 Refining (old scrap/ Post-consumer scrap/impure scrap)

Refiners usually process highly contaminated, oxidized raw materials, i.e. frequently mixed scrap of all alloy classes as well as dross, dross and slag coarseness. This so-called old scrap is scrap generated after consumer use, hence post-consumer scrap, including collected scrap, shredded scrap, car shredder scrap and Aluminium from household waste. However, also a large proportion of new scrap is emulsified, painted or electrochemically coated, which is why it is often not possible to process it internally, so that it is also processed externally also in refiners (Krone 2000).

Before a remelting of this type of scrap is possible it has to undergo a series of treatment steps, ranging from simple manual sorting to sink-float processing and eddy current separation. Melting is usually carried out under molten salt in fuel-heated rotary drum furnaces. The melts are transferred in liquid form to holding furnaces, which are also fuel-heated. There they are alloyed, treated for cleaning and microstructure adjustment and finally cast or filled into liquid transport containers. Products of the smelters are casting alloys in the form of ingots or liquid Aluminium. Deoxidation Aluminium, which is also produced, is mainly marketed in the form of granules.

8.3.3 Basic processing principles for smelters and refiners

The basic operations in the production of cast and wrought alloys in the remelters and refiners are basically the same once they reach the operations (based on Krone 2000)

- Initial weighing of the material
- Interim storage (up to 8 weeks of production capacity is stored)
- Preparation of the raw materials (if necessary)

- Storage of pre-material
- Alloy classification
- Batch provisioning
- Melting down in furnace
- Melt treatment in holding furnace (alloying, purging gas treatment, microstructure adjustment and filtration if necessary)
- Casting
- Exit weighing

In principle, a distinction can be made between recycling with and without salt (Figure 43). The amount of salt depends on the process technology and the material used.

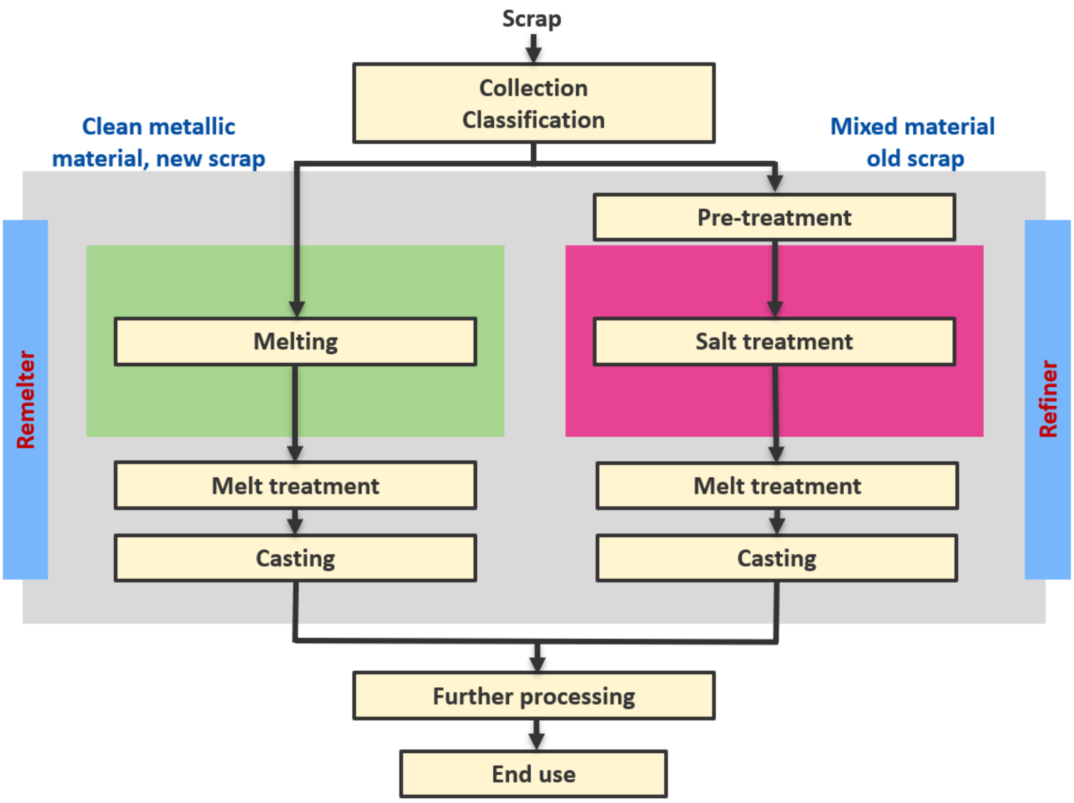


Figure 43 - Recycling processing routes of secondary Aluminium (Friedrich 2010, translated)

Environmental impact of Remelting and Refining

(1) Material efficiency: Aluminium has one of the best recycling (remelting and refining) rates of all metals with close to 100 % of new scrap being recycled and 90 % of old scrap in the transport and construction sector. The success of old scrap recycling depends on the collection systems installed (World Aluminium 2018e).

(2) Land use and residue management: There is little land use in Aluminium recycling processes, only company grounds and storage facilities. In terms of residue 4 types can be accounted for: salt slag, filter dust, refractory material and dross as shown in Table 11 (Krone: 2000).

Table 11 - Residues in secondary production route (Krone 2000)

	Salt slag	Filter dust	Waste refractory material	Dross
Accrual (kg/t Al)	300–500	10–40	2–3	20–30
Place of accrual	Melt in rotary drum furnace	Exhaust gas filter, rotary drum furnace, holding/purification furnace	Rotary drum furnace, holding/purification furnace	Holding/purification furnace, foundry
Avoidable	Possible	Hardly possible	Not possible	Hardly possible
Environmental considerations	Evolves gas, leachable with water	Leachable with water	Leachable with water	Evolves gas, leachable with water
Recycling method	Solvent crystallisation process	Solvent crystallisation process	-	Dross processing, smelting processes
Disposal	Cannot be landfilled (ban)	Underground landfill	Landfill	Cannot be landfilled (ban)

Salt slag occurs in the refining, not in the remelting process. BAT would be compulsory slag reprocessing or at least prohibition of depositing the slags as is the case for example in Austria according to the Waste Management Act AWG 2002 ABGI. 102/2002 (Antrekowitsch et el. 619) and which leads to reprocessing as the only option. Dumping slag is environmentally not recommendable due to its leachability and gas formation. Dross occurs in the remelting process which can be recycled in the refining process.

(3) Water use: In terms of water use the secondary route is much more efficient than the primary one. In primary production water use is around 10 m³/ t of Al and in secondary production only around 2 m³/ t of Al (The Aluminum Association 2013).

(4) CO_2 emissions and energy use: The CO_2 emissions associated with Aluminium recycling are around 0,4 t CO_2/ t of Al. In comparison, the production of primary Aluminium from Bauxite emits around 10 t CO_2/ t of Al. Specific CO_2 emission values differ of course depending on the source of energy used for the Aluminium production (The Aluminum Association 2013). Energy demand for producing a ton of Aluminium from Bauxite is around 140 GJ/ t and from recycled Aluminium around 10 GJ/ t (The Aluminum Association 2013). So recycled Aluminium has a very favorable carbon and energy balance. Recycled Aluminium can be produced with a roughly 95 % reduced carbon impact and roughly only 7 % of energy demand.

(5) Chemicals and pollutants: (The Aluminum Association 2013):

Table 12 - Chemicals and pollutants in secondary Al production

Chemicals and pollutants	
Type	**[kg/t of Aluminium]**
Atmospheric Emissions (NO_x, SO_x, C, Cl_2, HCl_2, CH_4, H_2 etc.), without CO_2	0,35314
Dust particles	0,2829
Heavy metals	0,0011
Organic emissions to air (VOC)	0,0882

9 Assessment Instructions

The herein developed responsibility assessment is always based on the same principles and procedures, independently of the material evaluated. However, the basis that constitutes the assessment scheme is the nature of an individual material flow (here called nature of unit processes), which may vary in the number of unit processes considered. The flow of a material has to be categorized into such unit processes that allow the evaluation of a unit process with respect to their PBs impact. Many unit processes are typically consecutive processes but the closer the unit processes come to the "product part" the more likely it becomes, that a material flow consists of parallel unit processes. The total assessment framework for one material always has to be individually set-up. The idea is to have a proto-typical framework and fixed unit processes for each material that will constitute its material (-flow) passport. However, not every assessment has to be carried out including all unit processes. It is anyone's choice to only work on parts of the any material assessment within this scheme and thus contribute to the material passport. As such it should ideally be looked as a whole, as the idea is to have a holistic picture of the responsibility potential of a material.

In the following part the specific application to Aluminium as material of choice for the case study is explained:

9.1 Material assessment matrix – How to compile it?

✓ First, the **indicators** are conditioned: the cause and effect of each PB are explained. Corresponding threshold values according to Rockström and his team (Rockström et al. 2009) are outlined. Additionally, Aluminium production system relevant thresholds are deducted for each boundary where appropriate and possible through existing knowledge of the production process (see chapter 7).

Planetary boundaries indicators:

The nine planetary boundaries are defined as climate change (1), novel entities (2), stratospheric ozone depletion (3), atmospheric aerosol loading (4), ocean acidification

(5), biochemical flows (phosphorus and nitrogen) (6), freshwater use (7), land-system change (8), biosphere integrity (functional and genetic diversity) (9).

- ✓ Second, the **framework system** is conditioned: the material (Al) life cycle system boundaries are identified according to the generic life cycle scaffold presented in Figure 44 and each thus defined unit process is subsequently described.

Al framework system boundaries:

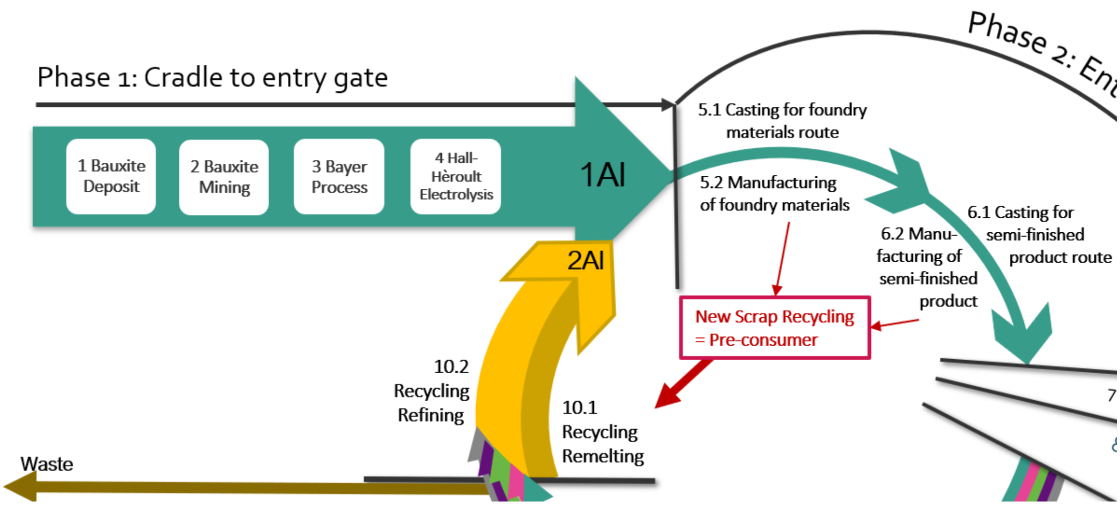


Figure 44- Unit process boundaries for assessment

The Aluminium production framework system boundaries are defined as bauxite deposit (1), bauxite mining (2), Bayer process (3), fused-salt electrolysis (4), casting for foundry route (5.1), (in parallel) manufacturing of foundry materials (5.2), casting for semi-finished product route (6.1), (in parallel) manufacturing of semi-finihsed product (6.2), final assembly (7), consumption (8), Aluminium use categories (9), recycling / remelting (10.1, 10.2). As the following case study is meant to solely try the assessment scheme with regards to its functionality and sense as well as due to capacity constraints, categories 5 to including 9 will not be taken into consideration in this assessment. Based on these unit processes a clear classification of the process units towards the PBs is possible.

- ✓ Third, the **material matrix** is compiled (Table 13): Each PB is numbered from 1-9 and put into horizontal boxes. Each identified unit process of the material (Al) is numbered (1-x) and put into boxes vertically. They thus constitute the previously introduced generic matrix that allows each PB to meet each material (Al) unit process and match up as a pair to be calibrated. Each calibration result is entered into the according category box (PB1.1, PB1.2 etc.).

Table 13 - Calibration matrix Aluminium with selected unit processes for assessement

CALIBRATION MATRIX – GENERIC			PLANETARY BOUNDARIES								
			PB1 – Climate Change	PB2 – Novel Entity	PB3 – Stratospheric Ozone Depletion	PB4 – Atmospheric Aerosol Loading	PB5 – Ocean Acidification	PB6 – Biochemical Flows (Phosphorus and Nitrogen)	PB7 – Freshwater Use	PB8 – Land-system Change	PB9 – Biosphere Integrity [loss] of functional and genetic diversity
ALUMINIUM LIFE CYCLE PRODUCTION STEPS	PHASE 1 – Cradle to Entry Gate	1 Bauxite Deposit	PB1.1	PB2.1	PB3.1	PB4.1	PB5.1	PB6.1	PB7.1	PB8.1	PB9.1
		2 Bauxite Mining	PB1.2	PB2.2	PB3.2	PB4.2	PB5.2	PB6.2	PB7.2	PB8.2	PB9.2
		3 Bayer Process	PB1.3	PB2.3	PB3.3	PB4.3	PB5.3	PB6.3	PB7.3	PB8.3	PB9.3
		4 Fused-salt electrolysis – Hall Hèroult Process	PB1.4	PB2.4	PB3.4	PB4.4	PB5.4	PB6.4	PB7.4	PB8.4	PB9.4
	PHASE 2 – Entry Gate to Exit Gate	5.1 Casting to foundry materials									
		5.2 Manufacturing of foundry materials									
		6.1 Casting to semi-finished products									
		6.2 Manufacturing of semi-finished products									
		7 Final Assembly									
	8 Consumption										
	PHASE 3 – Exit Gate to Grave or/and Entry Gate	9.1 Transportation and traffic									
		9.2 Packaging									
		9.3 Construction									
		9.4 Electrical Engineering, Mechanical Engineering									
		9.5 Other use and Future Energy Technologies									
		10.1 Recycling - remelting	PB1.10.1	PB2.10.1	PB3.10.1	PB4.10.1	PB5.10.1	PB6.10.1	PB7.10.1	PB8.10.1	PB9.1 10.1
		10.2 Recycling - refining	PB1.10.2	PB2.10.2	PB3.10.2	PB4.10.2	PB5.10.2	PB6.10.2	PB7.10.2	PB8.10.2	PB9.10.2
Sum											
Transgression Level Gravity Factor (sum*1/2/3/4/5) acc. to transgression level											

9.2 Assessment mechanism – How to assess properly?

- ✓ Subsequently, the **assessment starts**. Each material (Al) unit process is now actually calibrated with each PB individually (Figure 45). A calibration always asks the question *How does a chosen unit process contribute to transgressing the PB it is calibrated with?* For example, the unit process **1 Bauxite Deposit** is calibrated with **PB8 Land Use Change**. This would be category box **PB8.1**. Here the question would be asked: *How does bauxite mining contribute to land use change and to what degree?* To be able to answer if and how much a certain unit process contributes to the transgression of a planetary boundary it is important to (1) know about the planetary boundaries and their threshold values and (2) know about the unit processes, therefore be an expert concerning them.

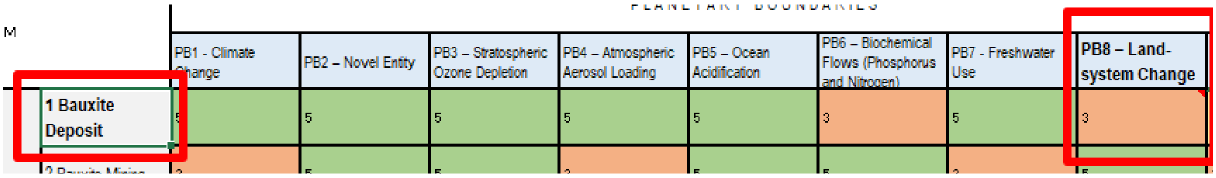


Figure 45 - Cross-matching a unit process with a Planetary Boundary

- ✓ Related *technologies*, *processes* or *practices* in the unit processes that generate certain PB relevant inputs or outputs should be scrutinized. The assessment should cover the aspect of a best-available-technology (BAT) scenario (What is already technologically possible today?) and reflect the best-available-practice (BAP) scenario (What is the reality in technology application today and why?). What would need to be done in order to change possible discrepancies?
- ✓ The calibration should be done thoroughly and all necessary research should be undertaken that fosters the understanding of the calibration. The information compiled can be entered into the category box as in Figure 46. In the XLS sheet this can be done via the comment function.

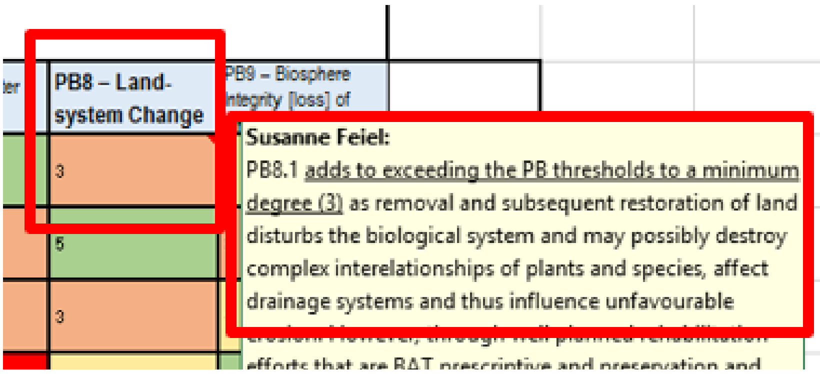


Figure 46 - Researched background information as basis for assessment points

- ✓ Negative findings must be discussed accordingly and suggestions for future positive environmental development for the unit process concerned must be brought forward.

- ✓ There is a point system and each calibration (e.g. PB8.1) is assigned points through the assessing experts according to the findings. The contents compiled should build a solid foundation for the points that are assigned to each calibration category. How to assign how many points specifically is explained in detail further below.
- ✓ A color code was developed that corresponds to the amount of points assigned. How the color code work is explained in detail further below.
- ✓ A corresponding familiar grading system was adapted to the point system which allows easy communication about the results.

9.3 The automated XLS matrix

- ✓ To be able to generate an easy to use tool for everybody the calibration can be compiled into an automated matrix in an XLS form that was programmed. The proposed matrix will be color-coded automatically once filled in properly. In this way it will resemble a material passport at the end that on the one hand provides an easy to understand color matrix on the surface, reflecting the responsibility potential of the material nicely. On the other hand, it will be filled with information in the background that explains why a certain color was assigned. Ideally, this would be a more professional computer programme.
- ✓ There is a five-step a color spectrum from negative (red) to positive (green) and each calibration category is assigned a color after successful assessment. The more the matrix is colored in the negative red colors the worse the environmental production system status of a material is. The more the matrix is drenched in green colors, the better the environmental production system status of the material is. The matrix can thus serve as a fixed 'Environmental Planetary Boundary passport' for a material. It can be altered and adapted over time, with the ultimate goal of achieving the best colors in each unit process and each PB.

9.3.1 How the scoring and color assignment works

The entire calibration matrix "material passport" will look like the example in Figure 47. The calibration matrix will be filled with colors as the assessment progresses and will resemble an easy to understand material passport once completed. The points and corresponding colors assigned in all following explanation **figures** do not reflect the actual assessment but have been added randomly only for explanation purposes. The explanations with regards to the point amounts are based on the selected unit processes for this specific assessment.

CALIBRATION MATRIX - ALUMINIUM			PB1 - Climate Change	PB2 – Novel Entity	Calibration Category PB 3 1 PB3 – Stratospheric Ozone Depletion	PB4 – Atmospheric Aerosol Loading	PB5 – Ocean Acidification	PB6 – Biochemical Flows (Phosphorus and Nitrogen)	PB7 - Freshwater Use	PB8 – Land-system Change	PB9 – Biosphere Integrity [loss] of functional and genetic	TOTAL
			PLANETARY BOUNDARIES									
ALUMINIUM LIFE CYCLE PRODUCTION STEPS	PHASE 1 – Cradle to Entry Gate	1 Bauxite Deposit	2	2	1	2	1	0	2	2	2	14
		2 Bauxite Mining	2	1	1	3	1	0	3	3	3	17
		3 Bayer Process	2	4	1	2	2	0	3	2	2	18
		4 Fused-salt Electrolysis	3	3	1	3	3	0	2	1	1	17
	PHASE 2 – Entry Gate to Exit Gate	5.1 Casting to foundry materials	Category PB1.5.1	Category PB2.5.1	Category PB3.5.1	Category PB4.5.1	Category PB5.5.1	Category PB6.5.1	Category PB7.5.1	Category PB8.5.1	Category PB9.5.1	0
		5.2 Manufacturing of foundry materials	Category PB1.5.2	Category PB2.5.2	Category PB3.5.2	Category PB4.5.2	Category PB5.5.2	Category PB6.5.2	Category PB7.5.2	Category PB8.5.2	Category PB9.5.2	0
		6.1 Casting to semi-finished products	Category PB1.6.1	Category PB2.6.1	Category PB3.6.1	Category PB4.6.1	Category PB5.6.1	Category PB6.6.1	Category PB7.6.1	Category PB8.6.1	Category PB9.6.1	0
		6.2 Manufacturing of semi-finished products	Category PB1.6.2	Category PB2.6.2	Category PB3.6.2	Category PB4.6.2	Category PB5.6.2	Category PB6.6.2	Category PB7.6.2	Category PB8.6.2	Category PB9.6.2	0
		7 Final Assembly	Category PB1.7	Category PB2.7	Category PB3.7	Category PB4.7	Category PB5.7	Category PB6.7	Category PB7.7	Category PB8.7	Category PB9.7	0
	PHASE 3 – Exit Gate to Grave or/ad Entry Gate	9.1 Transportation and traffic	Category PB1.9.1	Category PB2.9.1	Category PB3.9.1	Category PB4.9.1	Category PB5.9.1	Category PB6.9.1	Category PB7.9.1	Category PB8.9.1	Category PB9.9.1	0
		9.2 Packaging	Category PB1.9.2	Category PB2.9.2	Category PB3.9.2	Category PB4.9.2	Category PB5.9.2	Category PB6.9.2	Category PB7.9.2	Category PB8.9.2	Category PB9.9.2	0
		9.3 Construction	Category PB1.9.3	Category PB2.9.3	Category PB3.9.3	Category PB4.9.3	Category PB5.9.3	Category PB6.9.3	Category PB7.9.3	Category PB8.9.3	Category PB9.9.3	0
		9.4 Electrical and Mechanical Engineering	Category PB1.9.4	Category PB2.9.4	Category PB3.9.4	Category PB4.9.4	Category PB5.9.4	Category PB6.9.4	Category PB7.9.4	Category PB8.9.4	Category PB9.9.4	0
		9.5 Other use and Future Energy Technology	Category PB1.9.5	Category PB2.9.5	Category PB3.9.5	Category PB4.9.5	Category PB5.9.5	Category PB6.9.5	Category PB7.9.5	Category PB8.9.5	Category PB9.9.5	0
		10.1 Recycling Remelting	2	2	1	2	1	2	4	1	0	15
		10.2 Recycling Refining	2	3	1	3	1	2	4	1	0	17
		Sum	13	15	6	15	9	4	18	10	8	98
		UP Gravity weighting	26	15	6	15	9	16	18	20	32	

Figure 47 - Calibration matrix "material passport" example according to assessment unit processes

Point assignment instructions

How to assign points to each calibrated category is described step-by-step throughout the following passages:

Scorable grades per calibration category

Calibration category:

Every cross-match (calibration) of a PB and a UP is called a **calibration category** (e.g. *PB1 Climate Change* and unit process *1 Bauxite Deposit = calibration category PB1.1* or as in the figure below *PB8 Land Use Change* and unit process *1 Bauxite deposit = PB8.1.* The PB number always constitutes the first number of a category, followed by the number of the unit process).

Table 14 - Calibration category example

CALIBRATION MATRIX - ALUMINIUM					Calibration Category PB 3.1	PLANETARY BOUNDARIES		
			PB1 - Climate Change	PB2 – Novel Entity	PB3 – Stratospheric Ozone Depletion	P 4 – Atmospheric A rosol Loading	PB5 – Ocean Acidification	PB6 – Flows Nitrog
	Entry Gate	1 Bauxite Deposit	2	2	1	2	1	0

Grading: Each calibration category can receive a grade. **Grades range from 1-6, 1 corresponding to excellent and 6 corresponding to fail.** The underlying logic for how these grades are assigned depends on the degree that each category contributes to the transgression of the PBs or not. 1 hardly contributes at all but is a relevant category for the production process, 6 contributes to an unacceptable degree.

If a calibration category does not contribute to transgression at all due to irrelevance, i.e. it does not occur at all in the production process, then a 0 is assigned.

The nuancing, meaning the classification of how grades can be assigned according to which content criteria, is described below.

Overall matrix assessment

There is a point total assigned with defined thresholds for each UP and also for each PB, hence it is possible to rate single UPs with regards to their overall PBs compatibility but it is also possible to rate individual PBs in a material production cycle. As the UPs taken into consideration in any study may vary, the assessment matrix and the scoring points have to be adapted prior to each assessment according to how many unit processes are taken into consideration. The way overall points correspond to grades and the way they have to be calculated according to the study undertaken is explained below according the current assessment conditions.

Overall points and corresponding grades: In the current assessment the number of unit processes analyzed are 6. The grading scale is thus as illustrated in the picture here.

Table 15 - Overall points and corresponding grades

Grades are like points	Total overall points attainable	Total possible points for each UP	Total possible points for each PB (based on 6 UPs considered)	Color assigned to grades, score range and weighting ranges
Not applicable	0	0	0	
Grade 1	1 - 54	1 - 9	1 - 6	
Grade 2	55 - 108	10 - 18	7 - 12	
Grade 3	109 - 162	19 - 27	13 - 18	
Grade 4	163 - 216	28 - 36	19 - 24	
Grade 5	217 - 270	37 - 45	25 - 30	
Fail	over 270	over 45	over 30	

In this specific assessment the overall maximum amount of points is 270 points.

Calculation of overall points for this specific study: The 270 points are based on the logic that

- if 9 PBs are taken into consideration and are calibrated with 6 UPs, then we receive 9x6 = 54 calibration categories

- and if every calibration category (54) is assessed with a specific grade, then the following thresholds are valid:

54x1 = 54 maximum points for overall matrix grade 1
54x2 = 108 maximum points for overall matrix grade 2
54x3 = 162 maximum points for overall matrix grade 3
54x4 = 216 maximum points for overall matrix grade 4
54x5 = 270 maximum points for overall matrix grade 5
271 and more points for overall matrix grade 6

The fewer points a PB or a UP receive the better. It means the single calibration categories of the respective PB or UP have scored good grades.

Calculation of overall points for any study: The calculation is always:

Grade 1 maximum points: n planetary boundaries x n unit processes x 1 maximum pt = n pts
Grade 2 maximum points: n planetary boundaries x n unit processes x 2 maximum pts = n pts
Grade 3 maximum points: n planetary boundaries x n unit processes x 3 maximum pts = n pts
Grade 4 maximum points: n planetary boundaries x n unit processes x 4 maximum pts = n pts

Grade 5 maximum points: n planetary boundaries x n unit processes x 5 maximum pts = n pts

However, as there are PBs which are more critical than others in terms of their general transgression status, a criticality weighting factor is part of the scoring of single calibration categories (based on Figure 9).

Table 16 - Criticality weighting factor

Criticality weighting factor explanation	Criticality weighting factor	PBs with exisitng transgression	PB weighting factor
Staying within boundary line 1	*1	PB1 Climate Change	*2
Transgressing boundary line 1 - arriving in the second shell	*2	PB6 Biochemical Flows	*4
Transgressing boundary line 2 - arriving in the third shell	*3	PB8 Land System Change	*2
Transgressing boundary line 3- leaving shells, tipping point, overshhoot	*4	PB9 Biosphere Integrity - Genetic Diversity	*4
		all others	*1

<u>Max. category points per classification nuance attainable</u>

The **classification nuances correspond to the points and grades** as they are the content basis for assigning points.

Per calibration category:

Table 17 - Max. category points per classification nuance

Pts.	Grade	Points possible	Classification nuances *"To which extent does a chosen unit process contribute to transgressing the PB it is calibrated with?"*
	Grade 1	1 point	not
	Grade 2	2 points	minimally
	Grade 3	3 points	partially
	Grade 4	4 points	extensively
	Grade 5	5 points	severely
	Overshoot	*weighting factor	according to PB status

<u>Maximum points per unit process</u>

All **calibration categories of a unit process can be summed up** (e.g. 40 as illustrated).

Table 18 - One unit process example

									10
2 Bauxite Mining	2	3	1	1	1	1	4	3	2	18

Every unit process encompasses all PBs. All 9 PBs are calibrated with this unit processes. The attainable points in each calibration category are 1 to 5. The sum of all 9 calibration categories yields the **planetary boundary compatibility of a specific unit process**.

Table 19 - Maximum points per unit process

Pts.	Grade	Accumulated points possible
1	Grade 1 PB unit process	1 - 9 points
2	Grade 2 PB unit process	10 - 18 points
3	Grade 3 PB unit process	19 - 27 points
4	Grade 4 PB unit process	23 - 36 points
5	Grade 5 PB unit process	37 - 45 points
F	Fail = Overshoot	> 45 points

In the initial figure a **grade B** *PB compatible unit process* can therefore be found.

Maximum points per Planetary Boundary (calibrated across entire production cycle)

All calibration categories of a specific PB can be summed up (e.g. 31 as illustrated).

Every PB stretches across an entire material life cycle. All unit processes of this cycle are calibrated with this one specific PB. The attainable points in each calibration category are 1 to 5. The sum of all (in this case) 6 PB specific UP calibration categories yields the **compatibility of a specific material life cycle with a specific planetary boundary**.

Table 20 - Maximum points per Planetary Boundary

Pts.	Grade	Accumulated points possible
1	Grade 1 PB production cycle	1 - 6 points
2	Grade 2 PB production cycle	7 - 12 points
3	Grade 3 PB production cycle	13 - 18 points
4	Grade 4 PB production cycle	19 - 24 points
5	Grade 5 PB production cycle	25 - 30 points
F	Fail	> 45 points

In the figure beside a **grade 2** *production cycle with regards to PB1* - Climate Change can therefore be found. Through the weighting factor in becomes a **grade 3** process.

The goal for a responsible material should be an all green grade A matrix. It becomes clear that with this matrix an assessment of various aspects can be conveyed. Not only can a material be assessed regarding its entire PB footprint across its entire production cycle but also the unit process footprint across all PBs as well as the individual PB across an entire production cycle can be looked at. The system is easily accessible through its color coding and familiar grading system. It is furthermore flexible in terms of assigning points and can be adapted to any material. However, as the technicalities of assigning points have been resolved the much more interesting question of how to assign the points from 1 to 5 remains. The following overview and elaboration of the classification nuances shall provide an overview.

Table 21 - One assessed PB for Al

	PB1 - Climate Change
1 Bauxite Deposit	1
2 Bauxite Mining	2
3 Bayer Process	3
4 Fused-salt Electrolysis	1
5.1 Casting to foundry materials	Category PB1.5.1
5.2 Manufacturing of foundry materials	Category PB1.5.2
6.1 Casting to semi-finished products	Category PB1.6.1
6.2 Manufacturing of semi-finished products	Category PB1.6.2
7 Final Assembly	Category PB1.7
9.1 Transportation and traffic	Category PB1.9.1
9.2 Packaging	Category PB1.9.2
9.3 Construction	Category PB1.9.3
9.4 Electrical and Mechanical Engineering	Category PB1.9.4
9.5 Other use and Future Energy Technology	Category PB1.9.5
10.1 Recycling Remelting	1
10.2 Recycling Refining	1
Sum	9
UP Gravity weighting	18

Classification nuances "degree of contribution to PB transgression"

Generally, the manner in which points are assigned to a calibration category correlates to "how much a given technology, process or practice contributes to a transgression of the planetary boundaries." As was already mentioned in the instructions at the beginning the question has to be asked: *To which extent does a chosen unit process contribute to transgressing the PB it is calibrated with? And how much is how much?*

Therefore, a given technology, process or practice that contributes to an increase in negative environmental impact according to the PB will get many points. A given technology, process or practice that contributes to reduce a negative environmental impact or has little to no environmental impact will get little points. If a PB is irrelevant for a given technology, process or practice then the calibration category will be graded with 0.

The question is thus, how many points can be assigned for how much negative or positive impact? This definition is a rather difficult undertaking and it must be noted that the way in which this assignment of points can take place cannot be thoroughly objective. It is expected that the point assignment will depend to some extent on the person who assesses the material. As the assessment scheme is aimed at not only assigning points but to underpin these points with factual information that justify the points assigned, the assessor is obliged to feed this factual information into the system that underpins the assigned points (see chapter 8). Thus, the profoundness of the assessment will depend on the available time resources and expertise of the assessor or assessing group. This circumstance must in any case be included in a framework discussion around any assessment. Ideally, this calibration matrix will be used by research groups that have extensive time and human resources to dedicate to the assessment. As such the matrix has extensive potential and holistic evaluations with easily accessible passports can be undertaken with all sorts of materials. An entire material passport library could evolve over time, with peer review mechanisms to provide for the quality of the assessment, that would help decision makers and other stakeholders to better understand the dynamics of material production.

The assignment of points is attached to descriptions of the contribution of a given technology, process or practice to overstepping the planetary boundaries (Table 22). This is done through the adjectives: **severely, considerable, partially, minimally, neutral** to provide a general notion and feeling for the assessment. Unfortunately, as this is a classification scheme that is meant to "grade" a given technology, process or practice it is almost impossible to have a clear cut concerning when to start or stop using one or the other category. The border lines may be subject to the conception of an assessor. Not everybody draws the line between severe and considerable at the same dividing line. All adjectives that can be used will be gradable and thus have room for interpretation variation. In order to establish a common understanding as much as possible of what each category means they are described in more detail below. It was tried to establish standardized aspects for consideration (BAT and BAP standards) that correspond to transgression and environmental impact intensity (adjectives of transgression).

In this way the following questions were asked to define standard measures:

1. What is (always in relation to the PB indicator) the **best possible** BAT and/or BAP standard that can be achieved in a given unit process?
2. What is (always in relation to the PB indicator) a **generally good** BAT and/or BAP standard that is common in application in a given unit process?
3. What is (always in relation to the PB indicator) the **least** BAT and/or BAP standard that will still be considered **acceptable** in a given unit process?
4. Which **standard** (always in relation to the PB indicator) lies **between generally good and least acceptable** BAT and/or BAP standard in a given unit process?
5. Which BAT and/or BAP standard (always in relation to the PB indicator) is considered to be **unacceptable** in a given unit process?

Further the question was asked:

How **intense** is the **environmental impact** of any of the given BAP or BAT standards? e.g. How intense is an unacceptable BAP or BAP standard in relation to the PB indicator? Corresponding adjectives were delineated.

Table 22 - Classification nuances for "degree of contribution to PB transgression"

	F /5 points	D /4 points	C /3 points	B /2 points	A /1 point
Level of standardized personal perception	Unsatisfactory	Little Satisfactory	Sound	Acceptable	Outstanding
BAT/ BAP standard (in relation to specific PB)	Unacceptable standard	Least standard	Sound standard – lies between least and generally good standard	Generally good standard	Best possible standard
Transgression intensity definition	severe: harsh; unnecessarily extreme, grave; critical, causing environmental distress by extreme conditions	considerable: Rather large in size or extent, substantial, significant	partial: Limited, sectional, pertaining to or affecting a part, relating to, being, or affecting only a part; not total; incomplete	minimal: constituting a minimum, smallest in amount or degree	neutral: neither positive nor negative, not engaged on either side, belonging to neither extreme in type, kind etc.
Environmental impact and transgression degree definitions	BAP or BAT has **unacceptable standard** - it adds to transgressing specific PB thresholds to a **severe degree**	BAP or BAT has **least standard possible** - it adds to transgressing specific PB thresholds to a **considerable degree**	BAP or BAT has **sound standard** - it adds to transgressing specific PB thresholds to a **partial degree**	BAP or BAT has **generally good standard** - it adds to exceeding PB thresholds to a **minimal degree**	BAP or BAT has **best possible standard** - it does not add to transgressing specific PB thresholds, therefore adds to a **neutral degree**
Some fragmented notes on the categories	Impact is not only measured by its extent but also by its environmental extremeness. It concerns a technology, process or practice in its entirety. Due to its destructive environmental impact this technology, process or practice adds severely to transgressing the PBs and has to be changed if possible or abandoned and substituted with an alternative.	Impact is far reaching but not severe. It concerns the entire technology, process or practice and is the least acceptable standard there is. Chances are that this least acceptable standard is rather related to a specific societal context and that it could be changed with some effort.	Impact is not far reaching but concerns part of the technology, process or practice. It may be that the negative impact of the partial technology, process or practice is already mitigated to a certain extent but cannot fully be improved due to specific circumstances.	Impact of technology, process or practice is little in comparison. There could be room for improvement but this may not be the first priority in comparison to other life cycle related challenges. Standard is widely accepted as environmentally acceptable.	As any industrial activity has some sort of impact the adjective neutral was chosen here. It is meant to signify that the given impact has no negative effects at all but also no positive effects and is therefore neutral
Intensity adjective definition sources	https://www.dictionary.com/browse/severe https://www.thesaurus.com/browse/severe?s=t	https://www.dictionary.com/browse/considerable?s=t https://www.thesaurus.com/browse/considerable	https://www.thesaurus.com/browse/partial?s=t https://www.yourdictionary.com/partial	https://www.yourdictionary.com/minimal https://www.dictionary.com/browse/minimal	https://www.collinsdictionary.com/dictionary/english/neutral https://www.merriam-webster.com/dictionary/neutral https://www.yourdictionary.com/neutral

Gravity proposition: If a technology, process or practice is in any way harmful between 1-3 points, and cannot be changed then an additional point should be deducted.

To summarize all categories and associated gradings and point assignments a summary was compiled in Table 23.

Table 23 - Overview of grading table for Aluminium material assessment

Grades are like points	Total overall points attainable / threshold	Total possible points for each UP	Total possible points for each PB (based on 6 UPs considered)	Color assigned to grades, score range and weighting ranges	Definition of weighting factor: There are 5 boundary lines that can be transgressed. For each transgression of a PB the total sum of the Assessment category will be multiplied by an additional point. E.g. the Genetic diversity PB has arrived in the sixth shell: Bauxite mining scores 3 points in Genetic diversity = 3*6 = 18, no process should disturb genetic diversity in any way as the outermost boundary has been transgressed and a tipping point may have been reached.		So according to the latest PB model each PB is assigned such a factor, as each PB has a transgression status. Each assessment category thus has to be multiplied with this factor if in category	
Not applicable	0	0	0	not relevant	Criticality weighting factor explanation	Criticality weighting factor	PBs with existing transgression	PB weighting factor
Grade 1	1 - 54	1 - 9	1 - 6	neutral	Staying within boundary line 1	*1	PB1 Climate Change	*2
Grade 2	55 - 108	10 - 18	7 - 12	minimal	Transgressing boundary line 1 - arriving in the second shell	*2	PB6 Biochemical Flows	*4
Grade 3	109 - 162	19 - 27	13 - 18	partial	Transgressing boundary line 2 - arriving in the third shell	*3	PB8 Land System Change	*2
Grade 4	163 - 216	28 - 36	19 - 24	considerable	Transgressing boundary line 3 - leaving shells, tipping point, overshoot	*4	PB9 Biosphere Integrity - Genetic Diversity	*4
Grade 5	217 - 270	37 - 45	25 - 30	severe			all others	*1
Fail	over 270	over 45	over 30	disastrous				

10 CASE STUDY – ALUMINIUM LIFE CYCLE AND PLANETARY BOUNDARY MATRIX CALIBRATION

The main aim of this case study is to test the assessment scheme developed to ascertain its applicability and underlying sense. The assessment of each match-up (calibration) in this thesis is done as thoroughly as resources allowed. Certainly, the calibration of each PB with each production step can be done in greater depth in the future by scientists interested in contributing to a comprehensive materials passport inventory.

10.1 General proceeding

As this case study is meant to illustrate the applicability and general functioning of the developed assessment matrix not all unit processes were chosen for assessment. Only those unit processes that seemed essential in impact and thus for illustrative purposes, were included as to keep the study compact and simple as to better learn from it and get an overall idea of how results come together. Certainly, in order to obtain a holistic material footprint profile in a real assessment all UPs should be assessed. Unit processes 1-4 and 10 were selected to be part of the case study, thus:

- 1 Bauxite Deposit
- 2 Bauxite Mining
- 3 Bayer Process
- 4 Fused-salt electrolysis / Hall Hèroult Process
- 10.1 Recycling / remelting
- 10.2 Recycling / refining

The calibration matrix thus comprises the 9 Planetary Boundaries and the identified 6 Aluminium unit processes chosen, thus resulting in a total of 54 pairs that were scrutinized and color coded (see reference Tables chapter 9).

The case study was carried out with two experts in the topic Aluminium production route. The one expert is a Professor for Mining and the other a professor for Non-Ferrous metallurgy whose specialty is Aluminium production. They were instructed about the Planetary Boundaries and their relevant threshold indicators as well as made familiar with the knowledge gathered already on the production route. The unit processes were defined beforehand in accordance with them as to make sure they are the logic sequence and the system boundaries are logically defined. They were subsequently made familiar with the grading instructions. In a joint discussion the chosen unit processes were graded according to the assessment criteria of the previous chapter.

Table 24 - Case study assessment result

ALUMINIUM LIFE CYCLE PRODUCTION STEPS	CALIBRATION MATRIX - ALUMINIUM	PLANETARY BOUNDARIES: PB1 - Climate Change	PB2 – Novel Entity	PB3 – Stratospheric Ozone Depletion	PB4 – Atmospheric Aerosol Loading	PB5 – Ocean Acidification	PB6 – Biochemical Flows (Phosphorus and Nitrogen)	PB7 - Freshwater Use	PB8 – Land-system Change	PB9 – Biosphere Integrity [loss] of functional and genetic diversity	TOTAL
PHASE 1 – Cradle to Entry Gate	1 Bauxite Deposit	1	0	0	0	1	0	1	1	1	5
	2 Bauxite Mining	1	0	0	1	1	0	2	2	2	9
	3 Bayer Process	3	5	1	3	3	0	3	3	3	24
	4 Fused-salt Electrolysis	5	2	2	3	5	0	1	1	1	20
PHASE 2 – Entry Gate to Exit Gate	5.1 Casting to foundry materials	Category PB1.5.1	Category PB2.5.1	Category PB3.5.1	Category PB4.5.1	Category PB5.5.1	Category PB6.5.1	Category PB7.5.1	Category PB8.5.1	Category PB9.5.1	0
	5.2 Manufacturing of foundry materials	Category PB1.5.2	Category PB2.5.2	Category PB3.5.2	Category PB4.5.2	Category PB5.5.2	Category PB6.5.2	Category PB7.5.2	Category PB8.5.2	Category PB9.5.2	0
	6.1 Casting to semi-finished products	Category PB1.6.1	Category PB2.6.1	Category PB3.6.1	Category PB4.6.1	Category PB5.6.1	Category PB6.6.1	Category PB7.6.1	Category PB8.6.1	Category PB9.6.1	0
	6.2 Manufacturing of semi-finished products	Category PB1.6.2	Category PB2.6.2	Category PB3.6.2	Category PB4.6.2	Category PB5.6.2	Category PB6.6.2	Category PB7.6.2	Category PB8.6.2	Category PB9.6.2	0
	7 Final Assembly	Category PB1.7	Category PB2.7	Category PB3.7	Category PB4.7	Category PB5.7	Category PB6.7	Category PB7.7	Category PB8.7	Category PB9.7	0
PHASE 3 – Exit Gate to Grave or/ad Entry Gate	9.1 Transportation and trafic	Category PB1.9.1	Category PB2.9.1	Category PB3.9.1	Category PB4.9.1	Category PB5.9.1	Category PB6.9.1	Category PB7.9.1	Category PB8.9.1	Category PB9.9.1	0
	9.2 Packaging	Category PB1.9.2	Category PB2.9.2	Category PB3.9.2	Category PB4.9.2	Category PB5.9.2	Category PB6.9.2	Category PB7.9.2	Category PB8.9.2	Category PB9.9.2	0
	9.3 Construction	Category PB1.9.3	Category PB2.9.3	Category PB3.9.3	Category PB4.9.3	Category PB5.9.3	Category PB6.9.3	Category PB7.9.3	Category PB8.9.3	Category PB9.9.3	0
	9.4 Electrical and Mechanical Engineering	Category PB1.9.4	Category PB2.9.4	Category PB3.9.4	Category PB4.9.4	Category PB5.9.4	Category PB6.9.4	Category PB7.9.4	Category PB8.9.4	Category PB9.9.4	0
	9.5 Other use and Future Energy Technology	Category PB1.9.5	Category PB2.9.5	Category PB3.9.5	Category PB4.9.5	Category PB5.9.5	Category PB6.9.5	Category PB7.9.5	Category PB8.9.5	Category PB9.9.5	0
	10.1 Recycling Remelting	1	2	1	1	1	2	1	1	1	11
	10.2 Recycling Refining	2	2	2	1	2	2	1	1	1	14
	Sum	13	11	6	9	13	4	9	9	9	83

Table 25 - Case study assessment result with weighting factor

CALIBRATION MATRIX - ALUMINIUM WITH WEIGHTING FACTOR			PLANETARY BOUNDARIES: PB1 - Climate Change	PB2 – Novel Entity	PB3 – Stratospheric Ozone Depletion	PB4 – Atmospheric Aerosol Loading	PB5 – Ocean Acidification	PB6 – Biochemical Flows (Phosphorus and Nitrogen)	PB7 - Freshwater Use	PB8 – Land-system Change	PB9 – Biosphere Integrity [loss] of functional and genetic diversity	TOTAL
ALUMINIUM LIFE CYCLE PRODUCTION STEPS	PHASE 1 – Cradle to Entry Gate	1 Bauxite Deposit	2	0	0	0	1	0	1	2	4	10
		2 Bauxite Mining	2	0	0	1	1	0	1	4	8	17
		3 Bayer Process	6	5	1	3	3	0	3	6	12	39
		4 Fused-salt Electrolysis	10	2	2	3	5	0	1	2	4	29
	PHASE 2 – Entry Gate to Exit Gate	5.1 Casting to foundry materials	Category PB1.5.1	Category PB2.5.1	Category PB3.5.1	Category PB4.5.1	Category PB5.5.1	Category PB6.5.1	Category PB7.5.1	Category PB8.5.1	Category PB9.5.1	0
		5.2 Manufacturing of foundry materials	Category PB1.5.2	Category PB2.5.2	Category PB3.5.2	Category PB4.5.2	Category PB5.5.2	Category PB6.5.2	Category PB7.5.2	Category PB8.5.2	Category PB9.5.2	0
		6.1 Casting to semi-finished products	Category PB1.6.1	Category PB2.6.1	Category PB3.6.1	Category PB4.6.1	Category PB5.6.1	Category PB6.6.1	Category PB7.6.1	Category PB8.6.1	Category PB9.6.1	0
		6.2 Manufacturing of semi-finished products	Category PB1.6.2	Category PB2.6.2	Category PB3.6.2	Category PB4.6.2	Category PB5.6.2	Category PB6.6.2	Category PB7.6.2	Category PB8.6.2	Category PB9.6.2	0
		7 Final Assembly	Category PB1.7	Category PB2.7	Category PB3.7	Category PB4.7	Category PB5.7	Category PB6.7	Category PB7.7	Category PB8.7	Category PB9.7	0
	PHASE 3 – Exit Gate to Grave or/ad Entry Gate	9.1 Transportation and trafic	Category PB1.9.1	Category PB2.9.1	Category PB3.9.1	Category PB4.9.1	Category PB5.9.1	Category PB6.9.1	Category PB7.9.1	Category PB8.9.1	Category PB9.9.1	0
		9.2 Packaging	Category PB1.9.2	Category PB2.9.2	Category PB3.9.2	Category PB4.9.2	Category PB5.9.2	Category PB6.9.2	Category PB7.9.2	Category PB8.9.2	Category PB9.9.2	0
		9.3 Construction	Category PB1.9.3	Category PB2.9.3	Category PB3.9.3	Category PB4.9.3	Category PB5.9.3	Category PB6.9.3	Category PB7.9.3	Category PB8.9.3	Category PB9.9.3	0
		9.4 Electrical and Mechanical Engineering	Category PB1.9.4	Category PB2.9.4	Category PB3.9.4	Category PB4.9.4	Category PB5.9.4	Category PB6.9.4	Category PB7.9.4	Category PB8.9.4	Category PB9.9.4	0
		9.5 Other use and Future Energy Technology	Category PB1.9.5	Category PB2.9.5	Category PB3.9.5	Category PB4.9.5	Category PB5.9.5	Category PB6.9.5	Category PB7.9.5	Category PB8.9.5	Category PB9.9.5	0
		10.1 Recycling Remelting	2	2	1	1	1	8	1	2	4	22
		10.2 Recycling Refining	4	2	2	1	2	8	1	2	4	26
Sum - Transgression Level for entire UP with weighting factor			26	11	6	9	13	16	8	18	36	143
Transgression Level Gravity Factor (sum*1/2/3/4/5/6)			2	1	1	1	1	4	1	2	4	

The general notion for grading was whether or not a specific unit process contributed anything at all to the transgression of a PB and if so, how impactful this contribution was and how well the unit process was designed.

All indicators that were deemed to be irrelevant as they do not occur in the process were graded with 0. All others were applied as in the assessment instructions. The result of the evaluation can be seen in Table 16. A weighting factor was applied according to the instructions once the grading was finished which is illustrated in Table 17.

10.2 Outcomes

"Where in its life-cycle can Aluminium decouple from its environmental impact?" is the research question specifically dedicated to this illustrative case study of Aluminium. The following impact instances were identified:

Table 26 - Identified impact instances per PB overall grade

Pts.	Grade	Accumulated points possible	Identified impact instances (per PB overall grade)
1	Grade 1 PB production cycle	1 - 6 points	PB3 – Stratospheric Ozone Depletion
2	Grade 2 PB production cycle	7 - 12 points	PB2 – Novel Entity PB4 – Atmospheric Aerosol Loading PB7 – Freshwater Use
3	Grade 3 PB production cycle	13 - 18 points	PB5 – Ocean Acidification PB6 – Biochemical Flows PB8 – Land-system change
4	Grade 4 PB production cycle	19 - 24 points	none
5	Grade 5 PB production cycle	25 - 30 points	PB1 – Climate Change
F	Fail	> 45 points	PB9 – Biosphere Integrity

Table 27 - Identified impact instances per UP overall grade

Pts.	Grade	Accumulated points possible	Identified impact instances (per UP overall grade)
1	Grade 1 PB unit process	1 - 9 points	none
2	Grade 2 PB unit process	10 - 18 points	UP 1 – Bauxite Deposit UP 2 – Bauxite Mining
3	Grade 3 PB unit process	19 - 27 points	UP 10.1 – Recycling Remelting UP 10.2 – Recycling Refining
4	Grade 4 PB unit process	23 - 36 points	UP 4 – Fused-salt electrolysis
5	Grade 5 PB unit process	37 - 45 points	UP 3 – Bayer process
F	Fail = Overshoot	> 45 points	none

In terms of the impact of a production cycle within a specific planetary boundary it can be said that only one single boundary is not affected, thus the Aluminium production cycle does not contribute much to the transgression of PB3. The Aluminium production cycle contributes in different intensities to the transgression of all other PBs. The production cycle minimally contributes to transgressing PB2, 4, and 7, it partially contributes to transgressing PB5,6 and 8, it severely contributes to the transgression of PB1 and it overshoots with regards to PB9. The matrix clearly illustrates that transgression levels of single PBs are associated with specific UPs and thus clearly highlights impact instances or specific decoupling potential (only grade 4, 5 and F are illustrated and explained as examples as they are the worst results and those that need urgent action).

Table 28 - Outcomes grade 4-F explained per calibration category

Pts.	Grades per calibration category	WF	Problem / potential mitigation action (discussion potential)	Pts. w/o WF
1				
2				
3				
4	PB1.10.2 – Climate Change / Recycling Refining	2	<u>Problem</u>: **(1)** The needed energy input for refining is 14-18 GJ/ t of secondary Al (including reprocessing of salt slag). The recycling processes of Aluminium work with energy systems based on fossil fuels (gas and oil burners) and therefore produce CO_2. (2) There are also some fluorine and chlorine emissions due to salt slags. They are bound in the fly ash or on activated carbon filters. <u>Potential mitigation action</u>: **(1)** Methane could be replaced by hydrogen in the natural gas pipelines **(1a)** All burners and furnaces have to be converted to electric furnaces, only then hydro or geothermal energy can be used **(2)** Fluorine and chlorine emissions: Bring them into slag processing for reuse. <u>Comment</u>: **(1)** On the primary production side (phase 1, UP 3 and 4) it is easier to replace fossil-fuel based electricity through renewable than in recycling processes, because in remelting and refining everything would have to be converted to electric furnaces first. (2) The cost of reprocessing the slag is larger than landfilling it, so this is an economic question. Technologically this could be implemented large-scale tomorrow everywhere and it is required in the EU.	2

Continuation Table 28

4	PB8.2 – Land-system Change / Bauxite Mining	2	<u>Problem</u>: Bauxite mining activity alters bio- and genetic diversity through stripping surfaces of land by removing 2-5 m of overburden before accessing the ore. However, because of high Al concentration in ore; related to a ton of Al, land use is comparatively little compared to other metals and despite bauxite mining happening in surface area (deposit geometry). In processing bauxite, mining is of little impact because there is in principle no concentration of the ore, a little beneficiation in some mines which is limited to baseline grain size sorting and there are also no tailings. <u>Potential mitigation action</u>: Many rehabilitation projects are ongoing that strive towards restoring natural land and genetic diversity after an area of land has been mined. Before the mining activity starts, the removed overburden is stored and plant and animal species samples are collected for later authentic restoration. These actions are relatively successful. However, in many countries due diligence, according legislation or implementation control systems are not of the quality hoped for and thus the biodiverse room needed for species to live decreases without proper reinstallation. International cooperation, company due diligence and assessment schemes through associations for the improvement of those is the least mitigation action to be implemented. More measures need to be discussed. Best practice has room for improvement in terms of amelioration of rehabilitation practices. <u>Comment</u>: Biosphere integrity is a crucial PB as thousands of species are in danger of extinction and thus this needs to be addressed with utmost urgency. Unfortunately, bauxite deposits are usually found in areas with above average density of bio- and genetic diversity. This boundary is closely related to PB9.2	2
4	PB9.1 – Biosphere Integrity / Bauxite Deposit	4	<u>Problem</u>: Taking an average value of 1m for soil coverage and 5 m for the overburden and 5 m for the thickness of a bauxite deposit, around 50 m of core drilling are sufficient to explore around 2,4 Mt of bauxite. This is actually an efficient process, compared to other mining exploration, however still an intervention in nature. <u>Potential mitigation action</u>: Research into the impacts of exploration on biodiversity. <u>Comment</u>: For mining this is a relatively low impact which explains the original grade 1. However, Biosphere integrity is a crucial boundary and bauxite deposits are usually found in areas with above average density of bio- and genetic diversity. It is therefore of utmost importance that exploration is carried out with high caution and awareness towards biodiversity. This is a topic that needs more research.	1
4	PB9.4 – Biosphere Integrity / Fused-salt Electrolysis	4	<u>Problem</u>: 20 kg of spent pot lining (SPL) waste occur per t of Al (at 60 Mt per year this results in 1,2 Mt per year. SPL). It needs to be landfilled or incinerated. It contains fluorides and cyanides. <u>Potential mitigation action</u>: There are some actions towards reprocessing the spent pot lines one of which has reached "TRL 7 and reprocesses the SPL into fluoride salts for Aluminium production, graphitized carbon for Aluminium production, alumosilicates for the refractory industry and manufactured aggregates for construction (geotechnical fill, bricks, concrete)" (Mladenovic 2017). <u>Comment</u>: In comparison to the red mud amounts this is a seemingly negligible issue. However, nothing is negligible in sustainable development. Otherwise there is only company area as land consumption and biodiversity consumer.	1

Continuation Table 28

4	PB9.10.1 – Biosphere Integrity / Recycling Remelting	4	Problem: Both processes, remelting and refining recycle Aluminium and can therefore be seen as positive. Remelting has a lower energy intensity than refining because refining work with salt slag as it reprocesses impure Aluminium fraction. Potential mitigation action: improve salt slag reprocessing Comment: Energetically remelting is better than refining. With regards to input material refining is better because it reprocesses the environmentally harmful impure fraction material which would otherwise have to be landfilled.	1
4	PB9.10.2 – Biosphere Integrity / Recycling Refining	4	Problem: Landfill leads to nitrification, but not in BAT because there the salt slag from the refining process is processed. Thereby ammonia is produced and is added in the exhaust system with diluted sulphuric acid and thus ammonium sulfate is obtained which is used as fertilizer. Potential mitigation action: In countries where this is not done, the practice of processing the salt slag according to BAT needs to be implemented. Comment: BAT is available and required in the EU (2) Refining reprocesses the impure Aluminium fraction which would otherwise, have to be landfilled, as remelting is not designed for this process.	1
5	PB2.3 – Novel Entity / Bayer Process	1	Problem: The amounts of red mud that are landfilled per year are enourmous. Potential mitigation action: Process technologies for solutions already exist. Large numbers of stakeholders work intensively on hydro and pyrometallurgical solutions to go into a material recycling of red mud. Comment: The material is ideal for the cement or refractory industry as Alumina carrier. The alkalis must be handled intelligently, however. Theoretically, all of this could be implemented tomorrow but this is not done because of economic reasons. However, some stakeholders already implement this because they are creating market advantages for themselves. The development goes into this direction.	5
5	PB5.4 – Ocean Acidification / Fused-salt Electrolysis	1	Problem: (1) High energy requirement with 150-160 GJ/ t of Al which results in CO_2 emissions (2) Anode consumption. The anode in the electrolysis dissipates to CO_2 as its carbon bonds with oxygen. Potential mitigation action: (1) Use hydropower or geothermal energy instead of fossil fuel systems and design of less energy intensive process. Hydropower and geothermal energy is already BAT and BAP, a less energy intensive process, therefore a different process is not in sight. (2) Develop and implement inert anode for electrolysis, potential savings: 1 t of CO_2/ t of Al = 65 Mt of CO_2 per year. Comment: Research is ongoing, solutions are in sight but not in near sight.	5
F	PB1.3 – Climate Change / Bayer Process	2	Problem: Through the high amounts of water that are evaporated in the Bayer process according energy demand is responsible for high CO_2 emissions as energy generation is based on fossil fuel systems. Bayer needs around 20-40 GJ/ t of Al, which is, although a lot, much less energy demand than electrolysis. Potential mitigation action: (1) Shift from autoclave systems to tube reactor systems, (2) Use geothermal or hydropower for pumps where possible and reasonable Comment: (1) tube reactors work under pressure and thus higher temperatures and therefore a lower NaOH concentration is necessary for Al hydroxide digestion. Furthermore, this means little water evaporation and no dilution of the supersaturated caustic is necessary after digestion. (2) Geothermal or Hydro power is not possible everywhere.	3

Continuation Table 28

F	PB1.4 – Climate Change / Fused-salt Electrolysis	2	<u>Problem</u>: There are three problems associated with the fused-salt electrolysis and climate change Points **(1)** and **(2)** from above PB5.4 (CO_2 generation through electrolysis energy requirement and anode consumption) plus <u>(3)</u> Fluorine gases are now minor because an exhaust gas encapsulation (no more fluorine in atmosphere) was introduced, however, according to legal limits a few milligrams per standard m^3 escape. <u>Potential mitigation action</u>: **(1)** same as above in PB5.4 **(2)** same as above in PB5.4 **(3)** Fluorine gas escape can be avoided by improving exhaust systems by making them 3-stage systems. Would happen immediately if limit values were lowered. (Interplay of many spheres) <u>Comment</u>: CO_2 emissions account for 99 % of emissions in this UP. Fluorine gases account for 1 % of emissions in this UP.	5
F	PB6.10.1 – Biochemical Flows / Recycling Remelting	4	<u>Problem</u>: The melting process produces ammonium nitrides and when these react with moisture ammonia is obtained which can go into the ground water range. However, dross and salt slag are reprocessed in the EU. <u>Potential mitigation action</u>: in countries where this is not done, the practice of reprocessing dross and salt slags needs to be implemented. <u>Comment</u>: BAT and BAP are available and required in the EU	2
F	PB6.10.2 – Biochemical Flows / Recycling Refining	4	same as PB6.10.1	2
F	PB8.3 – Land-system Change / Bayer Process	2	<u>Problem</u>: (Include company land area and landfill in grading): red mud landfilling uses a lot of land as well as decreases and endangers biodiversity. The amounts of red-mud are large (2-3 t/ t of Al = 180 Mt per year that have to be landfilled). Although the area is much smaller than needed for Bauxite mining, this is more problematic as there is no rehabilitation option, hazardous waste landfill cannot be rehabilitated. There are sometimes safety issues with securing the damns and damn breakage disasters have happened that have large scale impacts on the biodiversity of the affected spillage areas. <u>Potential mitigation action:</u> Implementation of red mud utilization applications (there are various available), economic viability of red mud utilization and according legislation. E.g.: when red mud is reduced, ferrotitanium silicon alloy is produced which is ideal for use in the steel industry, thus replacing primary raw materials. Also, the energy needed for ferroalloys is thus replaced. The result is a building material. <u>Comment</u>: Even without the weighting factor this category would have scored in the middle range only.	3

Continuation Table 28

F	PB9.2 – Biosphere Integrity / Bauxite Mining	4	Same as PB8.2	2
F	PB9.3 – Biosphere Integrity / Bayer Process	4	Same as PB8.3	3

It can be seen that some calibration categories would have received a good grade but that the weighting factor actually put them in a very bad grade. This means that even though processes may seem to be relatively harmless if not viewed systemically they are to be considered critical in terms of their contribution to the planetary boundaries, as can be seen with the example of category PB9.1, 9.4, 9.10.1 and 9.10.2 that in the non-weighted assessment were green grade 1 and turned into light red grade 4 with a weighting factor.

It becomes clear through this assessment that the Aluminium production process is problematic in three core aspects with regards to the planetary boundaries (as they often reoccur in many PBs) and therefore problematic with regards to the environment, namely:
(1) the red mud of the Bayer Process,
(2) the high energy requirement of the Fused-salt Electrolysis and
(3) the anode consumption of the Fused-salt Electrolysis.

Those three aspects are in many ways contributing to the transgression of PBs and are the three central issues that need resolution if the grading of the Aluminium matrix is to be improved and the material to become a systemically responsible one. The crucial point with this is that there are indeed possible mitigation actions to a large extent to solve the impact problem of Aluminium.

In case (1) there are established ways to reprocess the red mud, however, landfill is 3-5 €/ t but reprocessing costs 300-600 €/ t, depending on the nature of the red mud. Today, it is therefore not a technological but an economic question whether the red mud is reutilized and therefore deeply rooted in the responsibility discussion.

In case (2), in the absence of an alternative less energy intensive process, there is the possibility to supply the electrolysis with hydro- or geothermal power instead of fossil fuel-based power. This is already done in some cases but on a worldwide level extensive catch-up is required.

In case (3) the development of an anode that does not get consumed is a possible mitigation action. Such action is currently being undertaken (see chapter on UP4, CO_2 emissions and energy use) but results are not satisfying as of yet. TRL of the inert anode is 5 and small-scale tests have been conducted in the past several years, the key challenge being the affordability of the materials used and finding a material that does not corrode in the process. Therefore, a mitigation action has been identified but not yet been successfully developed.

The importance is with this assessment is that the key is whether or not a mitigation is possible at all. If, for a material, impact instances are identified and no mitigation is possible, be it because of technological, chemical, physical, economic reasons etc., then a principle discussion and decision regarding societal use of this material should follow. In the case of the inert anode, even if this approach does not work, there is an outlook that the generated CO_2 can somehow be at least captured.

The overall grade for Aluminium is 143 and therefore a grade 3 material. Assigned color

11 Evaluation, Discussion of Results and Conclusion

11.1 General outcomes

One of the questions that this new assessment scheme and the related case study was meant to answer was *"Where in its life-cycle can a certain material decouple from its environmental impact?"* As a general outcome it can be said that the matrix did indeed allow for the identification of the decoupling space in an overall material flow through identification of its respective relevant unit processes and an assessment and grading of these. It was shown through the case study that a material flow as whole can be systematically depicted and its crucial environmentally weak points, or impact instances, can be identified. These environmental weak points can be defined as the decoupling space of a material. In the case of Aluminium these were three crucial points (red mud, energy requirement, anode consumption) alongside several other important but not as weighty ones. As all societal activity is based on material flows it can be said that this decoupling space of materials is the crucial one to be taken into consideration when assessing environmentally responsible production systems.

11.2 Strengths of the assessment matrix

The assessment matrix definitely has the potential to mirror the responsibility potential of material production systems if done correctly. If applied thoroughly and responsibly (!) the matrix delineates the environmental decoupling moment and thus points out where improvement discussions are necessary. It may be an extensive system to compile but it is an easy system to read. As such it can positively influence decision making of policy makers and politicians or it can positively contribute to creating materials awareness in society.

The grades as such in the assessment provide a good overview and guidance as to where in the material flow system action is necessary. It could be seen as a weakness that the grading is not 100 % certain as it is difficult to consider every little detail of a unit process and then accurately weight it properly against the other unit processes. It is questionable if every expert who grades would come to the exact same result. However, and especially if many people work on such matrixes jointly, results will improve and be robust. The grade accuracy is not decisive as long as the general notion is correct because the matrix as such provides a systematic systemic way of looking at material flow systems. It is meant to trigger a discussion in/for the correct decoupling space, because society as a whole is duty bound to enact responsible material flows.

Another question to be answered was *"What needs to be done to make a certain material responsible in case there are deficiencies?"* The matrix of course does not offer solutions to the problems pointed out in the system. It merely points towards where solutions are needed. It is important, however, to be able to point out impact instances in the flow system as only then solutions how to eliminate these can be elaborated. This was done to a certain extent in the case study. If solutions exist then they should be implemented, if no solutions exist and none are in future sight then the societal use of materials needs to be questioned as well as abandoning the use of such a material should be considered. This is the answer to the question that was asked at the beginning: *"What should be done if there is no possibility to improve the materials environmental impact?"* Certainly, the creation and trial of the case study itself did not generate this answer but the intensive occupation with the matter while designing and carrying out the scheme was certainly leading up to this answer.

An additional question that was to be answered was *"To which extent is a certain material a responsible material in our society?"* A strength of this assessment mode is that the matrix comprehensively points out if a flow system has a few or very many impact instances and thus provides a good overall picture of a single material. It does not, however, imply the degree of responsibility of a material. Nevertheless, the more material flow systems are depicted in the form of this matrix, the more materials will become comparable to each other in terms of their environmental impact. This would maybe yield the insight that even if some unit processes of some materials are not 100 % responsible, the material may nevertheless be system responsible in comparison to other material systems which holistically have a much worse outcome. In this way it can be used as a responsibility weighting system. For this, however, more robust data frameworks, as for example robust CO_2 statistics have to be filed that allow for comparison.

One more advantage of this matrix is the transferability of the scheme and that it can actually be applied to all materials and/or indicators. With each material unit process, boundaries and individual parameters have to be adapted but the general concept works. As such it is thought to also work for social or environmental indicator frameworks as well as the consumption sphere as outlined in Table 2.

11.3 Missing indicators in matrix

The following points illustrate additional important points that should be assessed in an environmental material assessment. The planetary boundaries are crucial indicators regarding the biophysical stability limits of our ecosystem but when assessing the responsibility factor of materials used in society other aspects seem to be important additionally. Until now, these aspects are not very well defined and it would need further research to design them towards decisive indicators that would also guarantee for comparability. In the following some basic thoughts towards these are outlined.

11.3.1 Ideal BAT Conditions vs. Real Production Conditions

A shortcoming of the assessment scheme is that it generically looks at BAT and thus relies on generic information sources. Operations that do not produce according to BAT may have worse ratings in some of the unit processes if analyzed individually. BAT is the best attainable quality level we can achieve to-date and if BAT does not fulfil sustainability requirements then no operation does and a generic BAT low rating is therefore all the more a reason for concern and should be a motivating factor to change this instance. However, the matrix should also work for assessing real-life production chains on an operative level, in this way capturing the status-quo of real companies within real production chains and benchmarking them against the BAT.

11.3.2 Recycling Potential of Materials

The matrix only captures the general recyclability potential of a material partially. However, this potential is an important indicator for the circularity potential of a material and should be considered when assessing whether or not a material as such should be in use or abandoned. Every material has different properties in terms of recycling but there are three very basic distinctions that should at least be made: (1) no possible recycling, (2) partial recycling and (3) high degree recycling. (1) Coal, e.g., cannot be recycled as its use (when burned) disintegrates it and it becomes unavailable. Therefore, it cannot be reintroduced into a cycle, which is to be rated negatively. (2) Materials such as and similar to talcum can only be partially reused as their use is oftentimes dissipative and it is lost to the environment, thus also not available for reintroduction. This is also a rather negative factor, however, each case has to be assessed individually, as it also depends on the form in which the raw material ends up in the environment and whether it is biocompatible. (3) Materials such as metals are generally very good to recycle with regards to their properties, here a close systematic scrutiny can show which one is better or worse as this depends on the processes installed. Of course, if a material cannot be recycled as is the case with coal the grading of this matrix does not capture this as, due to the absence of the unit process, there will be no grade at all to what should be a negative grade.

11.3.3 Interface Management – Consumption Production

The unit processes that constitute a material life cycle do not function in isolation from each other but interact as they continuously pass on the material they work on to the next unit process. Within SDG 12 it is important to establish not only production schemes that are responsible but also consumption schemes that are responsible. This does not only refer to the end consumer who is usually associated with consumption but all the procuring entities along the production cycle. They are consuming what they need for their production. One crucial point for this type of procurement, from now on called consumption procurement, is the point where a raw material/raw product/semi-finished product enters a new unit process, where it is passed on to another company in a different location. Although the process of one such material production unit process in itself may be sustainable, the production process preceding it may not be. For that matter it is important to scrutinize the interface processes that this passing down or receiving materials undergoes. The end consumer usually is not aware of the origin and the long downstream journey of their product. It is likely that because of this disconnect our materialized society has not yet developed an intensive market demand for responsible sourcing and production. If every procuring entity would attach value to where it procures their raw materials from and how responsibly they were produced, supply chains would be more informed, transparent and responsible. However, this might be a more relevant topic for social or economic indicator development.

Often companies may have the highest production standards regarding their final product, they are nevertheless procuring raw materials of which they often do know the responsibility factor. If a European company adheres to all local environmental and social standards but works with a REE from China, which is classified a critical raw material not extracted in Europe and may not be environmentally and socially friendly produced, there is a responsibility gap. The EU criticality assessment, e.g., does not provide any information on this. There are various initiatives guiding downstream companies on their procurement practices (for example OECD Due Diligence Guidance 2016) but they are very complex and hard to apply for companies as well as they are not compulsory.

Companies who install sustainable practices and make this be known to the customer will have a market and policy advantage to their competitors because they trigger a new need in the consumers. If someone can buy a car made with environmentally and socially responsibly sourced raw materials why would they buy a car which is not, if we assume the price was the same. Consumers will thus more and more demand this type of responsibly produced car. Why then in the long run would a company stick to producing with raw materials of which the "responsibility origin" is unknown? Even more, they will probably have to make sure to also switch to responsible procurement as policy will most likely adapt to prescribe responsible sourcing once a big company is running the market. "Pro-active companies [to implement sustainability practices] might actually turn to politicians and ask for harsher legislation, regulation or tax, with the general purpose of increasing the pace of change and at the same time gain relative advantages for themselves." (Broman and Robèrt 2017: 21).

One very important indicator for a responsible consumption process is therefore the identification of interface management strategies, systems or maybe the absence thereof as they will trigger upstream responsibility mechanism. Unfortunately, this matrix does not provide for this sort of information. However, it can be applied to depict generic BAT material streams which can serve as general guidance for companies to define their position within a stream and navigate their responsible consumption procurement mechanisms.

11.3.4 Material Loss

Material loss is an efficiency indicator. In any material cycle material loss should be avoided, as this is unsustainable. Aluminium losses can be detected across all three phases. In Aluminium production it occurs amongst others e.g. during Bayer Process. During alkaline digestion many Alumina plants today carry out pre-silica removal after wet grinding, so-called pre-desilification to avoid the formation of dense crusts on the heating surfaces of the preheaters and autoclaves. This results in losses of Aluminium and caustic. Additionally, large proportions of Aluminium are lost in the red mud that is landfilled, which on average still contain 12 % - 30 % Al-oxide. An additional loss occurs during electrolysis where Tabereaux and Peterson note that "[t]he Aluminium production per day for one Aluminium electrolysis cell operating at 350 kA and 95 % current efficiency is 2678 kg/day, which represents a 5 %, or 121 kg/day, loss in Aluminium per day" (Tabereaux and Peterson 2014). Usually this loss occurs in the form of dross and oxidized Aluminium. During the consumer phase loss occurs because not all Aluminium is returned to collection systems. Furthermore, during recycling Al loss occurs due to sorting and storage issues, dross and oxidized Aluminium or lost Aluminium in salt slags. Also, the ignoble character of Al results in the fact that it is close to impossible in phase 3 production to extract different alloy elements out of the alloy composition. Thus, the recycled material can only be reused in the form of cast Al which, in comparison to wrought Al, has significant material quality deficiencies. The Al cannot be rolled anymore as it becomes more brittle. However, an optimal microstructure of Al is required for many applications, especially e.g. for security related parts in the automotive industry that need to be supplied with zero-error-guarantee (Rosefort et al. 2017: 2). The goal should be more wrought Al. How can the production system be influenced to achieve this? Material loss also occurs through e.g. oxidation and dust losses in processing, use and recycling etc. The matrix does not detect this indicator by nature of its design. Which losses can be avoided and which ones cannot due to process inherent dynamics or material properties should in any case also be an indicator that is relevant for an environmental material assessment.

11.4 Assessment mechanism

Another shortcoming is that there is no obligation mechanism to apply the assessment in depth. The question of sustainability is not a first order supply chain problem that only considers the main product which is the output of any given production process. It goes much more into depth. It is also a question of second order supply chain and all products and services that flow into the production of the main product/material. As a result, it is possible to apply this scheme superficially by strictly only considering the production cycle of the primary material, product or service as was done here. It can, however, also be applied thoroughly, considering the second level order of materials, products and services that go into the production of the main product (Figure 48). This assessment for example has not considered the environmental impact of transport associated with Aluminium production, nor has it considered all production system units that are necessary for production. Energy is also not considered holistically. At this second level, however, the analysis becomes dispersed and complex as it may touch upon numerous other supply cycles or chains. The solution may be to see the supply levels as separate entities and assess them as well.

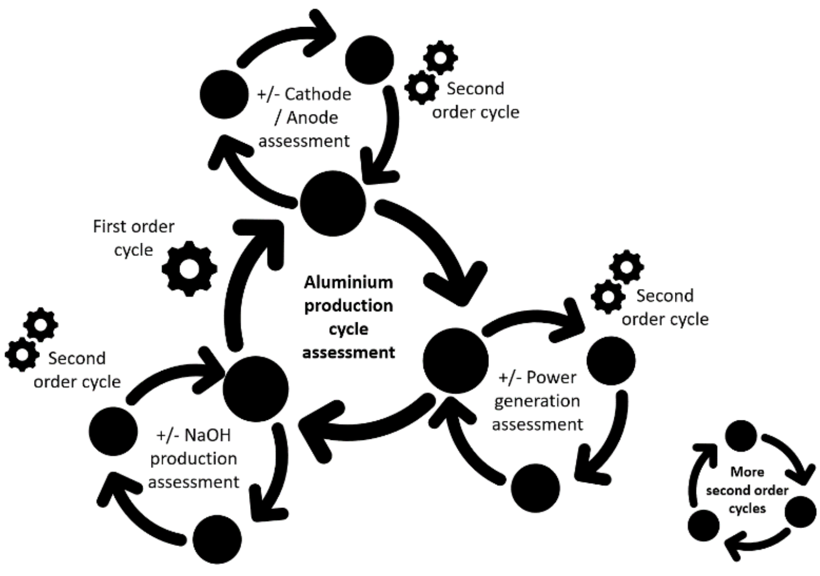


Figure 48 - Second order production processes

The analysis on this first level order needs to be very thorough and extensive to be of quality and for the grade given to mean something. The material production system of every single material is very extensive and so will the information applied for grading have to be. Therefore, if all materials should undergo such a scrutiny to obtain a material passport this would be quite an endeavor. Thousands of working hours would have to be dedicated to this, something one person could never achieve.

11.5 Conclusion and Outlook

This thesis aimed to systematically identify opportunities for targeted environmental impact decoupling within the responsibility proposition of SDG 12 in relation to material flow systems which are the basis of societal economic activity, growth and hence environmental impacts. In order to fulfil this proposition a responsibility assessment scheme was created that focused on the system boundaries *environment* and *production systems of materials*, within which it identified individual unit processes and environmental indicators. The assessment scheme designed was tested in a case study for its functionality. For the case study the example material *Aluminium* was chosen that was calibrated with the environmental indicators, for which the *Planetary Boundaries* were chosen. The case study showed that the assessment mechanism designed indeed allowed for the systematic identification of decoupling space within a material flow and can thus be considered a functional assessment scheme that can be transferred to other material flows, as well as other dimensions such as the social or economic, as well as the consumption dimension.

The main reason for taking this approach was that through scrutiny of the societal context it became clear that the current situation of projected continued population and economic growth until the end of this century will go hand in hand with extensive material consumption. As a result, extensive impacts are expected and although SDG 12 is a noble goal that calls for impact and resource decoupling, it lacks basic premises that allow for the identification of this specific decoupling space. The indicators thus far provided do not show where to decouple but only the results of decoupling. Therefore, a methodology to do so was urgently needed. Through scrutiny of general and specific sustainability models it became clear which dimensions are important to focus on and that the environment is of uppermost priority when trying to decouple for the uppermost goal of SDG 12, namely human-well-being. The assessment mechanism that was developed and systematically analyzed every unit process of a material flow against all planetary boundaries seems to be a solid approach that allows for the identification of decoupling space which is crucial for systemic strategic development of our future material flow systems. Although it became clear that the identified decoupling space is not complete and leaves room for negotiation, it also became clear that the framework is solid basic structure from where it is possible to start a material flow assessment when looking for systematic opportunities of decoupling. Its advantage is the systematic nature that provides a systemic overall material profile, calling all stakeholders involved in the production flow into their responsibility proposition. Although it is not complete, as was shown in the evaluation, it represents as such a new insight with regards to sustainability assessments and evaluations.

The methodology applied to develop the assessment scheme proved to be successful although it showed that the original approach that tried to include all three dimensions of sustainability as well as both SDG 12 dimensions was too broad and the system boundaries needed to be limited with environmental questions regarding production processes. The results clearly showed that the scheme successfully works within these dimensions but also raise the question whether this exact assessment works in the other dimensions.

Based on the learnings of this assessment future work should definitely focus on two different strings of action. On the one hand it is important to refine the facts at hand within the dimensions already worked with. The environmental indicators should be extended to material flow relevant aspects in a way that they are robust and comparable which should be backed with solid data regarding for example calculation of material loss along the cycle, environmental sink times, CO_2 balance per material etc. The system should also be digitalized in the form of a data base which will allow comprehensive collection and accessibility of facts for every material cycle much more efficiently. Through the implementation of AI and algorithms the system may be automatized and grading thus much easier. The data base should be an open source format and allow the scientific community to contribute their knowledge into the data base as well as allow them to access the information, just according to the SDG 12 premise of responsibility. Grading in this way should have with a peer review mechanism to be developed. On the other hand, it is important to extend research towards the other dimensions that were left out in this work in order to test the functionality of the assessment mechanism as a first step.

If such a database with a comprehensive set of material flow passports according to the assessment scheme developed in this thesis was actually compiled in the future, it could be a useful tool for policy and decision makers to identify decoupling space of materials as it is an easy to read system. Existing systems have shown that no such thing that focuses on single materials in their life span exists. It would thus enable interest groups, companies and society as such to gain an easy overview of the responsibility potential of the materials we use. At the end of the day as one planetary community, we should focus on using materials which have little or positive impact to ensure our positive societal development and well-being for all, in all three sustainability dimensions. This approach can help achieve this!

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