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Sustainable Resource Management
– Challenges regarding the powertrain of electric vehicles

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‘*The river Jordan is the great source of blessing for the Holy Land. (...)*
This river of blessing flows into the lake of Galilee,
and anyone who has ever visited there (...),
will remember the banks of that lake as paradise.
Then the Jordan flows out of that lake and on,
and eventually empties into the Dead Sea.
But this body of water is absolutely dead. (...)
Its shores are parched desert.
The difference between those to bodies of water is that
the Jordan flows into the lake of Galilee and then out again:
The blessing flows in and the blessing flows out.
In the Dead Sea, it only flows in and stays there.’

David Steindl-Rast
Sharon Lebell
>Music of Silence<

Abstract

Electric vehicles are considered to be a promising alternative to conventional combustion engine based vehicles in the transition to a more sustainable individual mobility. Their broad implementation is expected to substantially contribute to a necessary reduction of greenhouse gas emissions (GHG) from road transport, which are threatening Earth's intake capacity and accelerating anthropogenic climate change.

However, the associated shift in resource requirements towards so-called special, respectively technology metals has been given reason to suspect that trade-offs could threaten the desired merits of e-mobility with regard to sustainability. Several recent studies have discussed the availability of metals for high voltage traction batteries – the heart of the electric powertrain, and major driver for an increased special metals demand. Available quantities though are only one aspect to think of when assessing sustainability issues with regard to resource requirements and uses. This study is aimed to obtain a more comprehensive understanding of challenges that the broad implementation of e-mobility could place on the sustainable management of special metals for high voltage traction batteries.

Accordingly, general claims, targets and challenges of a sustainable resource, respectively metals management are analysed, followed by a technological review on battery technologies to determine the state-of-the-art.

Latter reveals that Lithium-Ion technology is most promising in the short- and medium term. Material development within Lithium-Ion technology is currently still highly dynamic. Among the specific positive electrode chemistries that currently show the applicable performances are lithium-iron-phosphate ($LiFePO_4$, LFP), lithium-nickel-cobalt manganese-oxide ($LiNiCoMnO_2$, NMC) and the spinel prototype lithium-manganese-oxide ($LiMnO_4$, LMO), each paired with a graphite anode (negative electrode) . Based on these three battery chemistries and two scenarios for e-mobility development, a dynamic Material Flow Analysis (MFA) is conducted to gain insights on expected lithium and cobalt flows, as well as required quantities and recycling potentials between 2014 to 2050.

In the course of the research it becomes clear that a sustainable use of technology metals in general, suffers from a great number of challenges at different stages of the life cycle. Despite the fact that their geological availability has to be considered as finite, their life cycles suffer from inefficiencies that cause significant (dissipative) losses. In the case of lithium and cobalt, recycling rates, for example, are still low (cobalt), respectively non-existing (lithium). While there is a tendency to substitute cobalt use in high-voltage

traction batteries, lithium substitution is unlikely for the time horizon considered. Hence, especially in the case of lithium, these findings appear alarming considering that results from the MFA indicate that e-mobility will put considerable pressure on the future demand of both metals. Even in the case that recycling potentials could be exhausted, the results signal that the major share of required quantities would have to be covered by primary production, implying the necessity for significantly higher flow rates into society. Future production capacity potentials, however, are highly uncertain and additionally expected to be afflicted with increasing environmental impacts and social disruptions. Besides, the projected demand trajectories indicate that today's reserves, particularly in the case of lithium, would be exhausted within a time horizon that cannot be considered as sustainable. Even though there are still greater resource bases for both, lithium and cobalt, it is highly questionable if and when these can be turned into recoverable reserves. Under sustainability aspects, at least in some cases, it is even questionable if they *should* be turned into recoverable reserves. In light of these findings, strategies will be required to enhance the efficient use of lithium and cobalt, while at the same time avoiding, respectively minimizing, environmental, social and economic burdens. Likewise, alternatives must be seeked, not only in quantitative terms, but also in qualitative terms with regard to the core driver: the demand for non-restrictive mobility.

This will require further, more comprehensive, assessments in the future.

Assessments, as for example MFAs, are an increasingly important instrument for the facilitation of sustainable resource management. They are the means to identify challenges and their roots, and as such they enable to react to undesired developments and to face particular challenges. As a necessary precondition, this requires extensive, comprehensive and transparent information provision. However, adequate data availability and quality are found to be insufficient, which translates into a significant challenge for a sustainable management of resources in the future.

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List of Acronyms and Abbreviations

I-General

AEV	All-Electric Vehicle
ARA	Altstoff Recycling Austria (company)
BEV	Battery Electric Vehicle
BMU	Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety
BMVBS	Federal Ministry of Transport, Building and Urban Affairs
BRGM	Bureau de Recherches Géologiques et Minières (French geological survey)
cf.	confer (lat.); compare (synonym)
CDI	Cobalt Development Institute
CO_2	carbon dioxide
CRM	Critical Raw Materials
e-mobility	electromobility
e.g.	exempli gratia (lat.); for example (synonym)
EM	electric motor
EoL	end-of-life
EOL-RR	end-of-life recycling rate (as closed loop recycling quota)
ESD	energy storage device
EV	electric vehicle
FCEV	Full Cell Electric Vehicle
FHEV	Full Hybrid Electric Vehicle
Fraunhofer ISI	Fraunhofer Institut für System- und Innovationsforschung
GHG	greenhouse gas
HEV	Hybrid Electric Vehicle
i.e.	id est (lat.); that is (synonym)
ICE	internal combustion engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IRP	(United Nations) International Resource Panel
IWR	Institut der Regenerativen Energiewirtschaft
LCA	Life Cycle Assessment (method)
LCE	lithium carbonate equivalent
Li-air	lithium-air battery
Li-ion	lithium-ion battery
Li-poly	lithium-polymer battery
Li/S	lithium-sulphur battery
LMP/LM-poly	lithium metal polymer battery
LTO	lithium titanate oxide
MFA	Material Flow Analysis (method)
NiMH	nickel-metal-hydride battery
NIMS	National Institute for Materials Science
NPE	National Platform for Electromobility

NRC	U.S. National Research Council
OICA	International Organization of Motor Vehicle Manufacturers
OPTUM	Optimization of the environmental relief potentials of electric vehicles (Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen)
OSR	old scrap recycling rate
PbA	lead-acid battery
PHEV	Plug-in Hybrid Electric Vehicle
R&D	research and development
RC	recycling quota (recycling process efficiency)
REE	Rare Earth Element(s)
REEV	Range Extender Electric Vehicle
SEI	solid-electrolyte interphase
SMM	sustainable metals managament
SRM	sustainable resource managament
STAN	SubsTance flow ANalysis (Software)
UN	United Nations
UNEP	United Nations Environmental Programme
USA	United States of America
USGS	U.S. Geological Survey
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
ZEBRA	sodium-nickel-chloride battery (Zero Emission Battery Research Activities)

II-Chemical and organic compounds

DEC	dimethyl carbonate
DMC	diethyl carbonate
EC	ethylene carbonate
$Li(Ni_xCo_yA_z)O_2$ *also* NCA system	lithium nickel cobalt aluminium oxide
$Li(Ni_xCo_yMn_z)O_2$ *also* NMC system	lithium nickel manganese cobalt oxide
Li_2CO_3	lithium carbonate
Li_2O	lithium oxide
$LiCoO_2$	lithium cobalt oxide
$LiFePO_4$ also LFP	lithium iron phosphate
$LiMnO_2$	lithium manganese oxide
$LiMnO_4$ also LMO	lithium manganese oxide (spinel type)
$LiNiO_2$	lithium nickel oxide
LiOH	lithium hydroxide
LiPF6	lithium hexafluorophosphate
Zn-air	Zinc-air

III-Measures

a	Annum (lat.); year (synonym)
°C	degree celsius
C	theoretical specific capacity (mAh/g)
g	gram
kg	kilogram
km	kilometre
km^2	cubic kilometre
kWh	kilo watt hour
l	liter
mAh	mili-Ampere hour
Mt	million tons
ppm	parts per million
ppt	parts per trillion
t	ton
U	theoretical voltage (V)
V	Volt
W	Watt
Wh	Watt hour

IV- Elements

Ag	silver
Au	gold
Co	cobalt
Fe	iron
Ga	gallium
Ge	germanium
Ir	iridium
Li	lithium
Mn	manganese
Ni	nickel
Os	osmium
Pd	palladium
Pt	platinum
Rh	rhodium
Ru	ruthenium
Zn	zinc

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Appendices

1 Introduction

1.1 Problem setting

Sustainability and sustainable development are terms that are increasingly accompanying society, politics and science since the late 20th century. (cf. WCED, 1987) They have grown into more and more complex concepts over the time, touching somehow – directly or indirectly – almost every aspect in our lives.

One of the key concerns within the on-going debate and effort towards sustainability and sustainable development, are the limitations set by the Earth's carrying capacity in its function as source for natural resources and as sink for residues from human activity. (cf. Moriguchi, 2010) Rapid industrialisation and urbanisation over the recent decades and the fact that "(…) *'development' and 'prosperity' have become synonymous with increased consumption*" (UNEP, 2010, p.1) put enormous pressure on Earth's carrying capacity in both functions.

In a synopsis on their work, the *United Nations International Resource Panel* (IRP, 2012, p.7) emphasizes the severity of the situation: "*Current patterns of resource use and emissions are out of step with what the planet can sustain*". Not to forget that this statement has to be seen against the background of still-existing poverty and inequality – conditions that cannot be ignored. However, not only developing economies will constantly consume and produce more in the future – even wealthy economies are still following growth patterns that are, largely owed to the current 'growth' definition, closely associated with growing production and consumption. For the Earth's carrying capacity this translates into degrading ecosystems, depleting resource stocks, and climate change. (cf. IRP, 2012; Brunner & Rechberger, 2004) We are abusing and overstressing our own livelihood, ultimately damaging the planet and all its' creatures and ecosystems – be it reparable or irrevocable –, and thus it will become our own fate.

There is an urgent need for change and restructuring towards (more) sustainable practices at all levels: a sustainable use of resources and the reduction of emissions are essential for a sustainable future and 'prosperity'. In such complex matters and systems, of course, it is almost impossible to put the same effort on all ends. Priorities should be set where the impacts of human activity imply the highest constraints to sustainability. In other words, the attention should be focused on those activities that have the highest impacts, including environmental aspects, as well as social and economic dislocation and conflicts into the considerations. These impacts do increasingly apply to the search for, the extraction, and the use of non-renewable resources. (cf. Bringezu & Bleischwitz, 2009; Irrek & Kristoff, 2008)

At the same time, the IRP (2012) and the *Intergovernmental Panel on Climate Change* (IPCC) (Bernstein, et al., 2007) have identified the transport sector as one of the largest contributors to global warming, which can likewise have serious consequences for the environment, for societies and economies.

The warming of the climate system is primarily driven by long-lived greenhouse gas (GHG) emissions, with carbon dioxide (CO_2) emissions being the most important fraction accounting for 77% (in 2004) of anthropogenic GHG emissions. More than half (58,4%) of total GHG emissions between 1970 and 2004 came from energy supply, industry and transport (Bernstein, et al., 2007, p.36). Thereby, emissions from the transport sector are the fastest growing share that is particularly driven by road transport. CO_2 emissions related to road transport are likely to increase by a factor of almost 1.5 until 2030 – based on 2007 levels – mainly due to increased mobility and vehicle ownership in developing economies. (cf. Mondal, et al., 2011)

Not least in light of these developments, the concept of electro mobility (e-mobility) is gaining importance and has become more dynamic in recent years, particularly in developed economies. The electrification of the powertrain is considered to be a fundamental step towards a more sustainable, climate friendly mobility. Besides a significant reduction of mobility-related CO_2 emissions, e-mobility is also expected to minimize current dependency on oil, while maximizing energy conversion efficiency. From a systems perspective it is expected to offer promising options for sustainable systems integration related to and beyond mobility, e.g. by offering, respectively providing alternative energy storage devices (ESDs) for fluctuating renewable energies. (cf. Deutsche Bundesregierung, 2009; Thielmann, et al., 2010; NPE, 2012; Buchert, et al., 2009)

In the current dynamics of the topic, economic and social considerations are becoming major drivers for ambitious targets that have been announced by numerous governments worldwide: if all of those targets were met, there would already be up to 1.5 Million electric vehicle (EV[1]) registrations in 2015 and up to 7 Million registrations in 2020 (Thielmann, et al., 2012-B, p.5). In the mid- to long-term, the value chain of e-mobility (as system/ concept) and particularly of EV technologies bares promising possibilities for profit generation and employment. (cf. NPE, 2012; Thielmann, et al., 2012b)

However, potential trade-offs and unintended consequences have to be considered carefully. Numerous researchers (cf. for example Peters, et al., 2013; Konietzko & Gernuks, 2011; Angerer et al., 2009a,b; Buchert, et al., 2009) have alluded to the substantial consequences that the development of e-mobility will have for resource requirements, in particular non-renewable resources as metals.

Hence, a relief of the sink function of the Earth's system services through the implementation of e-mobility could possibly be debilitaed or even outweighed by simply shifting the 'overstress' to the source function or vice versa – a *dilemma*, which is moreover shared by numerous supposedly clean/ sustainable technologies or components of such. (cf. for example Moriguchi, 2010; Buchert, et al., 2009) So-called special, respectively technology metals are pivotal for high- and green technology innovation and diffusion, which is increasingly putting pressure on their demand recently. (cf. IRP, 2012, Angerer, et al., 2009a)

Unfortunately these metals typically suffer structural, technical and economical scarcities, which often grants them the attribute 'critical'. (Hagelüken & Meskers, 2010) The fact that the *criticality* of raw materials, and particularly that of metals, has recently been addressed in numerous studies on national and international level (cf. European Commission, 2008, 2014; Eatherley & Morley, 2008; BRGM, 2008; NIMS, 2008; NRC, 2007; Buchert, et al., 2009) only emphasizes the timeliness and exigency of the issue.

Several sustainability concerns related to the metal value chain – especially mining activities –, do add up to the *dilemma* of trade-offs. (cf. Buchert, et al., 2009)

Thus an important question, not only for e-mobility but also for many other clean technologies, is how to deal with limitations and/ or unintended consequences, posed by interacting areas. (cf. Graedel & van der Voet, 2010) The first necessary step towards valuable answers is a preferably holistic assessment of linkages and

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[1] Here only referring to Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV).

their potential implications. Only with a full, complete and impartial picture, the strategic choices should and can be made in the attempt to lead the world to a sustainable century. (cf. IRP, 2012)

Assessing the sustainability of resource requirements and uses – in this case those of metals – for the heart of the mobility transformation – the electric powertrain – can contribute to fill some of the gaps that are still missing for such a complete picture of e-mobility and its system-implications in the context of sustainability. As McLean, et al. (2010, p.199) state: An "*improved understanding of the global challenges and sustainability implications surrounding mineral resources is critical to (.)* [their] *management (...)* [as well as for] *guidance of social and technical innovation and related public policy*; especially when these resources are intended to be used for technological solutions whose existance is actually based on sustainability considerations.

1.2 State of the art, limitations and objectives

Shifts in resource requirements and uses, especially with view on valuable technology metals, that are accompanying the electrification of powertrains have caught researcher's attention in a number of prior works. Thereby, it is generally differentiated between major 'components' of the electric powertrain: the electric motor (EM), auxiliary power electronics and cables, and the power source. (cf. Buchert, et al., 2011; Peters, et al., 2013)

EMs, which convert electrical energy, provided by a source, into mechanical energy do actually have a quite long history of more than two centuries, since they have traditionally been used e.g. for engines and trains. Their development and production have already reached high levels why resource uses are broadly known and may only change in terms of required quantities. (cf. Peters, et al., 2013) Sifts in the use of resources and required quantities with regard to the EM have been discussed for example by Angerer, et al. (2009a) in *Resources for future technologies* (Original: *Rohstoffe für Zukunftstechnologien*) and within the OPTUM (Optimization of the environemntal relief potentials of electric vehicles) research project funded by the BMU (cf. Buchert M. , et al., 2011). In this study, EMs and auxiliary power electronics and cables will not be further addressed.

In contrast to latter components, research and development in the field of power sources for e-mobility is relatively recent and thus remains highly dynamic, which in terms of resource requirements and uses entails high uncertainties. (cf. for example Wagner, et al., 2013; Peters, et al., 2013) It has however become clear already that the energy source, especially battery technology, will significantly depend on the earlier mentioned technology metals. (cf. for example Angerer, et al., 2009a, b; Konietzko & Gernuks, 2011; Kesler, et al., 2012; Peters, et al., 2013; Vikström, et al., 2013)

Energy sources for the electric powertrain are generally based on electrochemical processes. There are two major technology path – with comparable electrochemical processes – which are under consideration for e-mobility: batteries on one side and fuel cells on the other. Despite their electrochemical similarities, they are considered as independent – in part competing but most of all complementary – technology paths, which is based on one major difference: while batteries provide electrical energy that has been stored priorly, fuel cells directly produce electricity from alternative fuels such as hydrogen or methane. (cf. Peters, et al., 2013; Thielmann, et al., 2010) Accordingly, with regard to the system and resource requirements for batteries and fuel cell technologies, there exist important differences. In fact, hydrogen production and the necessary supply infrastructure is still one of the major obstacles for the establishment of fuel cell technology in the field of e-mobility. A large-sclae implementation of fuel cells is thus not expected in the short- and medium term. (Thielmann, et al., 2010, p.18) In contrast, battery technology is much more promising in the short- and medium-term. High-voltage traction batteries are considered to be the most prominent and established energy source in the field of e-mobility (cf. Winter & Brodd, 2004; Huggins, 2009; Pollet, et al., 2012; Tie & Tan, 2013; Peters, et al., 2013; Thielmann, et al., 2010; Hawkins, et al., 2012)

One of the advantages of batteries is, for example, that the initially missing charging-infrastructure can be bridged by the existing infrastructure at home or workplaces. (Thielmann, et al., 2012a) Patent applications for battery technologies have been continously rising between 1994 and 2008, and even accelerated their upward trend since 2009, while patents with regard to fuel cell technologies for mobile applications have rather been regressive over the past five years. (cf. Peters, et al., 2013)

Hence, based on the still relatively limited importance of fuel cells, its rather technological independence from battery technology, and not least with view on the limited scope of this study, fuel cell technology will not be further analysed and discussed. Consequently the focus of this research will lie on the highly dynamic and promising field of battery technology.

In fact, one of the principal objectives of battery technology R&D is material development. This in turn is based on two major drivers: on the technical side, the choice of material has a significant impact on the overall performance of the EV, including range, acceleration speed, safety performance and aspects of 'conveniance' and consumer acceptance. On the economic side, the battery makes up for a significant share of the added value of an EV, accounting for 30 to 40%. This high value share in turn is not least owed to the high dependance on valuable metals. (Peters, et al., 2013, p.26, also cf. Gaines & Cuenca, 2000; Thielmann, et al., 2010; Hayner, et al., 2012; Tie & Tan, 2013) Both, technical and economic considerations do thus considerably contribute to a dynamic material development, which is a difficult status quo for a sustainable resource management.

Resource issues related to battery technologies have already been studied before by a number of researchers, however, sustainability of resource, respective metal, uses has only indirectly or marginally been of interest. Issues related to resource requirements and uses are generally reduced to resource economics, in terms of medium- and long-term (here around 50 to 100 years) resource avialability. (cf. Kesler, et al., 2012; Vikström, et al., 2013; Kushnir & Sandén, 2012; Konietzko & Gernuks, 2011). Other studies (cf. for example Hawkins, et al., 2012; Notter, et al., 2010a; Zackrisson, et al., 2010) solely focus on the comparison of specific battery chemistries under sustainability aspects, among others. Hence, with regard to what has been described as *dilemma* in chapter 1.1, the question wether future resource uses for e-mobility, respectively the high-voltage traction batteries, can be met in a sustainable way remains largely open:

Central question

Are there major challenges to satisfy the metals requirements for the electric powertrain, respectively for its main component the battery, in a sustainable way – and if yes, which are they?

Thereby, the central questions builds upon the development of the following sub-questions:

1. What are “critical factors” or claims for a sustainable resource management?
2. Which factors need to be specifically considered for a sustainable metals management?
3. Which are the expected metal requirements for the electric powertrain, respectively the battery as key component and major consumer of valuable metals?
4. Can the expected requirements be satisfied?
5. Which are the major challenges if the expected requirements are to be met in a sustainable way?

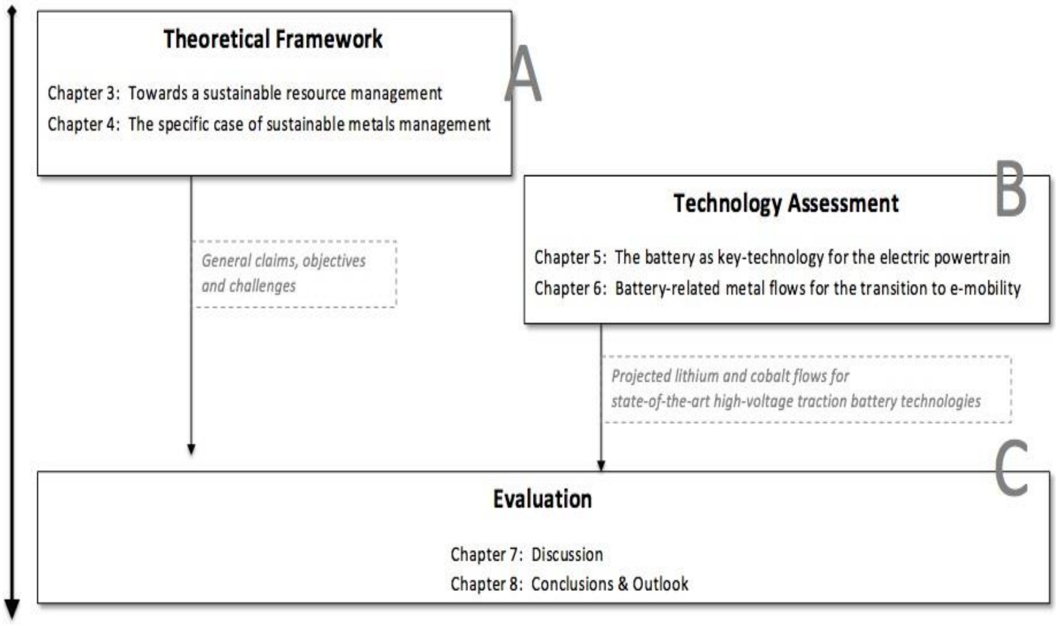
Answering these questions shall serve as necessary contribution to a better understanding, evaluation and strategic management of the sustainability of e-mobility as a holistic system, by identifying critical factors, limitations, obstacles and vulnerabilities related to batteries’ metal requirements.

2 Methodology

2.1 Research approach and paradigm

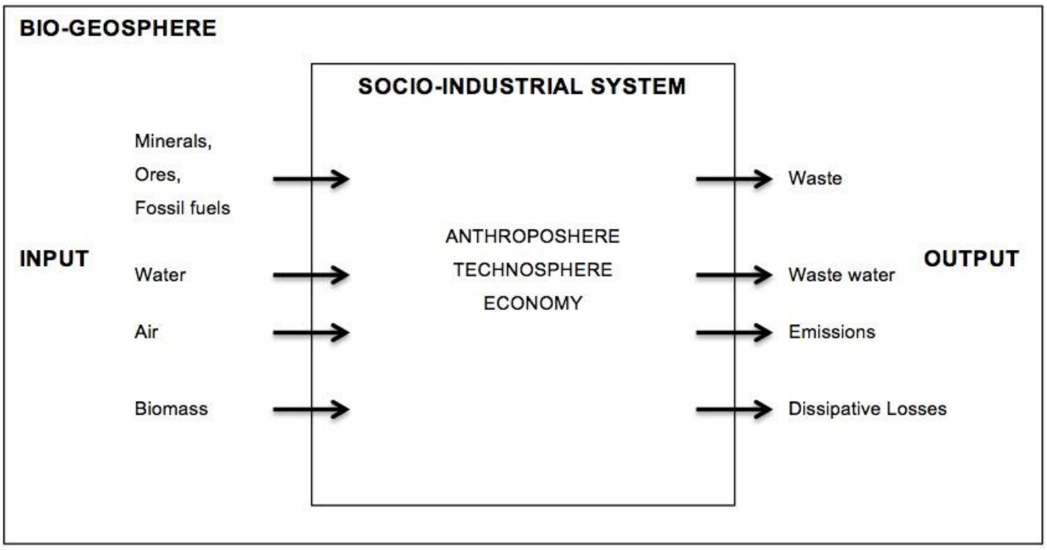
With the objective to answer the research questions, the approach can generally be divided into three blocks: a theoretical framework [A], a technology assessment [B] and an evaluation [C] (compare Figure 1). Latter does thereby constitute the link between the first two rather independent blocks. The research is generally following a theoretical-conceptual approach (qualitative, blocks A and C) with a quantitative component (block B), whereas the theoretical-conceptual parts are used to qualitatively assess/evaluate the quantitative part. Thereby, all parts are based on the broad review of technical and non-technical literature. With view on the research questions and the objective, the research approach will be based on and guided by the scheme or paradigm of *the (socio-) industrial metabolism* (seeFigure 2). This paradigm was introduced by Robert U. Ayres in the late 1980s as an analogy to the human or natural metabolism, whose throughput (flow) and balance (input equals output) perspective was adapted to the socio-industrial system in relation with the natural environment. (cf. Brunner & Rechberger, 2004)

Figure 1: Research approach



Source: own figure.

Figure 2: Simplified scheme of the socio-industrial metabolism



Source: based on Bringezu & Bleischwitz (2009, p.12)

By embedding the (socio-) industrial system within the natural system the concept provides for a useful framework to describe and analyse the dynamics of the physical turnover and circulation of resources/materials through the (socio-) industrial system and especially in its relation with the natural environment as source and sink. The concept can therefore be instrumental to gain valuable insights and knowledge on society's common and specific management of resources, as well as on interlinkages between and within the systems that are decisive for a SRM. (cf. Anderberg, 1998; Erkman, 1997; Bringezu & Bleischwitz, 2009) Because of its postulated material flow and balance perspective, today the concept has become the basis for most quantitative assessment methods in the field of resource, environmental and waste management, as for example Material Flow Analysis (MFA) and Life Cycle Assessment. (cf. Brunner & Rechberger, 2004) In the present study it will thus be applied both, as an orientation for the qualitative research, as well as in quantitative terms to conduct an MFA (cf. sub-chapter 2.2).

Its application in qualitative terms, as framework, will be particularly useful to clarify the coverage and claims of (sustainable) resource management from a metabolic perspective due to the paucity of a clear consensus concerning the reach of competence. These aspects will be examined in chapter 3 , while chapter 4 is aimed to narrow down, respectively specify, the particular challenges for the case of metals, which are deduced from the claims caved out in chapter3. The insights gained from both chapters will allow for an overview on the major general challenges that arise in the field of sustainable resource/ metals management. However, these cannot yet be assumed to apply automatically and in its totality for the case of e-mobility.

Therefore, with the 5th chapter, the conceptual part of the research is intermittet to provide space for the technological assessment. Chapter 5 itself provides for a comprehensive review on the field of battery technologies for e-mobility and examines the state of the art battery technologies which are needed as input for the quantitative assessment of metal flows in the next chapter. Hence, in chapter 6 an MFA (cf. sub-chapter 2.2) is applied to the identified state-of-the-art technologies, assessing relevant metal flows through the industrial metabolism. In the following chapter (7), the challenges identified on a conceptual level in chapters 3 and 4 will be brought into the context of the findings from chapters 5 and 6. Additionally, own findings will be checked against, respectively complemented by and/or contrasted with findings from earlier studies. Ultimately, final conclusions will be drawn in chapter 8.

2.2 Material Flow Analysis

2.2.1 Method

Material Flow Analysis (MFA) is a feasible method to describe and explore a material-based system, defined in space and time, by systematically assessing (all) its' relevant material flows and stocks, connecting sources with pathways and sinks. In other words, MFA is a method to depict and quantitatively assess the metabolism of anthropogenic and geogenic systems. Thereby, the term *metabolism* "(…) *stands for the transfer, storage, and transformation of materials within a system and* [in] *exchange* (…) *with its environment*" (Brunner & Rechberger, 2004, p.49). The quantitative assessment is primarily based on the law of conservation of matter, which means that all inputs, stocks and outputs of the defined system have to be balanced. This way, MFA aims to "(…) *deliver*(.) *a complete and consistent set of information*" (Brunner & Rechberger, 2004, p.3) on the particular system and its elements.

In its' earliest applications MFA has mainly been used for the purpose of environmental protection, analysing urban and regional material balances (metabolisms) (cf. for example Duvigneaud & Denayeyer-de Smet, 1975; Newcome, et al., 1978; Wolman, 1965), usually focusing on specific pollutant pathways and their fate in environmental compartments (cf. for example Huntzicker, et al., 1975; Ayres, et al., 1985). However, in the early 1990s, the concept 'metabolism of the anthroposphere' by Baccini et al. (1991, 2012) significantly influenced and pushed the use of MFA to solve more complex problems in the fields of resource and (formerly) waste management (cf. chapter 3). Hence, with regard to the debates concerning the integration of resource and waste management (discussed in chapter 3), MFA has become "(…) *instrumental in linking resources management to environmental and waste management*" (Brunner & Rechberger, 2004, p.16) if conducted in equal measure at both ends of the anthropogenic system. In terms of optimizing entire material cycles from raw materials to recyclates, waste products and final disposal it is therefore an attractive tool for the field of SRM, able to serve numerous design principles, as for example:

- control of pathways
- design and implementation of practices for closed material cycles
- dematerialization of the industrial output

- balancing the anthropogenic metabolism to natural carrying capacity (Ehrenfeld, 1997)

In more general terms, MFA can be used for many purposes, be it to compare scenarios as it is intended in the present study, to gain further knowledge on resource flows and pathways, as well as on final fates; or it can be used to measure performances e.g. of dematerialization efforts.

Even though MFA "*is not yet used as standard analytical tool in everyday decisions on materials management*" (Brunner & Rechberger, 2004, p.302), it does constitute the basis for almost all commonly known environmental impact assessment methods, as for example LCA and eco-balancing. According to the varying specific applications of MFA, the results are envisaged to generate a basis for managing resources, the environment, and wastes. In the first instance, MFA has the objective to provide insights into the behaviour of material-based systems and to reveal those system-components/dynamics with the most potential for improvements. Gained insights can ultimately serve to either evaluate existing systems, to optimize them against sustainability constraints or to even design new system-components or entire systems. If applied properly, it is possible to reveal the most important pathways of specific resources through the anthropogenic systems and along the entire life cycles of a material or product.

The life cycle perspective, or respectively the metabolic perspective, integrates all interfaces between anthropogenic systems and geogenic (natural) systems. By modelling resource consumption, MFA can facilitate early recognition of critical states of resource depletion, especially on the primary source side, also in relation to specific goods or services. At the same time, shifts in stocks can be traced and disclosed, which enables to identify hazardous environmental loadings and its' sources, as well as beneficial anthropogenic stocks that bare a potential for internal recycling loops. Where recycling is no option (or not yet implemented) potentials and limits of final sinks may become evident. MFA results can even serve to integrate environmental and resource concerns into the design of new materials, goods, or systems. (cf. Brunner & Rechberger, 2004)

However, MFA is in the first instance an assessment and analytical tool. Results must therefore be interpreted and evaluated. This process is generally quite prone to subjectivity. As Brunner and Rechberger (2004, S. 134) assert: "*Assessment is* *a matter of values, and values can change over time and may vary among societies and cultures*." There is the possibility to increase objectivity and comparability to the evaluation process, by applying indicators. The type of indicator used, is strongly dependant on the specific problem to be investigated. Nevertheless, even indicators fail to relieve decision making from all types of subjectivity. LCA method for example, implies an impact assessment based on its material inventory (MFA). However, it is the impact assessment that rises most objections within the research community, whereat questionable reliability stands out. Ayres, R.U. (1995) criticizes the almost unidirectional emphasis on the impact assessment, whilst neglecting the analysis and control of basis data. This problem is aggravated by the fact that LCA strives to assess as much data as possible. In turn, the main purpose of an MFA is to simplify reality without compromising the reliability. Therefore, even without an indicator-based impact assessment, MFA results can provide a valuable starting point for the analysis and evaluation of a system (cf. Brunner & Rechberger, 2004).

2.2.2 Methodology

As a method, MFA is also designated to allow for a common language, by establishing "*well-defined, uniform terms*" (Brunner & Rechberger, 2004, p.28) to describe a system and its components. Terminology and methodology of the present study will be based on definitions developed and defined by Baccini and Brunner (1991), which have been adopted and methodologically integrated by Brunner and Rechberger (2004) in the first practical handbook on MFA in 2004. Since MFA serves to study complex systems, it must settle the claim for a most possible transparency in order to be accepted and to be reliable. A common language with exact definitions of terms and procedures is therefore an *imparitive*. At the same time it allows for reproducibility and a simplified communication. To perform an MFA, several steps should be followed, whereupon a strictly consecutive procedure is not binding – a rather iterative optimization is often necessary and even recommended. Selections and provisions that are made during the entire procedure should be checked upon continuously, and adjusted if necessary. (cf. Brunner & Rechberger, 2004) Nevertheless, after having defined the objectives and goals of the analysis, the first step to any MFA should be the definition of *system boundaries* that limit the object of study in time and space. In graphical terms, the spatial system boundary is reflected by a discontinued frame line that encloses all other elements (cf. Annex A-2). As mentioned previously, the general objective of an MFA is to reduce complexity and simplify reality, which is why the system under research should be as small but consistent as possible. Ultimately though, the definition of boundaries is strongly dependant on the previously defined objectives and goals, as well as on the availability of data. This is why "[o]*ften, the only possibility is* (…) *to define* [spatial] *system boundaries as administrative regions, such as nations*, (…) *because information is systematically collected on these levels*" (Brunner & Rechberger, 2004, p.56). Similar considerations apply to the temporal system boundary, which is synonymous with the time horizon of investigation. To avoid short-term system unsteadiness to affect results, time spans of one year are common. For dynamic modelling, calculations are continuously adjusted for the defined time horizon.

When the system boundaries are set, the relevant elements of the system are selected. There are three main types of elements: flows, processes and stocks.

Before continuing with their definitions though, it is useful to first clarify the terms for those objects whose paths they are supposed to model: *materials, substances* and *goods*.

Materials and substances are often used synonymously. However, in MFA terminology material is an umbrella term for substances and goods, while the term *substance* in MFA rests on the definition set by chemical science (cf. Brunner & Rechberger, 2004):

> hence, '[a] *substance is any (chemical) element or compound composed of uniform units. All substances are characterized by a unique and identical constitution and are thus homogenous*'
> (Sax & Lewis, 1987 in: Brunner & Rechberger, 2004, p.35).

In turn, "[g]*oods are substances or mixtures of substances that have* [either positive or negative] *economic values assigned by markets*" (Brunner & Rechberger, 2004, p.3), which also includes waste. Compare Annex A-2, which provides for an overview of MFA elements and terminology.

Now, getting back to the selection of relevant elements to model the pathways of materials through the chosen system, *processes* are used to reflect a "(…) *transformation, transport, or storage of materials*" (Brunner & Rechberger, 2004, p.4). While the first two types of processes are symbolized by rectangular boxes (cf. Annex A-2), *stocks* are symbolized by a smaller box within the process-box in which material reservoirs occur. Stocks are generally dynamic, being either accumulated or depleted over certain time periods, which justifies their denomination as process (within a process). Where material residence time surpasses one thousand years, stocks are considered as *final sinks*. Stocks do constitute the only exception to the so-called black box approach of processes in MFA by allowing a certain insight to a process of transformation or transport. Besides this exemption, processes do not disclose their insides (therefore considered as ’black boxes’), since only their inputs and outputs are of interest. (cf. Brunner & Rechberger, 2004)

Processes are connected by *flows* or *fluxes* of materials, both symbolized by arrows (compare Annex A-2). A flow describes the mass of a certain material that flows per time – mass flow rate – with a physical unit of e.g. tons per year (t/a). In turn, a flux includes a further dimension, giving the mass flow rate per specific *cross section*, be it a specific region, a household or a company, among others. Flows or fluxes that cross the spatial system boundary are either called import flows/fluxes, when entering the system, or output flows/fluxes when exiting the system. In summary, while processes represent the physical components of a system, flows and fluxes establish their (inter)relations. The smallest possible system consists of one process, one import flow/flux, and one export flow/flux (cf. Brunner & Rechberger, 2004). An upper limit for the number of processes within one system does not technically exist; system containing more than 15 processes are considered as rather complex. (Brunner & Rechberger, 2004). As soon as the (preliminary) system with its’ boundaries and elements is compiled, data acquisition follows. Usually it serves to begin with rather rough estimations and provisional data, followed by continuous refinements and improvements. Besides, no matter the specific objective and target of an MFA, a mass balance of goods should constitute the base in order to obtain full information when/ if proceeded on substance level.

Establishing mass balances on both levels does also reduce error-proneness. Another advantage of establishing balances on both levels, even when the focus of the study lies on the substance level, is related to the final utility of the results; it is more likely to directly “intervene” in flows of goods, e.g. by legislation, than in flows of substances. (cf. Brunner & Rechberger, 2004)

2.2.1 Software tool

The software tool that is used to describe and assess the material mass flows for current state-of-the-art battery technologies for the electric powertrain of vehicles has been particularly developed to perform MFA and to overcome some deficiencies that had been detected related to the application of MFA. In 2004, at the time the software tool STAN – short for subSTance flow Analysis – was developed, there was usually more than one software product used to perform MFA. While flow models where often still designed manually with no software at all, data management and calculations where carried out via spreadsheet software like Microsoft EXCEL, whereas the results were visualized by graphical software. (cf. Cencic & Rechberger, 2008) As Cencic & Rechberger (2008, p.3), two of the developers of STAN, point out "*this procedure* (…) *turned out to be laborious and error prone*".

The development of STAN was lead by the *Institute for Water Quality, Resources and Waste Management* at the Vienna University of Technology in cooperation with INKA software. It was sponsored by *Altstoff Recycling Austria* (ARA), *voestalpine*, the *Lebensministerium* and the *Federal States of Austria*. The first version of the tool (STAN 1.0) was released in 2006. Since then it has been continuously upgraded and is currently operating in its third version (STAN 2.5), which was released in 2012 along with the official website (www.stan2web.net) where the tool is offered as free download. (cf. Cencic & Rechberger, 2008; IWR, 2012) STAN supports MFA by integrating all necessary components to define and depict a metabolic model, the management of data, calculation and the graphical handling of results within one software tool:

> "*After building a graphical model with predefined components (flows, processes, subsystems, system boundaries and text fields), known data (mass flows, stocks, concentrations and transfer coefficients) with corresponding physical units can be either entered or imported for different layers (good, substance, energy) and time periods.*" (Cencic & Rechberger, 2008, p.3)

The possibility to model over different time periods allows for the consideration of dynamics, i.e. in resource flows and respective stocks, instead of providing a static balance-snapshot of only one point in time. This is particularly relevant when assessing material flows based on non-renewable resources, facilitating the 'monitoring' of primary resource availability on one side and the potential for secondary sourcing – via the accumulation of anthropogenic stocks – on the other side. Latter, is in fact a very useful feature with respect to the proposition of the present study.

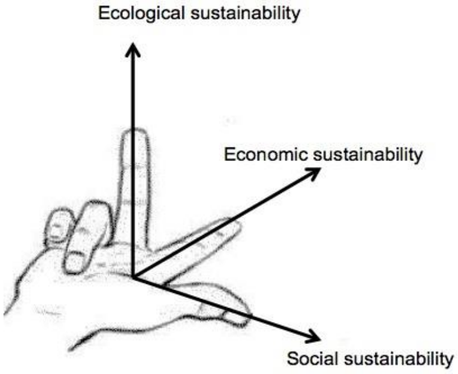
3 Towards sustainable resource management

If one wants to gain insights on a rather specific management field – as that of resources – within the context of sustainability, one first of all needs to understand the general complexity that goes along with this context. As von Gleich, et al. (2006a, p. 250) state, "*not a single issue, be it of a social, economic or ecological nature, emerge from the sustainability debate in the same form as when entered it*".

The most commonly known definition of 'sustainability', respectively 'sustainable development', was given by the *World Commission on Environment and Development* in their report *Our Common Future*, also known as the *Brundtland Report*, in 1987. They defined sustainable development as a development that "(…) *ensures* (..) [to] *meet*(.) *the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). This definition of course inherits a very high abstraction level, which can be conceived both, as positive in terms of integration potential (von Gleich, et al., 2006a, p. 249), and as rather 'negative' in terms of operationalization, complicating the tangibility of the concept. Either way, under these conditions it is more than obvious that a 'break down' into more tangible and concrete conceptions and steps is necessary. Thereby, the '*target vectors*' shall always be given by the commonly known dimensions of sustainability: the economic, social and ecological dimension (von Gleich, et al., 2006a, p. 250; see also Figure 3).

One possible first useful step towards lowering the abstraction level can be made by differentiating between two general understandings of the Brundlandt definition, as they have been described by von Gleich, et al. (2006a). According to the authors "(…) *there exist two understandings of sustainability in the public-political, as well as scientific debate on sustainability*", which lead to respectively particular 'translations' of the definition. (von Gleich, et al., 2006a, p.250) On one side there is the so-called 'defensive understanding', which conceives sustainability as a rather "*normative guiding principle*" and "*minimum condition* *for ‘future options’”* (von Gleich, et al., 2006a, p.250). Based on this understanding, sustainable development aims to protect the planet and future societies from substantial system collapses. Thus, key concerns to this understanding of sustainability are the limitations set by Earth’s carrying capacity, which do exist for all three dimensions of sustainability. (von Gleich, et al., 2006a) On the other side(cf. also Table 1), the ‘offensive understanding’ of sustainability is “*imbued with all our wishes, hopes and utopias*” (von Gleich, et al., 2006a, p. 251) of what von Gleich, et al. (2006a, p. 260) refer to as the “*good life*” at reach. This conception of sustainability is thus much more focused on present, visible and most of all tangible sustainability deficits providing for a more positive connotation, and a more widespread base of protagonists especially from civil society, i.e. larger participation and presence in public debate. (von Gleich, et al., 2006a, p. 260)

Figure 3: Target vectors (dimensions) of sustainability



Source: own figure, based on Paroc Group, 2014.

The rather long-term orientation and global perspective of the defensive understanding grants the most attention to long-term and potentially irreversible effects of today’s and future sustainability deficits, as well as those deficits that tend to impact on a global scale. It is thus much more ‘frequented’ and discussed among specialists. This is not much of a surprise: on one hand, the focus on creeping, not necessarily perceivable, deficient developments requires to a considerable degree the development, appreciation and processing of a scientific knowledge base. On the other hand, the not immediately discernible nature of the problems does constrain the motivation among society to deal with these problems. (von Gleich, et al., 2006a, p. 251, 259)

Table 1: Major differences between the two conceptions of sustainability[a]

	Defensive understanding	**Offensive understanding**
How the goal of sustainability is understood:	min. maintenance of carrying capacities	min. 'good life' (at reach)
Which problems are focused on:	Long-term, creeping, irreversible	Immediately, discernible, acute

Note: [a] as goal

Source: reflecting van Gleich et al., 2006a, p. 251-252.

However, in neither case (defensive and offensive understanding) the particular conception of the sustainability definition "(…) *does (.) describe the possibilities of a realisation of sustainable objectives but restricts itself to the desired effect*[s]" (Baitz & Wolf, 2006, p.519). Specific concepts, measures and approaches towards or in line with desired targets are ambiguous and very much dependent on the particular interest group leading the discussion. The challenges and along with them the possible perspectives and actions are complex and thus manifold and opaque. Piecemeal approaches run the risk of failing the difficulties and complexity of sustainability as a systems problem. Nonetheless further 'break-down' of the sustainability issue is important and inevitable in order to formulate feasible steps. (Baitz & Wolf, 2006; von Gleich, et al., 2006a) Hence, disaggregation is likewise of interest with regard to the necessary scientific knowledge base: details are as important as the holistic systems perspective. While latter allows to grasp the context, smaller scales are more useful when it comes to understand the underlying mechanisms (Sagar & Frosch, 1997). The critical factor lies in the reintegration of details within the systems perspective; against this background, findings from a rather small scales may appear in a different light, which again can make a decisive difference when it comes to the point of formulating and taking concrete action.

SRM can be considered as a specific perspective on the sustainability target, determined by such a further 'break-down', setting its 'own' particular focus and emphasis. Thereby, the use and availability of resources is a typical example (other examples are the climate and biodiversity) for a rather long-term problem of global scale, which is additionally related to questions of carrying capacity in a multidimensional way. These problems are particularly pressing with regard to the sustainability target forasmuch as once they become preceivable and acute it will most likely be too late for measures to counteract them. (von Gleich, et al., 2006a, p.251)

Even though SRM can be considered as a ‘broken-down’ concept with regard to the sustainability target it is still itself based on a systems perspective, as it will become clearer after taking, at this point, a look at the (recent) developments from traditional resource management towards SRM.

As mentioned in the beginning of this chapter, SRM is not just a simple extension of traditional resource management. The traditional view on resource management has rather experienced significant changes in paradigms, which have been shaped by the sustainability debate. Resource management has traditionally been limited to the early stages of a resources life (use), i.e. resource exploitation and upgrading (Brunner & Rechberger, 2004). While the use phase of a resource as part of a material or product has been mainly neglected, the ultimate life stages have been the concern of waste management. In both cases, environmental concerns related to the life cycle of the resource (material or product) have thereby been falling under the scope of environmental management. (Brunner & Rechberger, 2004)

This trinomial division of management tasks along a resources life has inherently been based on a linear perception of the economy and its respective resource throughput, also referred to as ‘river economy’ – a perception that has been key subject to revision with regard to the sustainability debate. (cf. Stahel, 2006) In order to give feasible consideration to sustainability deficits related to resource use, most experts agree on the need for a more integrated resource management approach that addresses the entire life cycle of resources including all related environmental, economic and social concerns, in their relation with the bio-geosphere, the anthroposphere and the technosphere (e.g., Allen, et al., 2009; Dijkema, et al., 2000; Brunner & Rechberger, 2004; Stahel, 2006). Such an integrated management approach would thus imply a shift from managing primary resources, resource uses and waste separately, towards managing ‘materials’, i.e. resource flows and its implications over the entire life cycle and in its relation to the different spheres (bio-geosphere, anthroposphere and technosphere) (cf. Allen, et al., 2009, p. 662). Accordingly, with view of the ‘traditional’ trinomial management approach, this shift firstly requires or respectively implies a change in paradigms with regard to the conception of ‘waste’.

By definition, the term ‘waste’ has a negative cast, related to something that society wants to dispose off, a fact that can hardly be changed. Nevertheless, waste is less an attribute than a label, which society decides to assign to a product, material or substance when the economic/ industrial system (society’s metabolism) **cannot make use** of that specific product, material or substance anymore. (Dijkema, et al., 2000) This makes waste a “*subjective concept*”, or as Dijkema, et al. (2000, p. 634) further suggest, “*a qualification of a particular substance or object, which* (…) *may change*”. The fact, that society’s metabolism is not able to make any further use of a substance at a certain point in time, does not automatically imply that there is no further potential for usage. Consequently, Dijkema, et al. (2000, p. 636) suggest a redefinition of waste as *“an emerged quality of a substance”*, or resource. While the quality label ‘waste’ will of course remain to exist, its new perception enables and, most importantly, motivates to change the label whenever possible by means of any transformation process. This way a change in paradigm turns into an important potential trigger for technological and (socio-industrial) system innovation. At the same time it paves the way for an integrated, systemic life cycle consideration of resources of any quality, which in turn is an important prerequisite for a SRM, also synonymously referred to as sustainable materials management (SMM)[2].

By adding and focusing on a perspective emanating from the concept of sustainability, the overall claim of an integrated resource or materials management becomes the establishment of a sustainable materials economy, in respect of which the *Enquete Commission Protection of Humanity and the Environment* formulated four general management rules (von Gleich, et al., 2006b, p.15, also cf. Table 2). These in turn allow the argumentation that a SRM/SMM based on these guidelines, is the means to “*implement sustainable development with regard to natural resources*” (Wellmer & Wagner, 2006, p.55).

As Gößling-Reisemann (2006, p.195) summarizes:

> The management rules “(…) *specify how the use of natural resources and the input of substances to the environment should be managed in order to*

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[2] From here on jointly addressed as SRM.

> *preserve the functionality of nature as a supplier of resources and an absorber of residuals from economic activity*”.

Table 2: Overview on the guidelines for a sustainable materials management

Guideline		**Limited by**	**Refers to**
1		Source function	Renewable resources
2	The use should not be larger than the replacement of its functions.		Non-renewable resources
3	Anthropogenic input to the environment should not exceed absorption capacity.	Sink function	Absolute input
4	Rate of anthropogenic input to the environment should be below the natural regeneration time.		Rate of input

Source: based on Enquete Kommission "Schutz des Menschen und der Umwelt" - 12. Deutscher Bundestag (1993) in: Wellmer & Wagner, 2006, p.55-56.

While the first guideline refers to the use of renewable resources, which will not be further discussed according to the context of the present study, the second guideline sets conditions for the use of non-renewable resources with respect to Earth’s source function. Accordingly and in line with the limitations set by Earth’s supply capacity, their consumption should not surpass “*the amount that can be substituted by functionally equivalent renewable resources*” (Wellmer & Wagner, 2006, p.55), neither should their consumption exceed their natural regeneration time (von Gleich, et al., 2006b). Hence, important targets or even preconditions with regard to a sustainable use of non-renewable resources are their substitution with renewable resources (here meant as “*transmaterialization*”, cf. Karlsson, 2006, p.240), and an increased resource efficiency, respectively productivity, which will be discussed further when looking in more detail at the corresponding sustainability strategies.

Different to the first two guidelines, numbers 3 and 4 are concerned with the limitations set by the sink function of Earth’s carrying capacity. They claim that the anthropogenic input to the bio-geosphere should be within the limitations of the environment “*to absorb them with minimal detrimental effects*”, while taking into account the necessary time for nature to “*react and cope with environmental damage*” (Wellmer & Wagner, 2006, p.56).

Hence, the management of material flows through the anthropogenic (socio-industrial) system, and linked to the bio-geosphere and technosphere, is one of the core approaches of a SRM. Within its conceptual framework, two sustainability strategies prevail that "*deal explicitly with materials and material flows*": "(…) *the more quantitative efficiency strategy and the more qualitative consistency strategy or 'industrial ecology' respectively*" (von Gleich, et al., 2006a, p. 261). Both strategies basically inherit their focus on materials and material flows, with one side effect as von Gleich, et al. (2006a) ascertain after intensive studies: the ecological view becomes the centre of focus with regard to the dimensions of sustainability, especially in the course of the efficiency strategy. For the sake of completeness, the third and last strategy in the group of major sustainability strategies– that of sufficiency – shall be mentioned, even though the emphasis of the present study will lie on the efficiency and consistency strategy as rather 'technological'- and 'material'-oriented strategies. In turn, the sufficiency strategy has a much more 'cultural' and 'philosophical' cast, which cannot be discussed in detail within the scope of this study. However, it is important to point out the equal status and validity of all three strategies, i.e. from a holistic systemic point of view none of them should be neglected in favour of the other/s in order to achieve sustainability. The strategies must thus be seen as complementary, particularly with regard to at times ambiguous delimitations and consequently the occurrence of intersections, respectively interdependencies.

However, for now, the focus shall be put again on the efficiency and consistency strategy within the framework of material flow management. Latter is strongly bound to the concept of the socio-industrial metabolism, which helps to illustrate boundaries and linkages, when it comes to the target of optimizing material flows. Therein, the efficiency strategy primarily corresponds to the target of an improved resource efficiency (productivity) set by the previously mentioned guidelines for sustainable resource management. In general, the strategy aims to reduce the throuput of the socio-industrial metabolism based on a maximum efficient use of resources (no wasting), while simultanously reducing "*environmentally dubious materials*". It "*rests on the theory that in everyday business life there are still untapped and/or undiscovered potential efficiencies*" (von Gleich, et al., 2006a, p.263f). Tapping such potentials will lead to an improved effort-utility ratio, a possible extention of the availability of non-renewable primary resources, and thus to an enhanced resource efficiency. In addition, economic effects, in form of cost-savings, can be achieved. Hence, the efficiency strategy can lead to classic win-win situations. (von Gleich, et al., 2006b)

Nonetheless, a potential sustainability improvement, with respect to natural resource efficiency, must be accompanied by dematerialization and the aforementioned sufficiency (lowering consumption) efforts; if not, it is most likely that positive effects are consumed by negative developments due to absolute increases in resource consumption. Dematerialization cannot only be achieved by an absolute reduction of resource inputs; first steps can be accomplished "*slowing down the net materials throughput in society*", e.g. by enhanced product lifetimes, reuse and recycling (Karlsson, 2006, p.237). However, dematerialization can only arise from a proper interplay of all three sustainability strategies. In the context of dematerialization and generally improved resource efficiency, decoupling resource consumption from economic growth is a further important task with regard to an aspired sustainable resource use. There are suggestions that

> "(…) *countries will gradually dematerialize their economies as they evolve from manufacturing to services* (…) [, which] *means that use of* (.) *resources increases early in the history of a country but levels off and decreases later as material is used and recycled more efficiently*" (Cleveland & Ruth, 1999 in: Kesler, 2010, p.116).

However, this relationship has shown inconsistencies in the past, which should once more push the endeavours. (cf. Kesler, 2010; Stahel, 2006)

Compared to the efficiency strategy, the consistency strategy is primarily concerned with the quality of the socio-industrial metabolism and its underlying material flows. Targets are the integration of the "*anthropogenic metabolism into 'nature's metabolism'*", and working their sound compatibility. This can be accomplished by reducing the interlinkages between the technosphere and the bio-geosphere, thus closing the anthropogenic system and sealing it with regard to the bio-geosphere, and/or by consciously and sustainably opening the system boundaries, e.g. by shifting to renewable energies and resources. (cf. von Gleich, et al., 2006a, p.265). Targeted reuse and recycling, which has been thought of even before production processes are initiated or designed (design for recycling, design for resource efficiency, green design) are major elements of the consistency strategy, especially with regard to the most possible closure of the

socio-industrial system by shifting from a linear economy to a loop, respectively 'lake' economy. (cf. Stahel, 2006) These elements can surely be seen under efficiency aspects as well, however, the consistency strategy takes them a step further by focusing primarily on the quality management of cycles and flows. Thereby, dissipative losses and 'consumption' in terms of a declining 'usefulness' of resources and materials constitute major challenges (for further details cf. sub-chapter 4.3). Accordingly, compared to the efficiency strategy, consistency does much more depend on fundamental innovations and restructuring, with the implication that higher risks must be taken. (cf. von Gleich, et al., 2006a)
Nevertheless, material losses in general, be it in absolute or dissipative terms, are major challenges for all three sustainability strategies.

Table 3: Impact factors for losses

Impact Factor	**Examples**
Material properties	Physical composition or degree of complexity Value
Technology	Material Properties Selectivity Efficiency/yield Processing costs Environmental impact
Societal and legislative	Awareness & 'culture' Incentives Take-back infrastructure
Lifecycle structure	Closed loop structures vs. open loop structures: Frequency in changes of ownership Product mobility (traceability) Formal vs. informal

Source: based on McLean, et al., 2010, p.209.

They are not only an indicator for missing quality of cycles, but withal they are an expression of inefficiencies with far-reaching consequences, as McLean, et al. (2010, p.211) capture it adequately: "*Total efficiency is the combination of individual inefficiencies along each step of the life cycle. The weakest link in the chain has the largest overall impact on losses*." As the quote already suggests, inefficiencies and thus losses can occur at diverse stages of the life cycle, which can be attributed to four general key parameters (as listed in Table 3) Some of the specific examples will be discussed further in connection with the (particular) challenges of a sustainable metals management; the remaining factors will not be further delved into, due to limitations with regard to relevance for and scope of the study.

4 The specific case of sustainable metals management

As it has already been pointed out in the first chapter, many (new) so-called clean or high-technological applications or components of such – as the batteries for EVs – highly depend on metals – among them some that are commonly referred to as critical elements. (cf. for example IRP, 2012, Angerer, et al., 2009a; Karlsson, 2006) Metals constitute an extensively important group of elements due to many unique features, which is probably why they also "*provide the clearest example of the challenges and opportunities that mineral resources present to society, in terms of both primary production and recycling*" (McLean, et al., 2010, p.200), especially from the perspective of sustainability. This chapter, thus, aims to explore the most important characteristics, targets and related challenges/opportunities with regard to their sustainable management.

4.1 Metals as valuable, non-renewable resources

With two thirds, the metals group is the biggest share among those chemical elements that occur naturally on earth, even though "*only very few of them – particularly precious metals – also occur in 'native' metal form*" (von Gleich, et al., 2006b, p.3). There is a broad consensus about metals forming part of the non-renewable resources group, even though, based on the law of conservation of materials, they will always continue to exist. (cf. von Gleich, 2006b; Kesler, 2010; Hagelüken & Meskers, 2010) Nevertheless, there are two restrictions that, with no doubt, legitimate this classification: the replenishment rate and the 'usefulness'. (cf. von Gleich, 2006b; Kesler, 2010; Hagelüken & Meskers, 2010) The usibility of metals is strongly dependant on the thermodynamic form in which they are available to us; forms "*far from the thermodynamic equilibrium*" are required, i.e. "*higher order conditions, higher energy density and higher material concentrations*" (von Gleich, et al., 2006b, p.17). As mentioned before, most elements do not occur by themselves in nature, but in chemical bonds – called minerals – whose physical combination again forms rocks. Such a combination of elements, minerals and rocks is referred to as ‘ore’ whenever the concentration of the desired component is high enough to be produced econonomically. (Kesler, 2010, p.111) In this sense, the term ‘ore’ stands – similar to the term ‘waste’ – for an emerged quality (usability). The presence of ore deposits in nature is nevertheless a result of “*geophysical and geochemical processes related to the plate tecntonics*” (von Gleich, 2006b, p.18), which allow and govern utilisable and accesible enrichments (formation of ores). These replenishment processes are neither influenceable, nor controllable, and they take time periods far beyond economic (and even historical) time horizons. Hence, metals are extracted and used at a much higher rate than they are usably enriched in the Earth’s crust by geological processes. (von Gleich, 2006b; Kesler, 2010) Other factors that limit the availability of usable metals, reinforcing their classification as non-renewable resources, is their ‘consumption’ and ‘losses’ during utilization. After being isolated from the ore, most metals experience various transformations throughout their utilization cycle, which influence their thermodynamic form, their concentration and their point of accessibility. ‘Consumption’ and ‘losses’ do thus not occur in their original, rather finite sense, but in terms of a debasement or even annihilation of usability. (von Gleich, et al., 2006b) As mentioned earlier, metals do certainly not cease to exist because of their use, but “*they can* [and most likely will] *be “used up”, i.e. they can be ‘devalued’ under thermodynamic aspects*” (von Gleich, 2006b, p.18). The dimensions of these factors, however, underlie anthropogenic processes within the technosphere and are in theory, compared to the geological processes, both influenceable and controllable – a core task for a sustainable metals management.

In summary, the availability of metals as resource for anthropogenic purposes is not a question of existence, but rather one of ‘usable enrichment’ and accessibility. Under thermodynamic aspects, ores are the result of a number of fortunate circumstances that only as such provide valuable resources, such as metals. They are valued based on their specific characteristics, such as “*brilliance, good electrical and heat conductivity, high strength, hardness and toughness*” (von Gleich, et al., 2006b, p. 3). At the same time, they do not age as most other non-renewable resources, and they can easily be reshaped. (von Gleich, 2006b, p. 17, 25) Their manifold properties and advantages are constantly increasing their importance and significance as resource. Their importance, even far in the past, has found its expression in the denomination of "*entire eras* [that] *were named after these materials*", as e.g. the Bronze Age and the Iron Age, marking "milestone[s] *in human history*" (von Gleich, 2006b, p.4). Since then metals have been critically linked to the development and prosperity of nations and have been a core material for the industrial revolution. (von Gleich, et al., 2006b; Wellmer & Wagner, 2006) Nevertheless, historic consumption has been rather low compared to the present. "*Since the end of World War II, humankind has consumed more raw materials than in the entire history before*", with mining operations mainly taking place at large scales (Wagner & Wellmer, 2006, p.44-45). With no doubt, population growth has been and will continue to be an important driver for a continuously increasing metal (mineral) consumption, but it is not the only one. (cf. Wellmer & Wagner, 2006) Today, an "*increase in variety of uses for metals and of metals in use*" (von Gleich, et al., 2006b, p.5) becomes apparent due to their increased particular functional relevance for major modern and high-technological applications, which at the same time reduces their substitution potentials. The overall demand for metals is thus likely to continue its increasing path. (cf. von Gleich, et al., 2006b; Wellmer & Wagner, 2006)

This rising demand is alarming in terms of a sustainable resource, respectively metals management and thus brings forth a number of serious challenges, especially with respect to limited availability and environmental burdens.

4.2 Major challenges related to primary production of metals

Naturally, and as examined above, the most obvious challenge with regard to primary production that has to be tackled when it comes to non-renewable resources, is that of their limited availability. The more specific challenges do thereby centre on the dynamics of availability and the time periods that are chosen for examinations. As it has been explained in the previous chapter, metals do not disappear but the do replenish in time periods that exceed historical and especially economic ones. Likewise, sustainability aims to consider time periods, "*which exceed those of classical resource economy by far*" (von Gleich, 2006b, p.23). Additionally, as is has been mentioned already, the term 'ore' inherits a qualitative cast, which is not fixed, i.e. minimum enrichment factors for what we consider an ore can change over time. Hence, when discussing availability of primary non-renewable resources and ultimately its sustainable use, the first major challenge lies in the quantification of stocks. (Moriguchi, 2010) However, "*their exact amount is a complex function of economic, technology and policy* (…). *This means that stock is no longer a fixed value, but that its amount may have potential to be altered.*" (Graedel & van der Voet, 2010, p.2).

Even despite extensive research on particular resource levels, their exact quantification (especially of ores in terms of usable and accessible enrichments) is unlikely, if at all, quantification will only provide for a static snapshot in time amid the previously mentioned dynamics. (cf. von Gleich, 2006b) Accordingly, a common approximation for resource availability is usually based on reserve lifetime, "*which is the ratio of the reserves known at the present to the current annual rate of production*" (Wellmer & Wagner, 2006, p.49).

'Reserves' do thus denominate those resources that are known with a high level of certainty and that can be extracted economically by means of current state of the art technology. In contrast, the 'reserve base' or resources refer to the reserves that are not yet economically exploitable, but geologically proven resources. This defintion in turn suggests that the exact level of resources remains largely unknown. (von Gleich, 2006b) The exhaustion of reserves and the reserve base/resources, however, is an important indicator for limited availability and accordingly a driver for innovation and exploration efforts. Approaching such points of exhaustion does usually lead to following subsequent process steps:

1. "*find new conventional deposits in poorly explored parts of the near-surface crust*"
2. "*seek conventional deposits at greater depths in the crust*"
3. "*attempt to use unconventional deposits*" ("*usually characterized by low grade or unusual mineralogy*")

(Kesler, 2010, pp.120,124)

Current exploration patterns do allude to the pressure today's consumption is already putting on the availability of certain metals, as an example for copper illustrates: "*the task for exploration to keep the balance between reserves and consumption translates into a mission to find more than one significant copper deposit every year*" (Wellmer & Wagner, 2006, p. 52)

Despite the fact that exploration can only lead to a temporary relief of an overall limited non-renewable resource as metals, exploration related environmental burdens and social deficits are further challenges with regard to sustainability.

Furthermore, the more we are forced to turn to deposits with lower ore grades or unconventional deposits, the greater the burden with regard to sustainability.

The benefication of crude ore (physical breakup) and the extraction of valuable elements (metallurgy) do inevitably generate significant bulks of solid waste rock (called tailings) and is additionally interacting with the requirement for water and energy. As the quality of metallic ores deteriorates, these (waste) materials tend to increase, whereas their amount is relatively large in comparison to the amount of extracted valuable resources. For example, the worldwide biggest mine (Bingham Canyon in Utah) produces 145,000t of ores per day, which are accompanied by 263,000t of waste material. (Wellmer & Wagner, 2006, p.44)

On the other side, in face of increasing requirements, the availability of water and energy could in fact, become a constraint for mining activity. (cf. Moriguchi, 2010; Norgate, 2010; von Gleich, et al., 2006b)

Nevertheless, detoriorating ore grades do only add up to the environmental burdens of mining activities. Mining and related processing activities are generally known to be "*dirty*" (Moriguchi, 2010, p.107). Tailings and inevitably removed overburden to arrive at the ore deposit change and degrade the landscape by ravaging the surface topography, causing severe (and sometimes irreversible) damage to entire ecosystems, biodiversity and wildlife habitats. Among other environmental concerns are depositions, sedimentation, as well as wind and water erosion. (cf. Moriguchi, 2010)

From a toxicological and ecotoxicological point of view, associated flows of e.g. heavy metals, cyanide and mercury (both latter used during benefication) do constitute another significant problem with regard to sustainability, not only at the specific point in time but especially in the long run: "*Accumulations in environment and food chain cause continous transition to less perceivable long-term and irreversible sustainability problems*". This transition does not only apply to asscociated heavy metal streams but also to other waste streams (e.g. acid drainage) and CO_2 emissions. Hence, by stressing Earth's source function through exploitation, the sink function is directly affected, too. (von Gleich, et al., 2006b, S. 12ff.; Kesler, 2010; Moriguchi, 2010) Latter can even become a restrcitive factor with regard to the availability of metallic ores, since "*not all resources can and should become reserves, as the increasing effort expended on extraction of* *poorer and more problematic ores goes to the limits of the intake capacity of sinks*" (von Gleich, 2006b, p.32).

Nevertheless, the extraction of lower graded ores is not only a function to a decreasing overall availability of resources. Economic aspects do often play a decisive role when it comes to the decision which ore grade to extract. Lower concentrated ores at existing sites, respectively their lower constitutents, are often consciously accepted as 'losses' during mining and mineral processing depending on the potential economic added-value. Even short-term fluctuactions in prices can dictate this selectivity – altogether, practices and mechanisms which are challenging sustainability efforts.

On the other hand, economies of scale can lead to the opposite case when "*large-scale open-cast mining* [often] *make it appear more economical to extract lower ore concentrations on a large scale as compared with higher ore concentrations in niche areas, for example*", while using the extraction of higher ore concentrations within the first years of a project for a fast amortization (von Gleich, 2006b, p.24). Of course, the combination of large-scale mining of rather low ore grades result in major intrusions on local ecosystems. This is only aggravated by the fact that often, deposits are to be found in rather sensitive ecosystems, e.g. rain forests. (von Gleich, et al., 2006b) Especially the last two examples, show that the issue of ore grades is delicate and prone to trade-offs with regard to a sustainable metals management, in particular primary production. Kesler (2010, p.109) states that, "*from an immediate standpoint, the greatest opportunity for mineral sustainability is to mine as much as possible of each deposit rather than focusing on ores of the highest quality*".

Of course, the overall reduction of primary extraction should be the first option to address the mentioned challenges. "*Increasing attention is* [thus] *being paid to human-made stocks of valuable material resources* (…), *often called 'urban mines'* (…)", for alternative supply (Moriguchi, 2010, p.105).

In this sense, reuse and recycling (secondary production) are important strategies, however, secondary production is facing its own sustainability challenges, too (next chapter). (cf. Norgate, 2010)

4.3 Major challenges related to metal cycles & secondary production

That the recycling of metals is of major importance to support metal supply is beyond dispute among experts, especially in view of a sustainable metals management. (cf. Rombach, 2006; von Gleich et al., 2006b) In fact, metal recycling has always been coexisting since the early beginnings of metal production, not last due the favourable chemical and physical properties of metals for high-quality recycling in comparison to most other materials. Another favourable characteristic in that sense is, as mentioned in sub-chapter 4.1, is the fact that metals do not age. (cf. von Gleich, 2006b) Especially in the case of large base metal flows, as those of iron/steel, aluminium or copper, recycling is already well established and "*exemplary with regard to both recycling qualities and also recycling volumes*" (von Gleich, 2006b, p.25). Nevertheless, metal recycling in general still faces challenges with regard to 'economics', 'effectiveness', 'efficiency', and 'quality'. Major challenges with regard to the effectiveness of recycling are dissipative losses and the insufficient and inefficient recirculation and collection of end-of-life (EoL) products. Together, these 'spillages' along the life cycle of metals become evident by assessing the 'resource-oriented recycling quota' and the 'technical recycling quota', two phrases coined by Rombach (in: von Gleich, 2006b, p.29). While the technical recycling quota makes reference to the effectiveness of the actual recovery of metals during technical recycling processes, the resource-oriented recycling quota considers the entire material cycle with regard to the "*extend the industry is able to recycle materials in a truly sustainable way*", thus considering the availability of secondary raw materials. Data on latter quotas, however, is rarely available yet. Nevertheless, structural cycle deficits, particularly the insufficient collection of EoL products are commonly known to represent the greatest deficit with view on the resource-oriented recycling quota. (von Gleich, 2006b, p.29f)

Generally though, losses do accumulate along the entire life cycle, especially dissipative losses must always be expected, which is why a holistic systems approach of all material flows is necessary for optimization. (cf. Hagelüken & Meskers, 2010; von Gleich, et al., 2006b) Adjustable preprocessing, along with efficient collection, can be decisive in rendering significant contributions to the effectiveness and efficiency of recycling, especially in view of the existing recycling technologies. Those are commonly based on primary production metallurgy, since the laws of chemistry and thermodynamics remain the same. In this sense, effectivness is primarily challenged either by metal combinations that do no occur in nature and/or by EoL products, respectively components and materials, that enter ‘wrong’ recovery routes or smelters, hindering or even impeding their recovery. (cf. Hagelüken & Meskers, 2010) Hence, “*in most cases* (.) *metallurgical technology itself is not the barrier to achieve good recycling rates*” (Hagelüken & Meskers, 2010, p.186).

Nevertheless, the aspired increase of the resource-oriented recycling quota does also bear a drawback with regard to sustainability due to its consequences on the quality of secondary materials. “(…) [C]*onstant innovation and research produces new alloys and improved metal specifications*” (Wellmer & Wagner, 2006, p.61), increasing material mixtures and composites, while often reducing particular concentrations. (von Gleich, 2006b) Even though this can be desireable with regard to resource intensity, it does constitute a major challenge for recycling. (Wellmer & Wagner, 2006) Products with complex alloys (and low concentrations of particular metals) can hardly be well sorted, respectively purified (with a realistic effort), before entering metallurgical processes, which impedes recycling on the same quality level. Secondary materials do thus result contaminated with tramp elements. Such so-called downcycling does ultimately result in an ‘alloy cascade’: by means of a cycling economy, impurities in the stock of secondary metals are increasingly enhanced. (cf. Rombach, 2006; von Gleich, 2006b) In contrast, the trend with regard to high- and clean technology innovation tends towards “*ever increasing purity requirements*” (von Gleich, et al., 2006a, p.270), thus exacerbating the challenges of a diminishing technical quality that reduces the usability and serviceability of contaminated secondary metal. Hitherto, the analysis and monitoring of the intersections between the geo-biosphere and the socio-industrial system have experienced the most attention, whereas the challenge of technical quality of material cycles requires a much deeper (complementary) focus on the inside of the technosphere . (cf. von Gleich, et al., 2006b) The restrictions to high technical quality, in terms of dissipative losses to the spheres and the contamination of metal flows in the technosphere, is in fact the primary and most decisive limitation to a perpetual recycling of metals and is thus a challenge of pressing importance with regard to a sustainable metals management.

However, there are no mature measures and analytical instruments for technical quality maintenance or losses in metal cycles so far, since the problem is only recently gaining attention; entropy[3] and exergy[4] analysis (which will not be discussed in further detail within the scope of the present study), as measures for (not) available usefulness, do constitute first promising approaches though. (cf. von Gleich, et al., 2006a, b) Practical ways to deal with the diminishing quality of metal cycles, especially with contaminated materials, mainly exist in two forms: low-quality (contaminated) materials are either 'upgraded' by adding primary metals or they are used for "*'contaminant-tolerant' products for 'other than prior' uses*" (von Gleich, 2006b, p.32). Nevertheless, neither option can be considered an acceptable solution in terms of sustainability for gradually driving primary production. In this context, recycling fails to enhance resource efficiency as intended by merely shifting the driving forces for primary metal demand instead of successfully reducing it. (cf. Rombach, 2006)

Another principal intention of recycling is the reduction of overall energy consumption and related emissions, as well as other ecological burdens compared to primary production. Thereby, especially the overall reduction of CO_2 emissions is, among many experts, considered to be the primordial aim of recycling, which translates into an optimum that rather diminishes overall energy consumption instead of reaching a resource-oriented recycling quota of 100%. (Wellmer & Wagner, 2006) With regard to metal recycling, ecologically "*problematic side-effects and after-effects*" can indeed not be neglected, as they "*appear to reach the level of those of primary production*" in many areas (von Gleich, 2006b, p.25). This is in part a temporary problem owed to a still rather immature recycling industry and related legislation deficits. Nevertheless, the previously mentioned increasing complexity of materials and alloys does just as well drive the negative side-effects of metal recycling through the according need for more complex, energy and chemical intensive recovery processes. (cf. von Gleich, 2006b)

In summary, increasing product and alloy complexity together with overall decreasing concentrations (of a specific substance) constitute a trend that must be taken very serious with regard to a sustainable management of metals since it

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[3] Simplified: 'Entropy' refers to 'not usable' (share) in terms of 'unavailable energy'.
[4] Simplified: 'Exergy' refers to 'usable' (share) in terms of 'available energy'.

affects all three target dimensions – efficiency, effectiveness, and quality – of recycling.

As mentioned earlier, a holistic system approach is decisive for the challenge of overall cycle optimization. “*Harmonious interaction among all actors in the resource cycle*” (Reuter & van Schaik, 2010, p.149) is an important first step for and within optimization efforts towards more successful closed material cycles. This does also include, as a decisive factor, design and material choices. (cf. Schäper, 2006) These choices have an enormous potential for positive chain reactions in view of a sustainable metals (resource) management:

> “*Functional and aesthetic specifications* (…) *affect*[] *material supply and demand, how much and how long resources are locked up in the material chain, and what technology is required now and in the future to recycle these materials*” (Reuter & van Schaik, 2010, p.150)

In turn, the greatest challenge for sustainability-optimised design is a sufficient knowledge on “*the geology and the fundamental properties of the elements*” in order to not compromise material recovery after utilisation (Reuter & van Schaik, 2010, p.150). Design choices should as well account for recyclability and recycling stream quality with regard to a favourable and eased material liberation, respectively separation. Thereby, concentrations of particular materials or elements are as important as their dispersal. (cf. Reuter & van Schaik, 2010)

4.4 Critical Metals: determinants and implications

Up to here the previous chapters have developed a broad overview on objectives, strategies and challenges related to a sustainable management of resources and metals in general. Nevertheless, there are metals that show some peculiarities, which propose that these metals are particularly ‘critical’. Because of their relevance for the object of investigation of the present study, mentioned peculiarities remain to be pointed out briefly.

Although there does not exist one consistent definition for the ‘criticality’ of resources, respectively metals, the most simple way to get hold of the concept is through its strong linkage to ‘scarcity’, whereas scarcity is not restricted to geological abundance, but rather refers to a non-favourable combination of high demand versus risks in supply. The concept is thus based on a certain kind of risk assessment, whereat typical determinants are geographic production concentration, political stability of supplying countries, recycling and substitution potentials, as well as environmentals risks related to production and processing. (cf. Graedel, et al., 2011) Accordingly, the denotation ‘critical’ could be considered a label, which is based upon various factors and circumstances that may change over time, and which may be differently weighted by actors e.g. nations or industries.

One group of metals that is commonly referred to as critical is the group of ‘minor metals’, which embraces precious metals and the so-called ‘special metals’. Special metals are those “*that have unique properties without being major or mass metals*” (Hagelüken & Meskers, 2010, p.166).[5]

Minor metals *“play a key role in modern industrial technologies as they are of specific importance for clean technologies and other high equipment*”, which includes the electric powertrain, and in particular the battery. Hence, minor metals are often synonymously referred to as ‘technology metals’. (cf. Hagelüken & Meskers, 2010)

Despite their geological scarcity as non-renewable resources, minor metals do typically suffer structural, technical and economical scarcities. Their use for (sustainable) technological applications has almost exploded recently and this trend is expected to further accelerate. (Hagelüken & Meskers, 2010; Moriguchi, 2010; Halada, 2008) At least 50 to 80% of the cumulative mine production for most special and precious metals has been realized after 1980. In comparison to materials and metals mainly used for infrastructure, “*a decoupling of the specific use of these technology metals from economic growth is not likely* (…)”. (Hagelüken & Meskers, 2010, p.169)

Substitution has been difficult so far, due to the specific properties of this group of metals. In most cases substitution fails its original purpose by replacing elements within the same group. Also from a sustainable life-cycle management perspective, ”*precious and special metals are very susceptible to suboptimal life/utilization cycles*” (Hagelüken & Meskers, 2010, p.164).

With regard to their primary production, minor metals do often occur in rather low ore concentrations, but geologically closely associated with major metal

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[5] Precious Metals: Gold (Au), silver (Ag), platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), and osmium (Os).
Special Metals (among others): cobalt (Co), lithium (Li), rare earth elements (REE), Gallium (Ga), Germanium (Ge). (Hagelüken & Meskers, 2010, p.165)

deposits. This way, minor metals become so-called by-products of their host-metal (coupled production). There are only a few exceptions; lithium, for example, can be mined on its own, while in other specific cases there might be no ‘real’ host or carrier metal and/or by-products become target metal. Coupled production, however, is problematic in many ways. First of all, as learned in the previous chapter, ore concentrations have an important influence on extraction decision-making. Contents that cannot be economically extracted are left behind, which is often the case for minor metals. Losses do thus already occur in the very beginning of the life cycle. Furthermore, the dependence of minor metal production on that of the carrier metal hinders common market mechanisms to work well, since amounts can hardly correspond properly to (changes in) demand. The interplay of supply/demand and prices becomes even more complex and volatile, thus hardly predictable. The resulting supply risk is in most cases exacerbated by a regional concentration of suppliers, which makes supply even more sensitive to disruptions. (cf. Hagelüken & Meskers, 2010) “*For most special metals, the combined output of the three main producers supplies over 70% of the market*” (Hagelüken & Meskers, 2010, p.178).

A further critical step with regard to losses related to primary production of minor metals is the mineral processing. The separation of minor and major metals requires different processes, which are ideally aimed at the respective recovery of the specific metals. Especially in the case of by-products, processes can be very complex and highly interconnected, which is why the appropriate technology for by-product recovery is often either missing or inefficient. (cf. Hagelüken & Meskers, 2010)

Similar challenges are faced at the stage of secondary production, respectively the recovery of minor metals from EoL products. Particular recycling paths and processing technologies are required to recover precious and minor metals – otherwise they will be lost. Both, precious and special metals are generally contained in very small amounts/concentrations per application. Nevertheless, precious metals are generally recycled due to their (relatively) high value, both with regard to the value share on unit level and prices, while the recycling of most special metals is still neglected based on rather unfavourable value shares and prices. Thus, significant amount of special metals are being lost at this stage. Recycling, however, is of major importance with regard to a sustainable metals management as already argued in previous chapters. Also with regard to the various consequences of coupled production in the context of an accelerated increase in demand, the recycling of special metals could be an important relief factor. (cf. Hagelüken & Meskers, 2010)

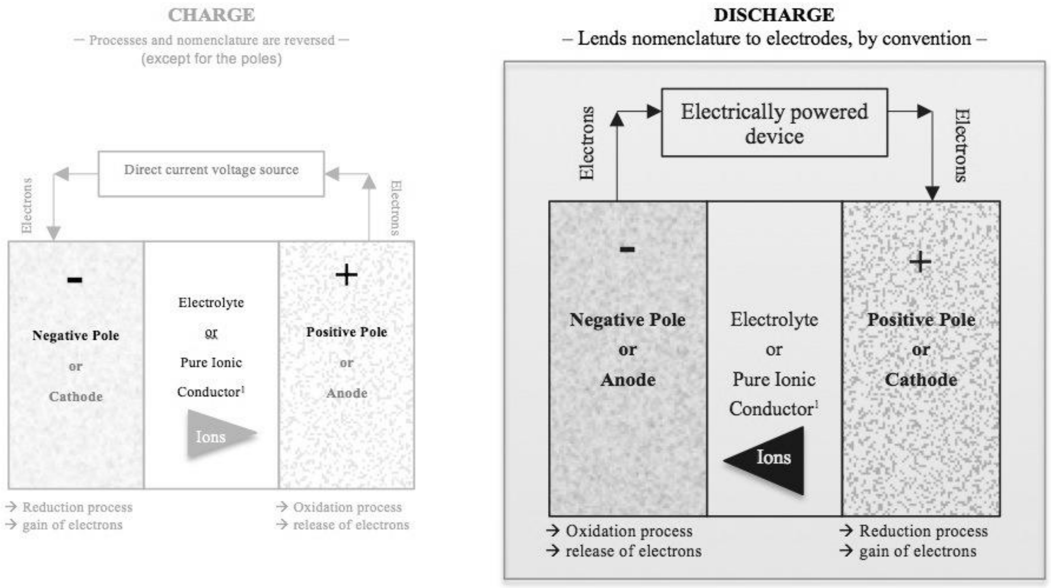
5 The battery as key technology for the electric powertrain

As it has been argued in sub-chapter 1.2, batteries are considered to be the most prominent and established energy source in the field of e-mobility (cf. Winter & Brodd, 2004; Huggins, 2009; Pollet, et al., 2012; Tie & Tan, 2013; Peters, et al., 2013; Thielmann, et al., 2010; Hawkins, et al., 2012). Battery research and development for EV application is still highly dynamic, which is reflected in an accelerated upward trend of patent applications. (cf. Peters, et al., 2013) This chapter is aimed to give an overview on the technology and its role and requirements with regard to e-mobility. Subsequenty, recent developments are reviewed to determine the current state-of-the-art.

5.1 Battery design and functional principle

Energy can take different ‘forms’ and consequently it is not always present in the form in which it is needed for a specific purpose. In this case, conversion of energy is necessary. Additionally, energy may be needed in certain amounts at times and places, which differ from the ones required. This, in turn, makes it necessary to store and transport energy, and to recall it on demand. Batteries are devices (so-called electrochemical storage systems) that serve both requests. They consist of one or more electrochemical cells that store energy in form of chemical energy and convert it into electrical energy on demand to power an application (discharge process). Thereby, the conversion of energy is based on a controlled chemical reaction. The direction of this conversion process can also be reversed, i.e. electrical energy is converted into chemical energy, thus the battery is being charged. Batteries or cells that do not support this reversed reaction and are discarded after their discharge, are generally referred to as primary cells, whereas rechargeable batteries are commonly known as secondary cells or accumulators. (cf. Huggins, 2009; Hayner, et al., 2012; Winter & Brodd, 2004) The common functional principle and technical architecture behind such an electrochemical conversion system is that of a galvanic cell. Note that the term ‘galvanic cell’ is not synonymous for ‘battery’, but rather stands for the basic component architecture and mechanisms that are shared among various electrochemical conversion systems. Hence, a galvanic cell consists of two ‘chambers’, in which electrochemical reactions take place at a respective electrode, whereas the electrodes are bridged through an electrolyte solution that transports ions between the electrodes, while electrically isolating them. In most cell designs a so-called separator is added for additional mechanical separation of the electrodes to prevent short circuit. As the electrolyte, it must be inert in the battery environment while permeable for ion transport. (cf. Peters, et al., 2013; Pollet, et al., 2012; Hayner, et al., 2012) The separator may also “(…) *serve as safety device by melting at too high temperatures and consequently plugging up the pores that allow ionic exchange and this way shutting off the cell current*” (Gaines & Cuenca, 2000, p.13). This process, however, damages the cell irreversibly.

Figure 4: Block diagram of a battery (cell) – basic architecture, mechanisms and nomenclature



[1] may contain an insulating material for separation of the electrodes.

Source: own diagram based on Winter & Brodd, 2004, S. 4253; Huggins, 2009; Hayner, et al., 2012.

Figure 4 (above) discloses the basic components, mechanisms and architecture of a galvanic cell transferred into a battery format. The electrode, where the reaction usually takes place at relatively lower electrode potentials is denominated the negative electrode (indicated as minus pole), also called the ‘anode’. In turn, the electrode, where the reaction usually takes place at relatively higher electrode potentials is denominated the positive electrode (indicated as plus pole), or ‘cathode’. Anode and cathode each contain active material (compounds) that generates electrical current by means of chemical redox reactions. Both active materials (compounds) together constitute the redox couple of the electrochemical system. By convention, the chemical reactions that take place at the electrodes are associated with their behaviour during discharge when electrical energy is delivered (although their behaviour is reversed during charge), i.e. the anode is usually associated with the oxidative chemical reaction, while the cathode is associated with the reductive chemical reaction. (cf. Peters, et al., 2013; Hayner, et al., 2012; Huggins, 2009; Pollet, et al., 2012)

Hence, during

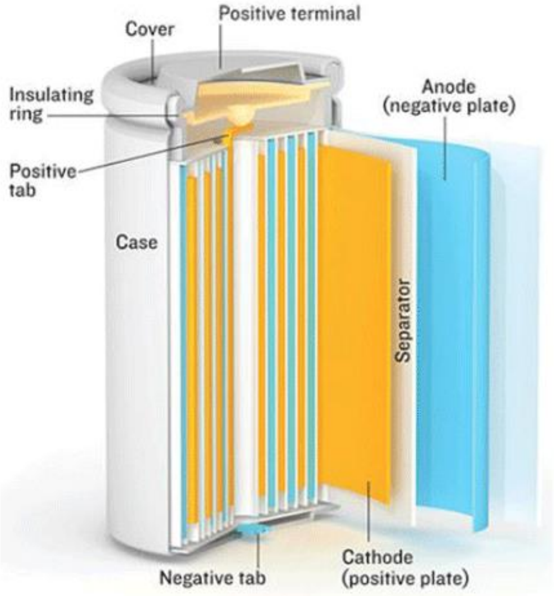
> discharge, ions migrate “*from the anode through the electrolyte to the cathode* (…), [while] *electrons are removed from the anode (oxidation); are transferred through an external circuit, which creates current to power a load; and enter the cathode (reduction). The discharge process continues until the potential difference* [voltage] *between the two electrodes becomes too low, at which point the cell is fully charged*.” (Hayner, et al., 2012, p.450)

Parting from the hitherto examined basic architecture and functional principles of a galvanic cell, respectively that of a battery, the ultimate cell chemistry (composition of active materials) and the battery design (or assembly) for a traction battery is much dependant on the automotive manufacturer. However, with regard to the design, some general observations can be made, even though deviances are possible.

As mentioned earlier, batteries do comprise one or more single cells depending on its targeted application. For the high voltage requirements in automotive applications, traction batteries usually consist of a large number of cells that are connected in series. There is no theoretical limit to the amount of connected cells, however, their accumulated weight poses practical limits. (cf. Brandl, et al., 2012; Gaines & Cuenca, 2000) The number of cells and the ultimate weight of a battery pack do thus depend on the specific characteristics (performance) of the cells applied, which in turn are dependant on the vehicle concept. These aspects will be further reviewed in the following chapters.

Returning to the general cell design for traction, cylindrical or pouch designs are usually the ones preferred over prismatic ones. Even though the cylindrical form does not facilitate an efficient use of space, advantages with regard to energy density and mechanical stability seem to balance the spatial inefficiency. In turn, pouch designs are most efficient in terms of space-use. (cf. Wagner, et al., 2013; Ramoni & Zhang, 2013; Gaines & Cuenca, 2000) Figure 5 shows an exemplary single cylindrical cell.

Figure 5: Construction of a typical cylindrical (Li-ion) battery/cell

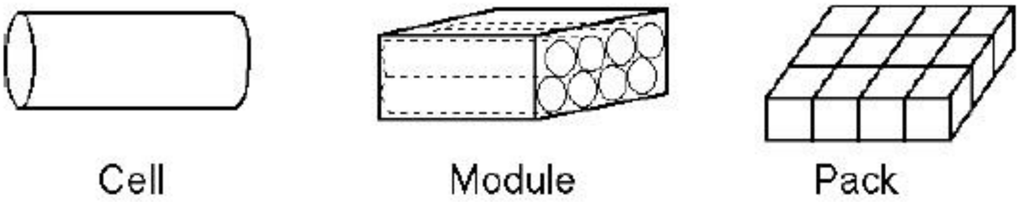


Source: IEEE , 2014.

Most electrodes today consist of quite porous structures of ever increasingly complex compounds of active material particles mixed with a conductive diluent and held together by means of a binder. The compound is coated to a conductive current collector, generally a "*thin metallic foil substrate*" (Gaines & Cuenca, 2000, p. 12; cf. Winter & Brodd, 2004) "[The] *thin layers of cathode, separator, and anode are* [then] *rolled up on a central mandrel and inserted into* [the] *cylindrical can. The gaps are filled with liquid electrolyte*", also entering the pores of the porous electrode structures. (Gaines & Cuenca, 2000, p.5) The (inside of the) assembled cell set-up looks like illustrated in Figure 5.

The single cells are connected in series and assembled into battery packs. Their designs can vary, however, in most cases they are grouped into modules, each typically containing between 6 and 12 cells. Depending on the used cell chemistry, a control system with a bypass circuitry is added to each module. The modules are then combined into the battery pack, which "(…) *is sized to match the requirements of the vehicle*" (also cf. Figure 6). As an example, to gain an impression of the potential dimensions, the battery pack of the *Nissan Altra* measures 100cm x 200cm x 18cm. (Gaines & Cuenca, 2000, p. 8,15)

Figure 6: Battery pack assembly – from cell, to module, to battery pack



Source: Gaines & Cuenca, 2000, p.7.

5.2 Electric vehicle concepts

As indicated earlier, cell and battery design is very much dependant on its target application. In this context it needs to be noted, that even within e-mobility it has to be differentiated between applications according to different vehicle concepts that affect cell and battery design. In practice, the common denomination 'electric vehicle (EV)' "(…) *covers many types of currently discussed and tested variations of electrical propulsion systems* (...)" for vehicles (Notter, et al., 2010a, p.6550).

Figure 7 (next page) gives an overview on the classification of vehicles. All-Electric Vehicles (AEVs) refer to electric vehicles in their purest form. These vehicles use exclusively electric power for propulsion.[6] Battery Electric Vehicles (BEVs) do thus use a battery as their only power source and an electric motor (EM) for traction to move the vehicle.

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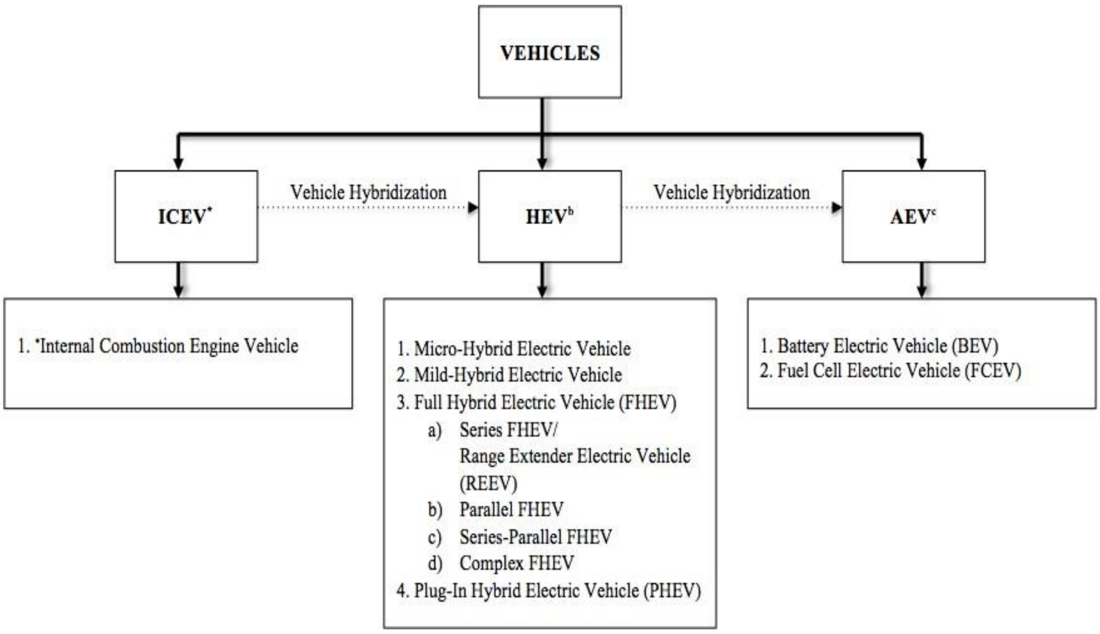
[6] Note that fuel cell technology has been excluded from the present paper. The correspondent vehicle type is listed in Figure 7 for the sake of completeness. However, it will not be further reviewed.

Figure 7: Classification of vehicles



with ^{b} Hybrid Electric Vehicle; ^{c}All-Electric Vehicle

Source: based on Tie & Tan, 2013, S. 86; adapted according to Kaiser, et al., 2008 & Peters, et al., 2013.

BEVs do in fact have a long history, which dates back to 1834, when the first BEV was build even before the first Internal Combustion Engine vehicle (ICEV). However, it was outperformed by the fast development of the ICEV, which today continues to be the conventional vehicle concept, powered by either gasoline or diesel. In the context of the sustainability debate, BEVs are re-gaining interest since the 1970s. (cf. Tie & Tan, 2013; Pollet, et al., 2012) With regard to transport and mobility, they are widely regarded as ‘white-hope’ in terms of “(…) *no tailpipe emissions, high efficiency and potential independence from fossil fuels* (…)” (Pollet, et al., 2012, S. 245). Since BEVs rely on the battery as their only power source, their performance is directly linked to that of the battery, among other factors as e.g. the efficiency of the EM. “*In terms of accelaration and power, BEVs are* [actually] *superior to IC*[EVs]” (Pollet, et al., 2012, p.245), however, in order to compete with ICEV ranges (delivered by an average tank of gasoline), BEVs require batteries that can deliver a comparable amount of energy with one ‘battey-charge’.

According to Peters, et al. (2013, p.25) “(…) *pure battery-powered vehicles that can compete with the technical performance indicators of conventional fossil fuel*

]

powered vehicles, does only appear to be realisable in the long run". Meanwhile, as long as BEV competitiveness continues to challenge R&D, particularly that of battery technologies (further discussed in the following sub-chapters), hybrid concepts are considered to be an attractive interim solution, (cf. Hayner, et al., 2012; Peters, et al., 2013)

In general, Hybrid Electric Vehicles (HEVs) all combine an electric motor and a combustion engine, and accordingly both respective power sources: a battery and a fuel tank. Hence, "*HEV, which combine the best features of the two power sources, gain* (.) *advantages of both ICE vehicles and BEVs, and overcome* [in part] *their individual disadvantages*" (Pollet, et al., 2012, p.244). For example, ICEVs generally suffer from very low conversion efficiencies. Only about 20% of the energy content of the fuel tank can currently be converted into useful energy, e.g. for propulsion. With the support of an electric motor supplied with energy from a battery, higher efficiencies can be obtained improving fuel economy and emission control. In comparison to BEVs, the challenge of the required energy capacity of the battery becomes less pressing. On the other hand, with regard to the use of fossil fuels and tailpipe emissions, they only constitute a compromise solution. (cf. Hayner, et al., 2012, Tie & Tan, 2013; Scrosati & Garche, 2010; (Thielmann, et al., 2012b)

HEVs come in various different powertrain configurations, respectively architectures, as illustrated in Figure 8[7]. Their differences are mainly based on the hierarchy (primary and secondary propulsion power supply) of the EM/ICE and the respective power sources and related to that, the degree of hybridization (ratio of electrical propulsion to conventional propulsion). The hybrid concept with the least degree of hybridization is the Micro-HEV. It is actually that close to a conventional ICEV that it is often not even considered as HEV, but rather considered as an 'advanced' ICEV. Accordingly it is not included in Figure 8. These vehicles are commonly known as vehicles with a start-stop function, *"(...) i.e. the motor turns off as soon as the driver declutches and brings the manual transmission into neutral position*" (Kaiser, et al, 2008, p.28). The ICE restarts immediately when the clutch is pressed again. This restart of the ICE is facilitated

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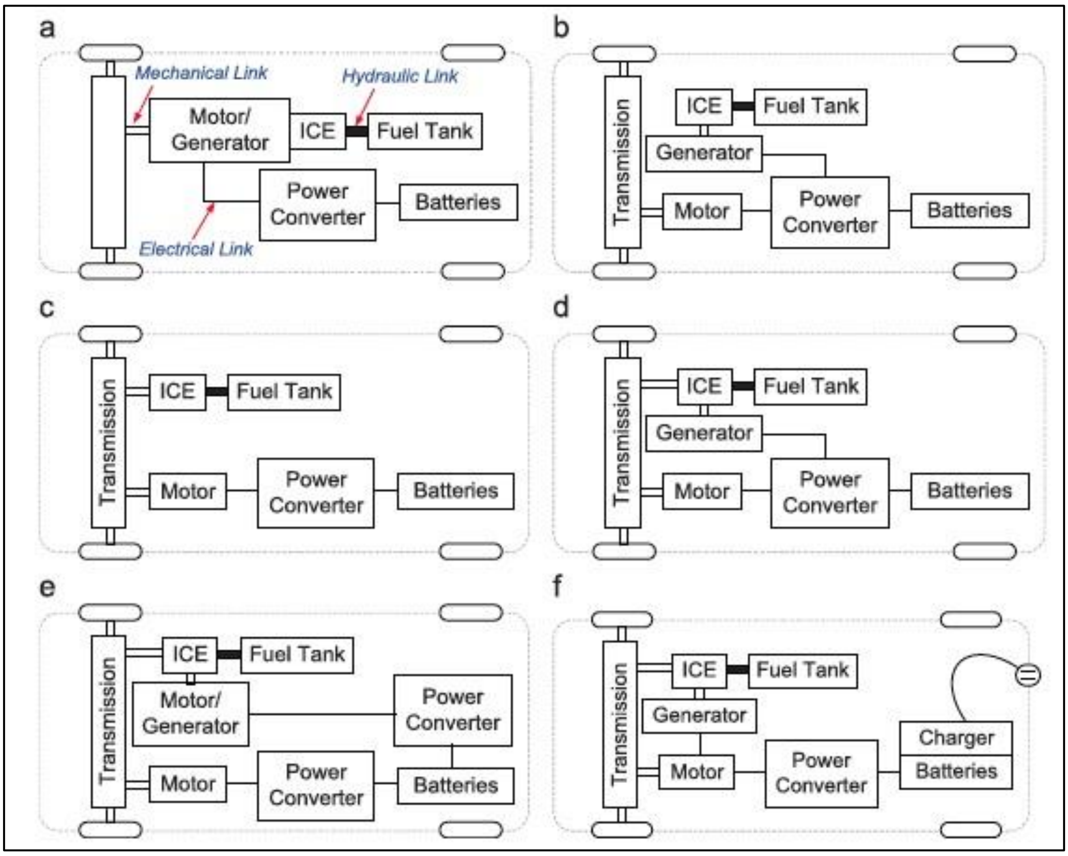
[7] Note that the letters (a-f) do not correspond to the letters (a-d) in

by an EM (startergenerator) fed by a battery, which is charged with braking energy. However, as in a conventional ICEV, propulsion power is still exclusively delivered by the ICE.

Figure 8: Powertrain architectures of HEV concepts



Note: (a) mild-HEV, (b) series FHEV/ REEV, (c) parallel FHEV, (d) series-parallel FHEV, (e) complex FHEV, (f) series-parallel PHEV. Source: Tie & Tan, 2013, p.87.

Similarly, the Mild-HEV (Figure 8 (a)) derives its propulsion power primarily from the ICE, while the integrated EM solely fulfils a support function. ICE and EM share the same shaft, which is why the vehicle cannot be run purely on electrical energy. As in the Micro-HEV, the battery recovers its energy from braking processes. (cf. Kaiser, et al, 2008; Tie & Tan, 2013)

In turn, a series FHEV, also called REEV, (Figure 8 (b)) derives its propulsion power exclusively from the EM. A high-efficiency ICE (the range-extender) is applied to either recharge the battery when recovered braking energy is not sufficient, or to directly supply the EM with energy for propulsion.

Therefore, the IC engine's mechanical power needs to be converted into electrical power first, by means of a generator. Hence, very generally speaking, the REEV is comparable to a BEV with an integrated 'charger' (the ICE).

A parallel FHEV (Figure 8 (c)), as the name suggests, uses the EM and the ICE complementary. Since the they do not share the same shaft, propulsion power can be delivered from either one of them or from both together. In addition, the EM adopts the function of a generator to charge the battery with breaking energy or energy surplus from the ICE.

The series-parallel FHEV and the complex FHEV (Figure 8 (d) & (e)) are very similar concepts on a general level. Both combine the advantages of the series FHEV and the parallel FHEV. Accordingly, their concepts are more complicated with differences that are to be found on a rather detailed technical level, which is also reflected in a relatively higher cost. Nevertheless, the series-parallel FHEV is quite prevalent on the commercial level. Especially the Toyota Motor Corporation, as the first company to sell hybrid-vehicles in series (starting in 1997), seems to prefer this hybrid concept. (cf. (Kaiser, et al., 2008; Pollet, et al., 2012; Tie & Tan, 2013; Peters, et al., 2013)

At last, the PHEV (Figure 8 (f)) is a rather particular concept. In general terms, it can be considered as the outcome of an add-on for any HEV concept, which leads to a decisive observation on HEV and the comprehension of the commonly used umbrella term 'electric vehicle' (EV). Theoretically, a "(…) *PHEV is directly transformed from any type of HEV* (...) *by adding a charger beside the battery*"[8] (Tie & Tan, 2013, p.86), i.e. the battery can be charged externally via the grid. In turn, this allows the conclusion that none of the other hybrid concepts described, is designed to be connected to the grid to charge the integrated battery. This is actually one of the reasons, why HEV are considered a suitable interim solution, since no additional charging infrastructure is needed for their widespread use. On the other hand, it is one of the reasons, besides their limited emission reduction potential, why most HEV are only regarded as 'electric vehicles' (EV) "*in a wider sense*". (Peters, et al., 2013, p.25; also cf. Kaiser, et al., 2008; Thielmann, et al., 2012b) Except for PHEV (and sometimes also REEV), HEVs are thus

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[8] The PHEV (f) depicted in Figure 8 is an example of a transformed serial-parallel FHEV concept.

excluded from most analyses and senarios in the field of e-mobility. (cf. for example Thielmann, et al., 2012b)

After this overview on the different possible architectures and propulsion hierarchies of BEVs and HEVs it becomes evident, as aforementioned, that there are different requirements regarding the specifications and performance of batteries, which affect cell and battery design in various ways. Mass composition, as well as energy and power requirements for HEV-type batteries differ significantly, in particular from those of BEV and PHEV-type batteries. Table 4 contrasts different requirements of the vehicle concepts with regard to their average battery capacity (in kWh) and system voltage (V).

Table 4: Suitable battery specifications for different vehicle concepts

Vehicle concept	System voltage (V)	Battery capacity (kWh)
ICEV	12	-
Micro-HEV	12 – 42	0.02 – 0.05
Mild-HEV[1]	150 – 200	0.125 – 1.2
FHEV[2]	200 – 350	1.4 – 4.0
PHEV[3,4]	300 – 500	6.0 – 20.0
BEV[4]	300 – 500	20.0 – 40.0

Source: based on Tie & Tan (2013, p.89); [1]Pasaran, Gonder, & Keyser, 2009; [2]Burke, 2007; [3]Pasaran, 2006; [4]Pasaran, 2009a in: Tie & Tan (2013, p.89).

These differences are mainly rooted in the fact that in most HEVs the battery is used as assistance for high power production during short periods of time, while in BEVs (and PHEVs) the battery, as primary energy source, is required to deliver energy constantly over long (maximised) time periods – i.e. the longer energy can be delivered the greater the range of the BEV. (cf. Majeau-Bettez, et al., 2011a; Pollet, et al., 2012; Gaines & Cuenca, 2000) These aspects do not only determine the choice, respectively the R&D, of active materials, but also the size of the battery, which is relatively reduced for HEVs in comparison with BEVs (and PHEVs). (cf. Huggins, 2009)

5.3 Battery performance parameters

Researchers are constantly working on improved battery performances to meet the specific requirements of electric vehicle concepts. As learned in the previous chapter, these requirements can differ among the different concepts. R&D of battery technologies needs to be aware of the respective relevance and prioritisation of battery performance parameters since trade-offs are common.

Two of the most discussed target dimensions of battery R&D for electric vehicle applications are the amount of energy and the electric load (power). (cf. Pollet, et al., 2012; Peters, et al., 2013; Hawkins, et al., 2012; Winter & Brodd, 2004; Huggins, 2009; Kaiser, et al., 2008) The energy amount stored in a battery is measured in Watt hours (Wh). It is *the* decisive factor in determining how far a vehicle can go (range in km) before a recharge of the battery becomes necessary. As it was already mentioned earlier, there are no theoretical limits to the amount of energy, considering that cells can be connected in series. However, there are practical limits imposed by acceptable mass and volume parameters for mobile applications, respectively e-mobility application. This is why the object is to optimize energy contents with regard to the weight (specific energy or gravimetric energy density in Wh/kg) and the volume (volumetric energy density in Wh/l), both on cell and system level. Dr. Peter Birke from *Continental Batteriesysteme* (In: Thielmann, et al., 2010, p.16) points out that the entire battery development for e-mobility is mainly driven by energy density.

The 'attainable' specific energy (Wh/kg) is highly dependant on the electrode materials and properties, as the stored energy (Wh) is the product of the operating voltage (in Volt, V) and the specific charge (mAh/g). (cf. Wagner, et al., 2013) Latter is an extensive quantity, which means that "*the amount of charge that can be stored in an electrode depends on the amount of material in it*" (Huggins, 2009, p.13). The voltage, in turn, is an intensive quantity that is not dependant on the amount of electrode material. Theoretically, "(…) *cell voltage is determined by the differences in the electrically neutral chemical composition of the electrodes*" (Huggins, 2009, p.25). Thus, for a high voltage, the standard redox potentials of the respective electrode redox reactions should ideally be high for the positive electrode and low for the negative electrode. (cf. Wagner, et al., 2013) High voltages generally indicate high quality (as of usefulness) energy. Table 5 shows an approximate energy quality ranking with regard to electrochemical cells, based on their output voltages. According to Huggins (2009, p.11), “*the utitlity of an electrochemical cell* (...) *in driving an electric motor is particualrly voltage-sensitive*“, typically demanding high operating voltages of 200V or more at system level.

Table 5: Energy quality of electrochemical cells based on output voltages

Voltage ranges	**Quality**
3.5 – 5.5 V	High quality energy
1.5 – 3.5 V	Medium quality energy
0.0 – 1.5 V	Low quality energy

Source: Huggins, 2009, p.11

The higher the voltage on cell level, the less cells are required, since higher voltages can be attained by connecting cells in series. As it has been stated earlier, weight and mass considerations are among the most important parameters for the use of batteries in mobile applications, certainly when speaking of e-mobility, which either way require relatively large sized battery systems. Nevertheless, voltage at cell level is limited at some point based on the electrochemical potential of the redox reactions at the electrodes. (cf. Peters, et al., 2013; Huggins, 2009)

With regard to the energy density (gravimetric and volumetric) it must also be noted that there is a significant gap between theoretical (based upon material properties) and practial (operation) values. It must be considered that the practical value is only around 25% of ist respective theoretical value. There are three major factors that explain the difference between the values. First of all, inert, passive components add up to the weight and volume of the system without contributing in the active transduction process. Secondly, the decomposition of electrolyte can lead to the formation of a thin layer on the electrode (particularly the anode). This so-called solid-electrolyte interphase (SEI), which usually forms during the first cycle, leads to a limited utilization of active mass. At last, the internal resistance needs to be considered. In addition, operating factors may have an influence on the ultimately achievable practical energy density. (cf. Huggins, 2009; Winter & Brodd, 2004; Hayner, et al., 2012)

As mentioned in the beginning, the second most discussed performance parameter, besides the energy content, is the power of a battery (system), which i measured in Watt (W). Power can be understood as an expression of rate capability, and accordingly the availibility of power peaks. (cf. Winter & Brodd, 2004; Peters, et al., 2013) As the stored energy, the attainable power should be optimized against the weight (specific power or gravimetric power density in W/kg) and the volume (volumetric power density in W/l) on cell and system level. The power density particularly determines the accomplishable accelaration behaviour (maximum and acceleraion speed) of the vehicle. (cf. Hayner, et al., 2012; Huggins, 2009; Gaines & Cuenca, 2000; Thielmann, et al., 2010; Winter & Brodd, 2004; Kaiser, et al., 2008) In comparison to the stored energy, which is highly dependant on the active material, the attainable power is much depandant on the proportion of supporting materials, as the current collector or separator (among others), that allow a fast delivery of the energy content. (cf. Majeau-Bettez, et al., 2011a)

Both, energy density and power density are key-parameters for mobile applications, however, they "(…) *cannot reach their maximum performance simultanously*" (Kaiser, et al., 2008, p.31). According to Majeau-Bettez, et al. (2011a, p.4549),

> there is „(...) *a fundamental trade-off between* [the two parameters that] *dominates battery engineering*[:] *A battery with maximum active material content will hold the most energy but will not be able to deliver it as fast as a battery with a higher proportion of 'supporting material'*(…)".

Reasonable compromises are necessary, respectively prioritization according to the target application. (cf. Angerer, et al., 2009) As HEVs generally make use of the battery to assist accelaration or start-up, a high power density of its' battery is required to quickly respond to stort-term power peak demands. Additionally, an internal recharge system is stipulated why the realizable range is of minor importance, hence, trade-offs regarding optimal energy densities can be accepted. In turn, for BEVs (and PHEVs), which use the battery as their primary energy source, the realizable range is a critical success factor. Accordingly, an optimal energy density of their battery is prioritized over an optimal power density. (cf. Pollet, et al., 2012; Majeau-Bettez, et al., 2011a; Gaines & Cuenca, 2000)

Besides energy and power density, and its underlying parameters, there are other important (linked) factors that influence and guide R&D activities, among them:

- Cycling behaviour and life span (cycle life and calendric life)
- Cost

- Safety
- Self-discharge
- Charge and discharge rate
- Surrounding requirements
- Maintanance and conveniance
- Environmental impact and recyclability

Source: compare Annex A-3.

The life span of a battery is an important factor that is linked to many of the other parameters. It can have a substantial impact on the cost, maintanence and conveniance, and it is particularly important with regard to environmental impacts (e.g. with regard to replacements and disposal) and End-of-Life (EoL) recycling. Cycle life refers to the number of charge and discharge processes that can be reached before the performance of the battery has decreased below the as ‘useful’ accepted level (today usually below 80% of initial capacity). (cf. Huggins, 2009)

Therefore it needs to be noted that batteries are “(…) *analogous to leaking tanks; they lose part of their content in the process of storing and delivering it*” (Majeau-Bettez, et al., 2011a, p.4549). Thus, a serious challenge of R&D is to optimize the cycling behaviour, i.e. to maximize the cycle number in which no property losses occur. This use-phase efficiency, usually expressed in Coulombic-efficiency, as “(…) *the fraction of the prior charge capacity that is available during the following discharge*“, depends on many factors. The depths of discharge is one factor. Different battery technologies, respectively battery chemistries, may react differently sentitive to this factor. (Majeau-Bettez, et al., 2011a, p.4549)

Costs and safety are also two very critical parameters. Safety, especially with regard to e-mobility applications, is an exclusion criterion. Especially the consequences of battery damage in crash situations belong to the necessary considerations. (cf. Peters, et al., 2013; Hayner, et al., 2012) The ecnomics are naturally of concern. The influence of cost aspects is often overriding compared to the other rather technical performance parameters. (cf. Huggins, 2009)

Environmental impacts and recyclability unfortunately seem to play a subordinate role. In most listings of the (most important) performance parameters and/or drivers for R&D, both aspects were not included. (cf. Annex A-3)

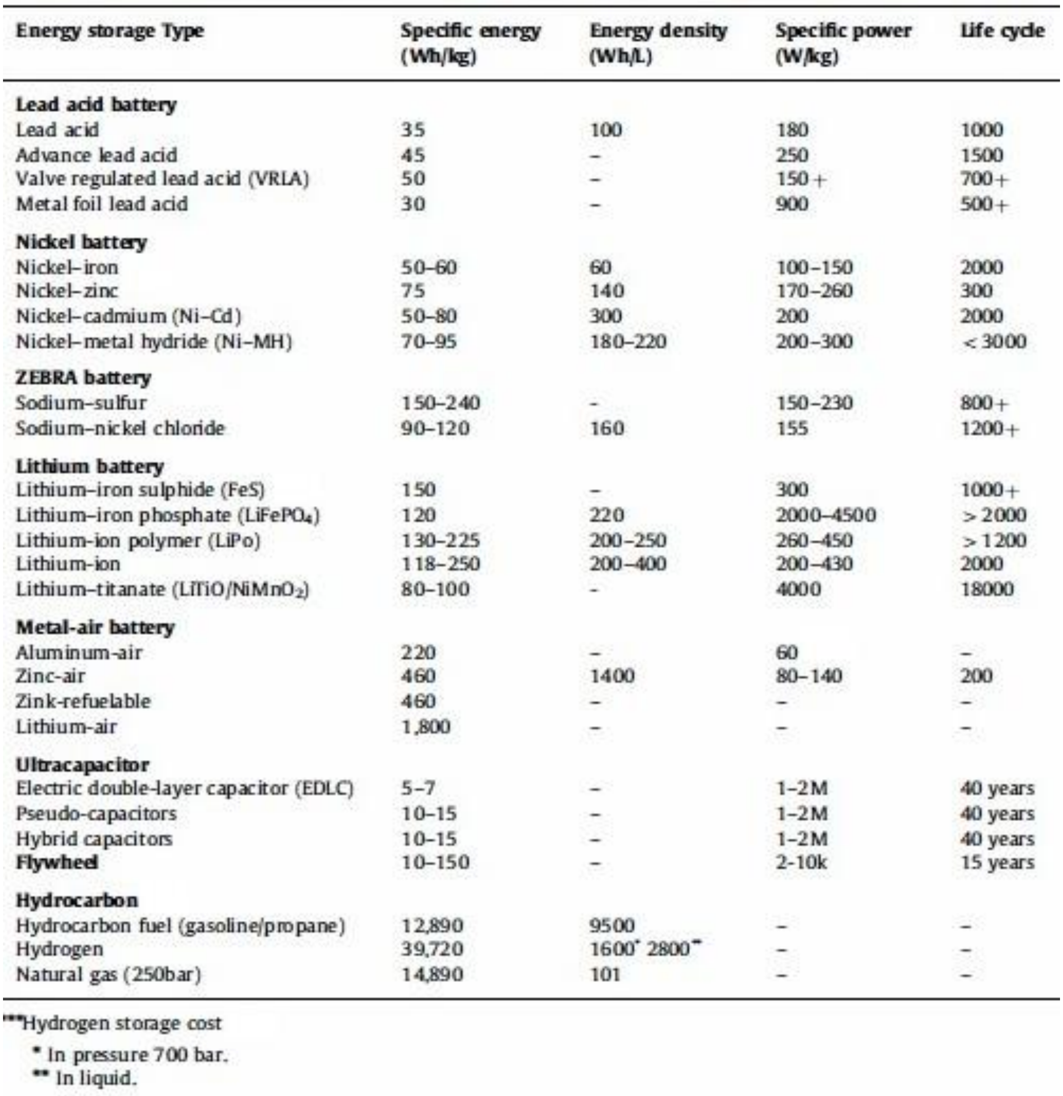
5.4 State of the Art battery technologies

The field of battery technology is a very dynamic one, driven by a number of factors. On one hand, there is an increasing demand in batteries originating from the field of portable consumer electronics. Also, batteries are increasingly required as backup energy sources e.g. for large database systems. On the other hand batteries are gaining interest with regard to future sustainable technologies, both for stationary (storage of renewable energies) and mobile use (e-mobility). Thereby, environmental as well as economic considerations constitute driving forces, e.g. with regard to the limited availability of fossil fuels. Besides these general drivers, the requirements of the different applications themselves are constantly putting incentives to the development of ‘better’ and more economic devices and systems. (cf. Huggins, 2009) General requirements for the application of batteries in the field of e-mobility have been discussed in the previous chapter. In recent years, requirements for traction batteries have been one of the greatest drivers for R&D, since current technologies are facing various limitations, particularly regarding the specific energy and costs. (cf. Gerssen-Gondelach & Faaij, 2012; Huggins, 2009) According to Peters, et al. (2013, p.102f), patent applications for battery technologies have been continuously rising between 1994 and 2008 and started to accelerate their upward trend in 2009. While Japan is still leading battery development activity, with around 40% of global patent applications, Germany has positioned itself among the leading countries with around 10% of global patent applications in the group of battery and fuel cell technologies.

The high rate of R&D activities has already led to important technological changes. “*A number of these have not just been incremental improvements in already-known areas, but involve the use of new concepts, new materials and new approaches*” (Huggins, 2009, p.x). More and more people from different scientific backgrounds are drawn into the area of battery R&D, contributing to the increasing dynamics.

The battery chemistries that have been most discussed for the field of e-mobility are lithium-ion (Li-ion), lithium-polymer (Li-poly), nickel-metal-hydride (NiMH), lead-acid (PbA), zinc air, and sodium-nickel-chloride (ZEBRA). (cf. Hawkins, et al., 2012; Gerssen-Gondelach & Faaij, 2012; Tie & Tan, 2013) provide an overview on five battery groups, with their respective specifications, that “(...) *are* *available in the market* [and,] *which are suitable for road transportation application*“ (cf. Table 6).

Table 6: Comparison of energy storage specifications based on type of energy storage device



Energy storage Type	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life cycle
Lead acid battery				
Lead acid	35	100	180	1000
Advance lead acid	45	–	250	1500
Valve regulated lead acid (VRLA)	50	–	150 +	700+
Metal foil lead acid	30	–	900	500+
Nickel battery				
Nickel–iron	50–60	60	100–150	2000
Nickel–zinc	75	140	170–260	300
Nickel–cadmium (Ni–Cd)	50–80	300	200	2000
Nickel–metal hydride (Ni–MH)	70–95	180–220	200–300	< 3000
ZEBRA battery				
Sodium–sulfur	150–240	-	150–230	800+
Sodium–nickel chloride	90–120	160	155	1200+
Lithium battery				
Lithium–iron sulphide (FeS)	150	–	300	1000+
Lithium–iron phosphate ($LiFePO_4$)	120	220	2000–4500	> 2000
Lithium-ion polymer (LiPo)	130–225	200–250	260–450	> 1200
Lithium-ion	118–250	200–400	200–430	2000
Lithium–titanate ($LiTiO/NiMnO_2$)	80–100	-	4000	18000
Metal-air battery				
Aluminum-air	220	–	60	–
Zinc-air	460	1400	80–140	200
Zink-refuelable	460	–	–	–
Lithium-air	1,800	–	–	–
Ultracapacitor				
Electric double-layer capacitor (EDLC)	5–7	–	1–2M	40 years
Pseudo-capacitors	10–15	–	1–2M	40 years
Hybrid capacitors	10–15	–	1–2M	40 years
Flywheel	10–150	–	2-10k	15 years
Hydrocarbon				
Hydrocarbon fuel (gasoline/propane)	12,890	9500	–	–
Hydrogen	39,720	1600* 2800**	–	–
Natural gas (250bar)	14,890	101	–	–

***Hydrogen storage cost

* In pressure 700 bar.

** In liquid.

Source: Tie & Tan, 2013, p.90.

Lead-acid batteries are the ‘oldest’ battery technology. They “*use lead as negative electrode (anode) and lead dioxide as positive electrode (cathode)*” (Gerssen-Gondelach & Faaij, 2012, p.114). The advantages of these batteries are their save and maintanence free operation and their relatively low cost. However, compared to other battery groups, their energy density and specific energy is relatively low, which limits their application in EVs to rather low speed vehicles or HEVs with lower degrees of hybridization. In the future, they are not considered a feasible alternative for the electric powertrain, at least in the European Union, especially since their technical potential is regarded as exhausted, which is why no further enhancements that could also meet BEVs (and PHEVs) requirements are expected. (cf. Peters, et al., 2013; Gerssen-Gondelach & Faaij, 2012)

Among the Nickel-based batteries, NiMH batteries have been most attractive for application in EVs, especially in hybrid vehicle concepts. Most current HEVs (more than 95%) rely on this type of battery. Particularly in the past, they have shown relative safety advantages compared to other technologies. (cf. Pollet, et al., 2012, p.237; Majeau-Bettez, et al., 2011a; Thielmann, et al., 2010; Gerssen-Gondelach & Faaij, 2012) NiMH batteries are "(…) *based on the release and absorption of hydrogen* (…) *by a nickel oxide anode and a metal-hydride cathode*" (Gerssen-Gondelach & Faaij, 2012, p.114). In addition to its good safety characteristic, NiMH batteries are flexible in terms of capacity, require low maintanence and are regarded as environmentally acceptable. (cf. Pollet, et al., 2012) Even though they are expected to continue competing with other battery types within the automotive industry, they are expected to be outrun by other technologies in the long-term since their specific energy is regarded as too low for BEV (and PHEV) application. In addition, these batteries are irreversibly sensitive to wrong handling (e.g. overcharge and deep discharge) and show significant limitations with regard to their operating temperature. Moreover, the relatively extensive use of nickel might hinder cost reduction targets with view on rising nickel prices. (cf. Peters, et al., 2013; Majeau-Bettez, et al., 2011a; Thielmann, et al., 2010; Gerssen-Gondelach & Faaij, 2012)

Among the sodium-based (ZEBRA) batteries, only the most common Sodium-Nickel-Chloride battery is seriously being considered for EV application, since the Sodium-sulfur battery suffers from substantial safety issues. The anode of the Sodium-Nickel-Chloride battery consists of molten sodium, which is paired with a nickel chloride cathode. (Gerssen-Gondelach & Faaij, 2012). This battery is attractive for EV application due to its uncritical energy management and a low dependance on the ambient temperature. Furthermore, it does not suffer from the so-called memory-effect[9]. However, sodium-based batteries require a high

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[9] Memory effect = loss of capacity owed to recharge before being fully discharged: the state of capacity is being memorized so that on recharge the nominal capacity is not being reached anymore. (Lipinski, et al., 2014)

internal operating temperature between 300 and 350°C (Gerssen-Gondelach & Faaij, 2012, p.114), which is why their application is rather limited to EVs of frequent use, e.g. for public transport. The relatively low specific energy and power constitute a further barrier for a more widespread use in BEVs. Therefore, a "*substantial redesign of the cells or even radical changes in chemistry*" would be necessary. Provided there will be improvements regarding the specific power, these batteries could remain a feasible option for HEVs. (Gerssen-Gondelach & Faaij, 2012, p.116).

The first generations of lithium-based batteries, Li-Ion batteries, are already being applied in EVs. (cf. Scrosati & Garche, 2010)

"*Li-ion batteries have electrodes that intercalate lithium, i.e. the electrode materials are a host structure for lithium ions*" (Gerssen-Gondelach & Faaij, 2012, p.114).

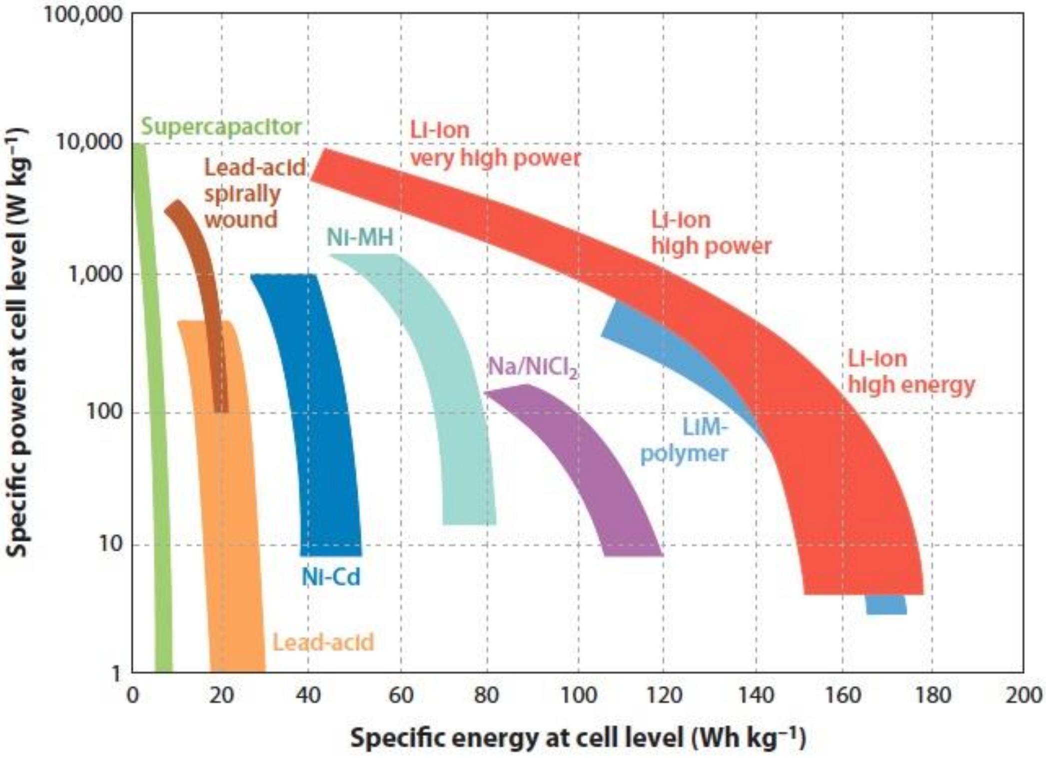
Li-ion technology is particularly convincing with regard to energy and power density, being superior to most other currently known, respectively established, battery technologies, as illustrated in Figure 9 (next page). Hence, Li-ion technology is currently considered the best available technology, realizing acceptable ranges for BEVs and PHEVs. They are regarded as most promising 'forerunner technology' that will pave the way for a widespread implementation of EVs, in particular BEVs and PHEVs, in the short- and medium term. Already today, most new EVs make use of this battery type. (Thielmann, et al., 2012b; Majeau-Bettez, et al., 2011a; Notter, et al., 2010a; Peters, et al., 2013; Brandl, et al., 2012; Notter, et al., 2010a) Dr. Peter Birke of *Continental Batteriesysteme* (in: Thielmann, et al., 2010, p.18) states, that it will be difficult to find serious alternatives for Li-ion technology until 2020 since the Li-ion electrochemical system is too distinguished in its position.

Batteries that pair a lithium metal (or a lithiated carbon) anode with a lithium intercalation cathode are in principle considered to best meet EVs requirements.

Besides, Li-ion technology has still not reached a comparable level of technological maturity as for example the lead-acid technology, which is why there is still potential (and in fact the necessity) for important technological enhancements. (cf. Peters, et al., 2013; Majeau-Bettez, et al., 2011a) According to Scrosati & Garche (2010, p.2429) this disposition to innovation "(…) *will place it in top position as the battery of the future*". Dr. Reinhard Mörtel from the

Fraunhofer Institut für Siliziumtechnologie (in: Thielmann, et al., 2010, p.5) is also expecting numerous technological developments after 2015-2025 that could establish the Li-ion battery as standard energy storage technology.

Figure 9: Comparison of energy and power densities of different rechargeable battery technologies



Source: IEA 2011 in: Hayner, Zhao, & Kung, 2012, p.445.

Accordingly, R&D of lithium based batteries follows two general patterns: on one hand known battery technologies are optimized in terms of energy and power density, while on the other hand new technologies are explored that are (in part) increasingly veering away from the originally established lithium-ion accumulator; this way hoping for significant improvements with regard to the performance parameters. (cf. Peters, et al., 2013)

High voltage Li-ion (5V) batteries, for example, are an evolutionary further development of current Li-ion batteries , which are envisaged to be applied for e-mobility in the mid-term. (cf. Thielmann, et al., 2010; 2012b)

Among the lithium-based batteries that differ from the general Li-ion technology are for example lithium-air, ithium-sulfur (Li/S), and lithium-metal-polymer (LMP) batteries.

"*In lithium-air batteries lithium is applied as anode material and oxygen from ambient air acts as cathode material*" (Gerssen-Gondelach & Faaij, 2012, p.114). This technology is expected to overcome the limitations with regard to specific storage capacities and energy densities that present Li-ion technology is facing. However, there are still a number of technical challenges that need to be overcome and still require considerable work. (cf. Gerssen-Gondelach & Faaij, 2012; Hayner, et al., 2012; Peters, et al., 2013; Scrosati & Garche, 2010) There are substantial difficulties in "(…) *mastering lithium metal and oxygen electrodes in an efficient, rechargeable and safe battery configuration*" (Scrosati & Garche, 2010, p.2428). Lithium-air batteries are thus not expected to become market-ready before 2030. (cf. Thielmann, et al., 2012a, p.6f)

Lithium-sulfur (Li/S) batteries are considered as promising, as well. They are expected to reach an even higher specific energy than both Li-ion and Li-air technologies. In Li/S batteries a compound of sulfur and carbon as cathode material is typically paired with a metallic lithium anode, even though other anode materials are possible, too. Even though there has been a lot of R&D activity regarding this technology, with some promising results, R&D is „(...) *still far from making real breakthroughs in the Li/S battery system*" (Scrosati & Garche, 2010, p.2429). Upon using the highly reactive lithium metal, safety is one of the major issues. Cycle life and the impacts of trade-offs from an enhanced specific energy are further challenges. Hence, Li/S battery systems are only expected to become relevant for EV application after 2020. (cf. Thielmann, et al., 2012a, p.6f; Gerssen-Gondelach & Faaij, 2012, p.116)

Lithium-metal-polymer (LMP) batteries are actually very close to Li-ion technology. Instead of a lithium intercalation anode material, lithium metal is used. While they reach a higher specific energy than Li-ion, drawbacks concerning the specific power are still challenging R&D. Additionally, cycle life still needs to be optimized, which is why LMP will not be relevant before 2020. (cf. Gerssen-Gondelach & Faaij, 2012; Thielmann, et al., 2012b)

Other than lithium-based batteries are not expected to appear as competition before 2030. (cf. Thielmann, et al., 2010; 2012b) One concept that should be be mentioned is the zinc-air (Zn-air) battery. As the lithium-air battery it makes part of the metal-air battery group, which is in fact *"(...) a hybrid form of battery and* *fuel cell* (…)" (Winter & Brodd, 2004, p.4247). Besides lithium and zinc, other metals as e.g. aluminium and iron, can be used as well. However, zinc-air has been the most promising prototype. It has been given the most attention since its "(…) *stage of development is significantly ahead of other types, and it is believed, that they could reach the cost level required for BEVs*" (Gerssen-Gondelach & Faaij, 2012, p. 114, also cf. Scrosati & Garche, 2010). Zn-air batteries face similar challenges as the one stated for lithium-air batteries above. Nevertheless, they have one major advantage compared to lithium-air systems: risks with view on their safety are rather believd to be low. (cf. Gerssen-Gondelach & Faaij, 2012)

Alltogether it should be noted that in general there is still the need o enhance or develop battery technologies, especially in order to make BEVs and PHEVs price and performance competitive. A systematic sequence of development paths for material combinations of cell components is not identifiable so far. Instead, technological development currently appears to be rather open in terms of a 2-way-strategy including li-Ion- and post-lithium-ion-technologies. For those technologies currently under development, the industry expects delays of additional 5 to 10 years – from the point at which the technology is considered as market-ready – before it is actually implemented in electric vehicles. This is why most technologies currently under development are not expected to become commercially available before a few years from now; most of them not before 2020 and some even well after 2030. (cf. Thielmann, et al, 2012b, p.2; 2010; Huggins, 2009; Peters, et al., 2013, p.34f) Even though excluded from this study, it should be noted that besides Li-ion technology, fuel-cell technology should be considered (as complementary) in the mid-term. (cf. Thielmann, et al, 2012b)

5.5 Li-ion Technology

As concluded in the previous chapter, Li-ion technology can be considered as the most prominent state-of-the-art battery technology for EV application, particularly BEVs and PHEVs. Especially for the introduction and market penetration of e-mobility Li-ion batteries are considered to be the key-technology. (cf. Thielmann, et al., 2010; Konietzko & Gernuks, 2011) As it has been shown in Figure 9 (p.55), they show the highest combination of energy and power densities among rechargeable batteries. This is particularly owed to the favourable characteristics of lithium, which as the lightest of all metals, allows the greatest electrochemical potential. Additionally, they show relative advantages in terms of cost, recharge rate, weight, maintanence, self-discharge and cycling life. Also, Li-ion batteries do not suffer from a memory-effect. (cf. Hayner, et al., 2012; Angerer, et al., 2009; Notter, et al., 2010a; Scrosati & Garche, 2010)

The development of Li-ion batteries was a quantum leap within battery technology. The fist rechargeable exemplar was commercialized by Sony in 1991. Since then, Li-ion batteries have been primarily used for consumer electronics; a segment, in which the technology has become very well established. (cf. Hayner, et al., 2012; Scrosati & Garche, 2010; Thielmann, et al., 2012a) More recently, "*the evolution of these batteries has been pushed to* [also] *meet demands of the automotive industry*" (Scrosati & Garche, 2010, p. 2429). The current market development shows high dynamics, and high growth rates –above average– are expected with regard to their application in EVs. (cf. Angerer, et al., 2009; Roskill, 2013; Notter, et al., 2010a; Gerssen-Gondelach & Faaij, 2012; Wagner, et al., 2013) In 2020, application of Li-Ion for e-mobility could make up for a share of 50-70% of all applications. (cf. Thielmann, et al., 2012a, p.9)

In general, Li-ion technology still leaves a wide range of possibilities for the choice of materials, as it, in contrast to most other electrochemical systems, "(…) *allows a variation of combinations of different cell materials*" (Brandl, et al., 2012, p.971). Thus with view on the still existing drawbacks and challenges of Li-ion technology, there is and has been a lot of R&D activity dedictaed to the major components of the Li-ion battery system: the anode, the cathode and the electrolyte. In other words, "(...) *several different Li-ion chemistries are being developed in parallel*" (Majeau-Bettez, et al., 2011a, p.4549) The choice of material for the three main components and their combination are decisive for the overall performance of the Li-ion battery. So far, innovations have usually been based on one component at a time with no simultaneous changes of the other components, thus keeping the conventional Li-ion structure. The pursued improvements, particualry for EV applications, do concentrate on safety, cycle life, cost, operational temperature range and energy densities. Material availability is also one of the concerns, respectively aspects that influence R&D. Large investments are thus channeled into R&D activites in numerous countries, which is also reflected in a high patent activity. (cf. Hayner, et al., 2012; Wagner, et al., 2013; Scrosati & Garche, 2010) Which Li-system will ultimately be dominant with view on applications in the field of traction is not clearly foreseeable yet. (Angerer, et al., 2009) Nevertheless, short- and mid-term tendencies for each of the three main components can be observed.

5.5.1 Anode (negative electrode)

In most current Li-ion batteries, graphite (a carbonaceous material with a highly ordered, layered structure) is used as material for the negative electrode. It has actually been used since Sony's first Li-ion battery was launched in 1991. The persistent use of graphite is owed to ist various relative advantages. First of all, it is an economic material that is abundant in nature, and easy to handle. Secondly, as anode material it offers good cycling stability and safety characteristics. Furthermore, it is of light weight, non-toxic and environmentally sound. (cf. Gaines & Cuenca, 2000; Scrosati & Garche, 2010; Scrosati, 2000; Wagner, et al., 2013; Hayner, et al., 2012; Battery Blog , 2010) However, using graphite as anode material, there are drawbacks as well, one of them being a rather low theoretical specific charge capacity. This value is tapped and thus the potential for further enhancements is restricted. Addtionally, lithiated graphite electrodes suffer from an extensive formation of SEI during the first cycle, causing irreversible capacity losses. (Wagner, et al., 2013; Battery Blog , 2010)

Recently, there have been a lot of R&D activities directed towards the exploration of alternative materials that enhance the specific capacity, the charge/discharge rate and the electrode stability. "*Candidates for next-generation anode materials include insertion alloys* (…), [transition] *metal oxides, and carbon allotropes* (…)" (Hayner, et al., 2012, p.450).

Before the first commercial Li-ion battery came to the market, lithium metal was considered as a promising candidate for the anode material due to its outstanding electrochemical properties as the lightest of all metals, offering high specific charges. In addition, lithium metal is also the most electronegative metal, which "(…) *leads to maximum cell voltage, when lithium metal is used in conjunction with any positive electrode* [cathode] *material*" (Wagner, et al., 2013, p.489). However, due to severe drawbacks with regard to safety, cycle life, and a necessary oversizing of the anode –which negatively impacts the gravimetric energy density – batteries using lithium metal as anode material are not expected to mature before 2020. (cf. Peters, et al, 2013; Wagner, et al., 2013)

Meanwhile, insertion or respectively lithium metal alloys have been found to be particualrly attractive since they allow the highest possible energy densities for Li-ion batteries, so far, significantly exceeding those of graphite anodes. Among the various possible Li-alloy elements, tin, and especially silicon are receiving the most attention. Silicon alloys allow the highest gravimetric energy density among the Li-alloy elements. As graphite, silicon is also considered to be economic, abundant in nature and environmentally sound. Nevertheless, there has not been a commercial breakthrough yet due the extensive material expansion and contraction during the intercalation process of Lithium ions. This causes severe continous mechanical stress with serious consequences for the morphology of the active material, accelerating its detoriation limiting both the calendric and cycle life of the battery. Modifications to improve the cycle stability, e.g. by using nanostructured configuations, are under development. (cf. Hayner, et al., 2012; Scrosati & Garche, 2010; Wagner, et al., 2013) However, Scrosati (2000, p.2462) concludes that "*even if improvement* [is] *obtained by controlling the morphology and the metallurgical structure of the alloys, the cycling behaviour is still unsatisfactory*".

Besides the insertion alloys, (transition) metal oxides constitute a further group of alternative anode materials. The most prominent and attractive ones, are titanites. In contrast to the insertion alloys, these anodes do not suffer from momentous volume variations during the intercalation process, which makes the less susceptible to detoriation. The greatest advantage, however, of LTO anodes is the absence of SEI formation. Other characteristics that raises the interest in this active material are, among others, a high charge/discharge rate, its possible operation even at low temperatures and high thermal stability. (cf. Hayner, et al., 2012; Scrosati & Garche, 2010; Wagner, et al., 2013) Nevertheless, according to Hayner, et al. (2012, p. 453)

> "*the theoretical capacity of LTO is (...) less than half of the theoretical capacity of graphite* [, which combined with its relatively lower operating voltage] *makes this material almost irrelevant for the high energy density batteries required for EV application*".

Other anode material alternatives include carbonaceous materials with structures that differ from those of graphite, i.e. non-graphitic carbon with disordered structures, that allow the intercalation of more ions per six carbon atoms (hexagon), thus enhancing the anode's capacity. (cf. Wagner, et al., 2013; Hayner, et al., 2012; Gaines & Cuenca, 2000) Carbon allotropes as for example graphene, have been found to be attractive. Graphene offers a great conductivity and robustness, and it is chemically stable. Nevertheless, the significant generation of SEI during the first cycle causes severe capacity losses. (cf. Hayner, et al., 2012; Scrosati, 2000)

In conclusion, it is likely that graphite will eventually loose importance within the next years, while the importance of silicon, metal alloys and graphene will increase. In the near future, however, experts agree that graphite will remain the the most relevant anode-material of choice. (cf. Ziemann, et al., 2014; Wagner, et al., 2013; Scrosati, 2000)

5.5.2 Cathode (positive electrode)

In order to obtain overall high operating voltages as well as energy and power densities for the battery, the anode must be paired cathode of high voltage and specific charge. (cf. Scrosati, 2000; Wagner, et al., 2013)

While for the anode, materials with high storage-capacities are known to exist, cathode materials, "(…) *the comparatively low storage capacity of most known cathode materials has been recognized as a major limiting factor in the overall performance of Li-ion batteries*" (Hayner, et al., 2012, p.455). Additionally, the relatively much higher costs for cathode materials lead to relatively higher R&D activities for cathode materials compared to anode materials. (cf. Gaines & Cuenca, 2000) Various types of cathode materials, with different advantageous and disadvantageous properties are thus being used in and developed for commercial Li-ion batteries. (cf. Notter, et al., 2010a; Gerssen-Gondelach & Faaij, 2012; Brandl, et al., 2012) Thereby, two major categories of cathode materials can be identified: layered compounds and materials with more open structures, respectively concentrating on compounds based on manganese and olivine lithium metal phosphates. (cf. Scrosati & Garche, 2010; Hayner, et al., 2012)

Layered compounds are well suited as cathode materials due to there structure that favours rapid ion intercalation processes. The most common compound, used successfully since the 1990s especially for consumer electronics, is lithium cobalt oxide ($LiCoO_2$). However, $LiCoO_2$ is not relevant for EV applications due to severe safety issues, based on its instability at high temperatures and higher voltages.

Other shortcomings that do as well affect its use in consumer electronics, have led to the proposal and use of new materials – among them the costs, environmental risks and material availability are regarded as decisive. The cobalt is increasingly being replaced by the more economic, abundant and less toxic materials nickel and manganese. (cf. Scrosati, 2000; Wagner, et al., 2013; Hayner, et al., 2012; Peters, et al., 2013)

Both, lithium manganese oxide ($LiMnO_2$) and lithium nickel oxide ($LiNiO_2$), offer higher capacities. However, $LiNiO_2$ is rather difficult to prepare and problems with thermal runaway (poor thermal stability) are often observed. Latter causing even more serious safety issues than $LiCoO_2$, thus being irrelevant for EV application. $LiMnO_2$, too, shows significant shortcomings; upon cycling it tends to change ist structure, lowering the electrode performance. The shortcomings of both alternatives can be controlled by partial substitutions, for example to form compounds of the $Li(Ni_xCo_yM_z)O_2$ type (with M= manganese (Mn) or aluminium (Al)), so-called NMC- and NCA-systems. NCA-systems still face serious challenges, particularly with regard to safety and costs that limit its future applicability and technological progress potential. In turn, NMC-systems with equal amounts of transition metals are already successfully used. (cf. Scrosati, 2000; Hayner, et al., 2012; Peters, et al., 2013; Wagner, et al., 2013) Their "(…) *overall performance is at least equal to or superior to* $LiCoO_2$ *electrodes*" (Wagner, et al., 2013, p.488). Even though cycling stability and rate cpabilities still need to be improved, the future of NMC-systems appear to be promising, based on the annual growth rate of related patent families that was approximately 46% between 2006 and 2010. (cf. Wagner, et al., 2013, p.488f; Scrosati & Garche, 2010)

An equally promising candidate is the three-dimensional spinel prototype lithium manganese oxide ($LiMnO_4$; LMO). For EV application they are particularly attractive due to its relatively easy and low cost production, and most of all do to its good safety properties (thermal stability). (cf. Notter, et al., 2010a; Scrosati & Garche, 2010) Batteries with LMO cathodes were already commercialized in the late 1990s. They were among the first alternatives to $LiCoO_2$ based on their intrinsic cost advantage, even though their specific charge is somewhat lower. In addition, LMO-based Li-ion batteries show a relatively poor cycle life and self-discharge at higher temperatures. These issues are countered with continues research efforts. One recent answer has been the partial substitution of manganese, e.g. with cobalt or nickel – latter, constituting the most common addition. Upon these modifications, voltage, specific charge and cycle stability can be improved, even though the initial capacity might slightly decrease. (cf. Wagner, et al., 2013; Scrosati, 2000)

Open structure compounds constitute the other category of cathode material alternatives. So-called phospho-olivine compounds of the form $LiMPO_4$ – where M may stand, for example, for iron (Fe), manganese (Mn), cobalt (Co), or nickel (Ni) – are found to be attractive cathode materials since the late 1990s. However, "(…) *among them only* [lithium iron phosphate,] *$LiFePO_4$* [(LFP),] *has become one of the most important practical cathode materials*"; other metal phosphates are still at an early stage of development. (Wagner, et al., 2013, p.489; also cf. Scrosati & Garche, 2010; Hayner, et al., 2012; Peters, et al., 2013). According to Brandl, et al. (2012, p.973) LFP is "(…) *one of the preferred technology for automotive applications* (…)" since it offers a good compromise among the most important performance parameters. LFP cathode material is economic, environmentally sound, and economic. It shows an excellent cycling performance and, a reasonable capacity, and most importantly, very good safety characteristics. Nevertheless, its rather low conductivity and voltage limit the rate capability and the specific energy respectively. Based on the relatively low energy densities, LFP-based Li-ion batteries are thus more attractive for smaller EVs or concepts requiring 'less' energy densities. (cf. Scrosati & Garche, 2010; Wagner, et al., 2013)

Based on the cathode material, three different Li-ion battery generations can be identified. The first generation is represented by the standard material $LiCoO_2$, which is considered to be irrelevant for EV application. Most currently, and in the mid-term, used Li-ion batteries use cathodes with improved materials belonging to the second generation. Hence, the second generation embraces (LiNiO2), LFP-cathodes, LMO-cathodes, as well as NCM- and NCA-material systems. In the third generation, high-voltage cathodes (5V) will play in increased role, including e.g. modified spinels and metal phosphates (other than iron). Batteries of the third generation are still under develeopment, which is why they are only considered to have the potential for application in EVs in the medium- to long-term. (cf. Peters, et al, 2013; Ziemann, et al., 2014)

5.5.3 Electrolyte

Besides the electrodes, the choice of the electrolyte is key to the operation and safety of the battery. Its importance and role is often underestimated. For example, the loss of capacity is often a consequence of the formation of the SEI, which in turn is owed to the decomposition of the electrolyte. The two major premises for an adequate electrolyte are a good ionic conductivity, and a high electrochemical stability. (cf. Wagner, et al., 2013; Hayner, et al., 2012; Scrosati & Garche, 2010) "*Most* [Li-ion batteries] *available in the market utilize nonaqueous electrolyte solutions, where lithium salts are dissolved in aprotic organic solvents*" (Wagner, et al., 2013, p.491). These are usually mixtures of a liquid component – e.g. dimethyl carbonate (DMC), diethyl carbonate (DEC), or ethylene carbonate (EC) – with the Li salt containing the li-ions, typically lithium hexafluorophosphate ($LiPF_6$). Additionally, electrolyte additives are used to improve the performance of the battery, for example to improve conductivity and/ or to reduce contaminations. (cf. Wagner, et al., 2013; Hayner, et al., 2012; Gaines & Cuenca, 2000; Peters, et al, 2013) "*Most commonly, $LiPF_6$ solutions in ethylene carbonate (EC) - dimethyl carbonate (DMC) are used for lithium ion battery, commercial fabrication*" (Scrosati, 2000, p.2464). Liquid organic electrolytes do still occupy an exceptional position, as it is reflected in an ongoing patent activity, wherein R&D is particularly focusing on additives. However, R&D is also focusing on the exploration of polymer and other solid electrolytes that could simultaneously function as separator. These R&D activities are particularly driven by the target to improve safety features and the electrochemical stability range, especially with view on next generation (third of Li-ion) high voltage cathodes. For these new generations of anodes and cathodes, new electrolyte systems will be essential. (cf. Wagner, et al., 2013; Peters, et al., 2013; Scrosati, 2000; Hayner, et al., 2012) “*The present electrolyte system is optimized for graphitic anode and $LiCoO_2$ cathode materials*” (Hayner, et al., 2012, p.463). Current $LiPF_6$ - organic carbonate solutions suffer from relatively low electrochemical stability range, steam pressure and flammability, as well as toxicity for the environment. (cf. Scrosati & Garche, 2010)

With regard to polymer electrolytes, gel and pure polymer electrolytes can be distinguished. In both cases, the ionic conductivity is lower compared to organic liquid electrolytes. In the case of gel polymer electrolytes this decrease, however, is not as significant. Batteries that use these electrolytes are already being applied, particualrly in consumer electronics, nevertheless, according to Wagner, et al. (2013) patent activity is rather low.

In contrast, patent activity for solid electrolytes, e.g. ceramics, has been noticably high between 2006 and 2010. Similar to the poylmer electrolytes they are expected to improve safety performance, as well as weight and design flexibility. However, currently there are still two major drawbacks that need further R&D: a high resistance (low ionic conductivity) and a possible lack of interfacial contact with the electrodes. (cf. Scrosati, 2000; Wagner, et al., 2013; Gaines & Cuenca, 2000; Scrosati & Garche, 2010)

6 Battery-related metal flows for the transition to e-mobility

With regard to what has been presented in chapters 3 and 4, it is of major interest to scrutinise resource requirements and flows for the examined battery technologies, which will inherently be associated with a transition to e-mobility, in order to identify major challenges and chances for a sustainable resource management. Hence, in this chapter, a dynamic Material Flow Analysis (MFA) of the most relevant material flows related to state-of-the-art battery technology, based on the previous chapter, will be conducted.

6.1 Limitations

Chapter 5 has shown that Li-ion technology is the dominant technology of choice in the short- and medium term. In turn, the review on Li-ion technology in particular has given in idea of the numerous specific chemistry possibilities, i.e. combinations of the three major components: the electrodes and the electrolyte.

However, it has also been stated that short- and medium term variations and innovations generally focuses on one of the components a time. With regard to the anode materials and the electrolyte, graphite and liquid organic electrolytes respectively, are expected to maintain their dominant position in the short- and medium term. Positive electrode (cathode) materials already offer various possibilities and do to the high R&D dynamics it is not foreseeable which chemistry will be dominant. In addition, the positive electrode is (currently) withal the component with the greatest share of metal use and thus with the greatest impact on metal flows. Consequently it has been found reasonable to consider more than one positive electrode compound for future scenarios, while the previously mentioned, most common anode and electrolyte materials are assumed to be equal for all three resulting battery cells.

Based on the literature review (and data availability) in sub-chapter 5.5, three cathode materials have been found to be promising candidates among the various positive electrode materials:

(1) The phospho-olivine compound lithium-iron-phosphate with an open structure (LFP, $LiFePO_4$)
(2) An NMC-material system with layered structure ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$)
(3) The three-dimensional spinel prototype lithium-manganese-oxide (LMO, $LiMnO_4$)

The anode material, as assumed to be made of graphite, is excluded from the model since, with view on chapter 4, the focus shall lie on the use of special metals, which require particular attention.

The special metals contained in the resulting active materials under consideration are lithium and cobalt. These are two elements whose use in batteries for e-mobility has raised concerns before. Accordingly, they have already been addressed in a several former studies (cf. Konietzko & Gernuks, 2011; Kushnir & Sandén, 2012; Vikström, et al., 2013; Andersson & Råde, 2001; Angerer, et al., 2009b) whose results, respectively conclusions, can thus be compared to the results from this study and be integrated into the final discussion. (cf. Table 7, next page)

Table 7: Choice of cell types, respective components and metal flows

		Cell type 1: **LFP**	Cell type 2: **NMC**	Cell type 3: **LMO**
Positive electrode (cathode)		$LiFePO_4$	$LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$	$LiMnO_4$
Electrolyte		$LiPF_6$ in ethylene carbonate (EC)	$LiPF_6$ in ethylene carbonate (EC)	$LiPF_6$ in ethylene carbonate (EC)
Metal flows	Li	X	X	X
	Co		X	
	Mn		X	X
	Fe	X		

Source: own table.

6.2 Synopsis on lithium and cobalt

6.2.1 Lithium

Lithium (Li) is an element that belongs to the group of alkali metals. It is the lightest of all metals and the one with the lowest density, under standard conditions. In its characteristic as alkali metal it is flammable and highly reactive, which is why in nature it only occurs in compounds and not freely. (cf. Vikström, et al., 2013; Evans, 2014; Wäger, et al., 2010) "*Due to its nuclear instability, lithium is less abundant in the solar system than 25 of the first 32 chemical elements*" (Vikström, et al., 2013, p.253, also cf. Wäger, et al., 2010). It is concentrated in the Earth's crust with an average of 17g per ton of solid rock, while the average concentration of particular rocks vary from 30g per ton (ppm) ingenous rock to 60g lithium per ton (ppm) in sedimentary rock. Lithium is also contained in sea water; average concentration though is much lower compared to solid rocks with approx. 0.18ppm (g/t). (cf. Evans, 2014; Wäger, et al., 2010; Vikström, et al., 2013) The literature states 120 to 150 minerals that contain lithium. Despite this fairly large number of lithium deposits, only a very small portion of these minerals occur frequently, respectively contain significant, i.e. commercially valuable, concentrations. (cf. Wäger, et al., 2010; Vikström, et al., 2013) The most important sources for lithium, especially from technical and economic points of view, are pegmatites and lacustrine evaporites from brines. More recently, rather unusual minerals and brines as hectorite, jadarite, geothermal brines and oilfield brines are also receiving attention. (cf. Evans, 2014; Wäger, et al., 2010) Since resources and reserves are to be considered as dynamic qunatities (cf. sub-chapter 4.2), published estimates vary significantly. Additionally, figures are generally the result of aggregated 'known' deposits, which however, is a vague definition and transparent statements on the included number of deposits is often missing. (cf. Vikström, et al., 2013) Inconsistencies in terminology are still a frequent shortcoming and, particualrly in the case of lithium, the lack of standardized assessment concepts affects estimations: according to Vikström, et al. (2013, p.254) "*for lithium, resource/reserve classifications were typically developed for solid ore deposits*", while "(…) *brine – presently the main lithium source – is a fluid and commonly used definitions can be difficult to apply* (…)". In general terms, it can be observed, that reserves and resources have been increasing with time based on new discoveries (applies to resources) and new projects (applies to reserves). (cf. Vikström, et al., 2013) Table 8 (next page) gives an overview on some of the most recent estimates for lithium reserves and resources.

As mentioned earlier, the most important sources for lithium are pegmatites (approx. 13% of total resources, based on estimates by Kesler, et al., 2013) and brines (approx. 70%). Pegmatites are ingenous rocks that have formed upon late magmatic fluids. The most common lithium-enriched mineral is spodumene, most other lithium enriched minerals are relatively rare and/or have little economic significance. (cf. Evans, 2014; Kesler, et al., 2012) According to Kesler, et al. (2012, 57f) ore grades of 2800ppm lithium as dominant element have been required historically for economic extraction, but as learned in chapter 4, required concentrations may vary dnymacially as technical and economic framework conditions change. Where lithium is not the only metal produced from the ore, lower grades could be accepted.

The currently known deposits (respectively those where data is available) studied by Kesler et al. (2012, p.60) "(...) *have grades of 0.3* [3,000ppm] *to 1.4%* [14,000ppm] *Li* (…)". (cf. Kesler, et al., 2012) In order to produce lithium, respectively lithium products as for example lithium carbonate, from minerals, the ore is generally crushed after mining and gangue is separated from the mineral (e.g. spodumene), typically followed by an acid leaching process. (cf. Evans, 2014)

Table 8: Estimates of lithium reserves and resources from the literature

Source	Reserves (rounded)	Resources (rounded)
Kesler, et al., 2012 (p.1)	-	31.1 Mt
Vikström, et al., 2013 (p.256)	12.1 Mt (min.) 15.0 Mt (as reasonable reference) 37.5 Mt (max.)	34.1 Mt (min.) 95.0 Mt (max.)
USGS (Jaskula) 2014	13.0 Mt	39.5 Mt
Evans, 2014 (p.242)	-	40.0 Mt

Sources: see table.

Continental brines[10] are the preferred and typically dominant source for lithium since the late 1990s, as lithium production from brine is much cheaper than from minerals and lithium contents are generally high (after concentration). Natural concentrations usually range from 170ppm to 1500ppm. (Vikström, et al., 2013, p.254) Just recently, supply from minerals and brines is balancing, due to an increased demand from China. (cf. Wäger, et al., 2010; Jaskula, 2014; Wolfs, 2010) However, in terms of lithium resource, brines bare substantially higher potentials. "*Even the largest pegmatite deposits* (…) *have estimated resources that are similar to only an average brine deposit*" (Kesler, et al., 2012, p.55). Of all lithium deposits assessed and compared by Kesler, et al. (2012, p.55) 69% of the resources where identified at brine deposits and only 13% in pegmatites. Similar conclusions were drawn by Vikström, et al. (2013, p.256) in whose data compilation and analysis of 112 known deposits 62-68% of the resources were identified at brine deposits. Most continental brine deposits are recently "*enclosed* (…) *basins where inflowing surface and sub-surface waters contain modest quantities of lithium* [and other elements that have] *(...) been released from surrounding volcanic rocks as a result of weathering*" (Evans, 2014, p.233). These basins are also often referred to as *salars*. Open lakes are also possible lithium brine sources as they are found for example in China. Salars are particularly (not exclusively) found in the *Puna Plateau*, an are of 400,000km^2 in

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[10] Brine = solution of salt in water.

the central Andean region of South America, covering parts of Argentina, Bolivia and Chile. The most important salar for global lithium supply from brine is the *Salar de Atacama* in Chile covering an area of 3,000km^2 that bears –in some zones– “(…) *unusually high lithium contents of several thousand* (…) *ppm*” and estimated lithium resources of 6.3Mt Li (Kesler, et al, 2012, p.62). In principle, the production of lithium products from continental brine (excluding geothermal and oilfield brines) is based on evaporation and *controlled* precipitation (of unwanted elements) processes by means of solar radiation. This way, concentrated lithium chloride is obtained, which can be further processed, respectively reacted to form lithium (intermediate) products. The specific production methods, however, may vary considerably among deposits, depending on the particular chemical composition of the brine. (cf. Kesler, et al., 2012; Wäger, et al., 2010; Evans, 2014)

With regard to lithium uses, basically two segments can be differentiated: chemical uses and non-chemical (mineral) uses. The major non-chemical use of lithium, which at the same time dominates overall global lithium demand with a market share of 35% in 2013, is the ceramics and glasses sector in which lithia (lithium oxide, Li_2O) is used as additive. The only further significant non-chemical use is in continuous steel casting. Around 200 products are marketed in the sector of chemical lithium uses, among them Li-ion batteries (for vehicle and consumer electronic applications). They constitute the market with the largest growth potential and expected growth rates above average, especially for traction batteries. Already today, they account for the second largest demand of lithium (with 29% in 2013) and the largest demand of lithium chemicals (with 27% in 2010). Other end-uses include lubrication greases (9%), continuous casting mold flux powders (6%), air treatment (5%), polymers (5%), primary aluminium production (1%) and others (10%), with respective shares in overall global lithium demand in 2013. Lithium primary production in 2013 was approximately 35,000 tons, not including figures for the United States of America (USA). Lithium carbonate (Li_2CO_3) is by far the most important lithium product (approx. 42%), followed by lithium hydroxide (LiOH, approx. 14%), while lithium metal is rarely produced (approx. 4%). Lithium carbonate and lithium hydroxide are also the principal chemicals used for Li-ion batteries. (cf. Evans, 2014, p.238f; Jaskula, 2014, p.94f, Kesler, et al, 2012; Angerer, et al., 2009; Roskill, 2013) Annex A-28 shows the approximate development of lithium production in lithium carbonate equivalent (LCE) between 2005 and 2012. LCE is a measure that is often applied for lithium production, since lithium carbonate (Li_2CO_3, approx. 18,787% lithium content), as mentioned above, is the most important lithium intermediate product. (cf. Evans, 2014)

According to the USGS (Jaskula, 2014, p. 94) "*lithium recycling has been insignificant historically* (…)". This is consistent with the findings from the Global Metal Flows working group at the UN IRP who listed, in their status report on metal recycling rates, lithium among those metals with recycling rates below 1% for all three categories assessed: the share of in-use stock ending up in the recycling flow (old scrap recycling rate, OSR), the recycling process efficiency (share of recycling flow reaching the scrap market, RC) and the closed loop recycling quota (share of in-use stock being reused in its prior function, EOL-RR). (IRP, 2011, p.36) However, according to the USGS (Jaskula, 2014) recycling of lithium is increasing particularly owing to its use in Li-ion batteries, with individual projects in place, at very different stages. (cf. for example Kwade & Bärwaldt, 2012; Treffer, 2011; Müller, et al., 2011)

6.2.2 Cobalt

Cobalt (Co) is one of the world's essential[11] elements, belonging to the group of transition metals. In the Periodic table, it appears between iron and nickel in the first long period. As lithium, cobalt is not found in nature in its native form, but rather bonded to other elements. (cf. CDI, 2014; Darton Commodities Ltd, 2014; Roberts & Gunn, 2014; Buchert, et al., 2009) Cobalt is not actually a rare element (in relative terms), considering that it is the "(…) *33rd most abundant element in the Earth's crust*" (Darton Commodities Ltd, 2014), with an estimated concentration of 15 to 30ppm. However, cobalt resources are widely scattered in the crust. Highest average concentrations are particularly found in so-called 'ultramafic'[12] rocks, while sea water concentrations are markedly low, around 10pp*t*. (cf. Darton Commodities Ltd, 2014; Roberts & Gunn, 2014, p.122) Concentrations suitable for mining exclusively cobalt are seldom and since it is usually found in combination with other elements, preferentially with nickel and

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[11] Among all known elements, only 27 are considered as essential to men. (CDI, 2014)

[12] A particular kind of rock that has formed billions of years ago, and thereby enriched magnesium and iron minerals upon numerous transformation processes. (Tabor & Haugerud, 2013)

copper, cobalt is generally mined as a by-product of these bonded elements. Today, approximately 57% of cobalt production is related to nickel production, 37% to copper production (& others, e.g. precious metals), and only 6% of the produced cobalt stems from primary cobalt operations. (cf. Roberts & Gunn, 2014; Buchert, et al., 2009; CDI, 2013) Estimates for cobalt reserves and resources are rarely found. Most studies cite estimations by the USGS, which are annualy updated. In their latest update, 25Mt of cobalt (terrestrial) resources are estimated (>120Mt marine resources) and 7.2Mt of cobalt reserves (Shedd, 2014, p.47).

The most common geological settings for cobalt recovery, according to the USGS, are “(...) *sediment-hosted stratiform copper deposits* (...), *nickel-bearing laterite deposits* (...) *and magmatic nickel-copper sulphide deposits hosted in mafic and ultramafic rocks* (...)“ (Shedd, 2014, p.47) Furthermore, resources in the order of approx. five times the terrestrial resources (see above) have been identified in manganese nodules and crusts, situated at the submarine ground of the Pacific, the Atlantic and the Indian Oceans. Resources of up to 1 billion[13] tons are speculated (hypothetical, unidentified) to exist at these grounds, however, figures with regard to marine resources should be treated with caution since being afflicted with high uncertainties. (cf. Shedd, 2014, p.46; CDI, 2013; Darton Commodities Ltd, 2014) Magmatic nickel-copper sulphide deposits with recoverable cobalt content, typically show concentrations between 400 and 800ppm for cobalt. Nickel-bearing laterite deposits, which embody around 70% of global nickel resources, show cobalt concentrations between 250 and 1800ppm. The extraction, processing and refining methods for cobalt vary according to the sources. Flow sheets generally follow leaching or milling processes of the ore, followed by the production of either a flotation concentrate (hydrometallurgical route) and/or a smelting matte (pyrometallurgical route), and finally a purification step before the cobalt and the other elements are recovered. (cf. Roberts & Gunn, 2014) For magmatic nickel-sulphide ores, generally a hydrometalurgical process is followed by a pyrometallurgical process; thereby, the recovery rates for cobalt from smelters only account for 30-80%, compared to those of nickel and copper that lie well above 90%. In the case of nickel laterites, either hydro- or

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[13] 1 billion = Milliarde in German.

pyrometallurgical techniques are applied, with emphasis on latter techniques. While hydrometallurgical techniques allow for the recovery of cobalt, it is ‘lost’ in the smelters. Similar problems as the ones mentioned, can be observed for cobalt recovery from copper-cobalt ores. (cf. Roberts & Gunn, 2014, p.134-136) The commonly used “(...) *sulfide flotation process is inefficient for cobalt, with recoveries as low as 40 per cent for mixed oxide-sulfide ores*“ (Roberts & Gunn, 2014, p.136) However, alternative improved recovery routes are increasingly being applied. Additionally, projects are being put in place that are aimed to either recover cobalt from tailings and slag stockpiles, i.e. leftovers from inefficient former recovery, or originally uneconomic deposits by means of improved technologies and techniques. (cf. Roberts & Gunn, 2014)

Due to its unique properties, as for example a high melting point, a high strenght-retaining potential at high temperatures, as well as being multivalent and ferromagnetic, cobalt has diverse “*strategic and irreplaceable*“ uses (Darton Commodities Ltd, 2014). Its functional potentials are best tapped when being combined with other metals and it bears catalytic qualities, why ist applications are not always obvious at first sight. In the past decade, applications have changed significantly, though. Especially with view on future sustainable technolgies, cobalt is “(…) *now recognised as important technology enabling metal*“ (CDI, 2014). (also cf. Buchert, et al., 2009) Chemical and metallurgical applications are quite balanced. Cobalt products are particualrly used in batteries, with approx. 38% of all end-uses in 2012 (CDI, 2013, p.56). Note that battery technology driven demand for cobalt has increased substantially in the past years, accounting for only 3% of all end-uses in 1995 (Buchert, et al., 2009, p.45). Other end-uses following battery shares, are super alloys, catalysts, cemented carbide and diamond tool applications, high speed steels and high-strength alloys, pigments in glass, enamels, pottery and china, in medical applications, and electronic connectors. (Robert & Gunn, 2014, pp.140,142) According to the USGS (Shedd, 2014), cobalt mine production in 2012 totalled approx. 103,000t and estimated 120,000t in 2013.

Recycling of cobalt is regarded as widely common, both for pre-consumer recycling and post-consumer recycling with “(…) *focus on rechargeable batteries, spent catalysts but also on alloys*” (Buchert, et al., 2009, p.47). In their report on gobal metal recycling rates the UN IRP states recycling rates of 50% for the share of in-use stock ending up in the recycling flow (old scrap recycling rate, OSR), 32% for the recycling process efficiency (share of recycling flow reaching the scrap market, RC) and 68% for the closed loop recycling quota (share of in-use stock being reused in its prior function, EOL-RR). (IRP, 2011, p.31) It should be noted, however, that this data is based on an USGS analysis for the USA in 1998. (cf. Shedd, 2004) In its current commodity summary on cobalt for 2013, the USGS states that "(…) *cobalt contained in purchased scrap represented an estimated 26% of cobalt reported*" (Shedd, 2014, p.46). For Europe, enhanced recycling flows are expected, with a particular view on re-circulated batteries according to the quotas set by the European Battery Directive from 2006. (cf. Buchert, et al., 2009)

6.3 Approach, system boundaries and basic assumptions

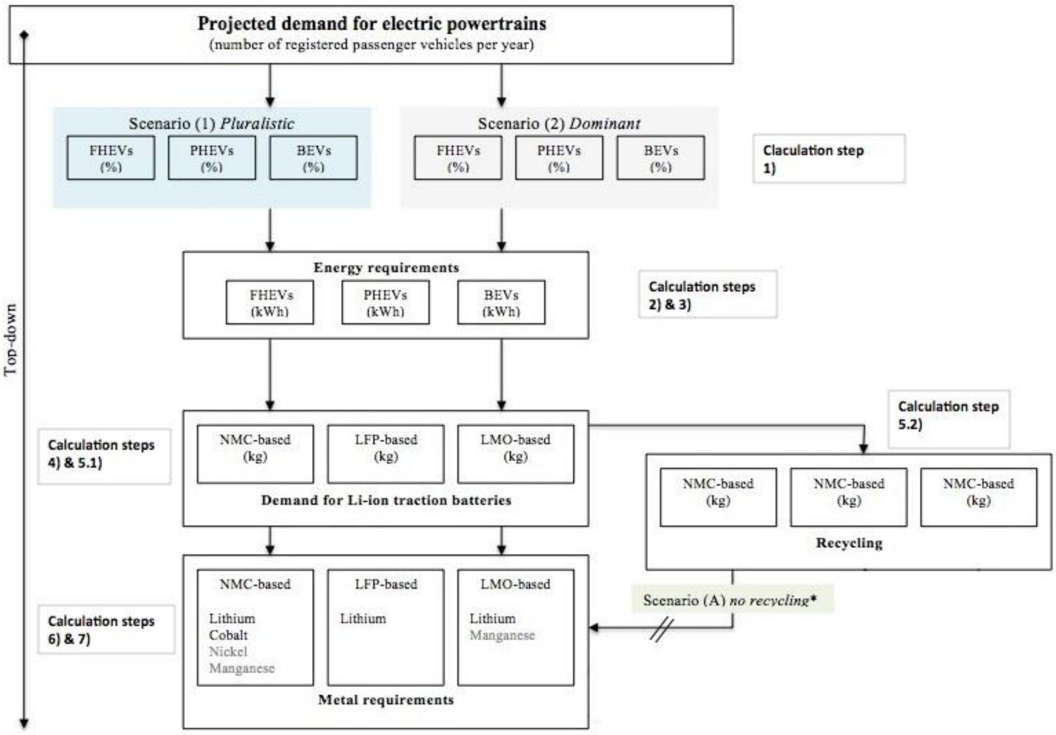
The calculation steps to build up the model for the analysis (data is first prepared in EXCEL) are based on a top-down approach, following a similar approach used by Konietzko & Gernuks (2011), as demonstrated in Figure 10.

Note, that this chapter only serves to give a general overview on the procedure and basic assumptions. A more detailed review of the data and the assumptions is iteratively provided in the next chapters. In order to follow the actual calculation steps also compare Annex A-4 to A-13. The analysis parts from the projected demand for different electric vehicle concepts (ratio of new vehicle registrations), based on two scenarios that were developed for a similar study by the Fraunhofer ISI in 2009 (Angerer, et al., 2009b). The demand-ratios are given in annual terms and at a global scale (system boundary in space). They are transferred into absolute numbers based on 2013 passenger vehicle registrations and an annual growth rate (cf. sub-chapter 6.4.1, also cf. Annex A-6: calculation step 2). With regard to the challenges of a sustainable resource management, particularly metals management, both a global and a regional analysis – for example of Europe – could be of interest. Nevertheless, considering the geological availability of primary resources, the global perspective has been chosen for this analysis. Data availability and quality do also advocate a global scope. With view on the system boundaries in time, the Fraunhofer ISI scenarios project the annual demand until

2050. Hence, flows will be analysed over a period of 36 years, from the present (2014) to 2050.

In a next procedural step, the demand for each considered vehicle concept is transferred from the absolute number of vehicles to the respective annual energy requirements (in kWh/a), by means of the particular energy requirements per vehicle concept (cf. Annex A-3: calculation step 3).

Figure 10: Iterative approach structure of the MFA



* equates recycling potential

Source: own figure, based on Konietzko & Gernuks (2011, p.7)

Subsequently, the annual energy requirements are transformed into the respective battery mass requirements (in kg/a), by means of the material intensity I_B (kg/kWh) for each battery based on a particular cathode type (cf. Annex A-8, A-9: calculation steps 4 and 5.1). Therefore, due to differing performances, different market penetrations for each cathode type and vehicle concept under consideration are assumed.

In order to obtain resource input requirements, inventories from different LCA studies on the three cathode types are used to reconstruct the respective production chain/material flows (cf. Annex A-11: calculation step 6). Production processes and flows, shared among the cathode types are integrated.

With the objective to quantify recycling potentials at certain points in time, respectively material stocks in the anthroposphere, assumptions regarding the useful life of traction batteries and collection efficiency are adopted.

6.4 Data and specific assumptions

The data for the different calculations steps, explained on a general level in the previous sub-chapter, is derived from different sources, then adjusted to the requirements of the analysis and prepared in EXCEL before transferred into the MFA model in the software STAN.

6.4.1 E-mobility scenarios

The choice of adequate e-mobility scenarios is critical to the analysis, since these provide its fundament and thus significantly influence the determination of ultimate mass flows. Several studies on e-mobility market studies and scenarios for different regions and of different vehicle concept coverage have been published since 2007. They have been summarized just recently in an overview by Peters, et al., (2013, p.63f). Five out of the therein 17 (18[14]) listed studies consider e-mobility development on a global scale. Among them, the Fraunhofer ISI scenarios (Angerer, et al., 2009b) are the ones with the most far-reaching forecasting horizon (until 2050). They are based on prior work of the Fraunhofer ISI, by Wietschel & Dallinger (2008) that dealt with e-mobility at national (Germany) level. They were adjusted for global application by Angerer, et al. (2009b) to assess lithium availability. They have also been applied by Konietzko & Gernuks (2011), the study which serves as major reference for the present analysis. Konietzko & Gernuks (2011) have pointed out the advantagous public availability of the data for each projected year as one important decision criteria, which is likewise a decisive precondition for this study (see Annex A-14). Accordingly, the Fraunhofer ISI scenarios are the scenarios of choice for this analysis. On one hand, this choice bears the chance to make results more comparable to the mentioned prior works. At the same time of course, the risk lies in the adoption and continuance of generally mistaken assumptions on the market penentration of e-mobility. This uncertainty, however, cannot be eliminated. Nevertheless, other factors (data) can be adjusted, as it has been done in some

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[14] Instead of the Fraunhofer ISI scenarios from 2009 (Angerer, et al., 2009b), a prior version from 2008 and the renewed 2011 version were listed, while latter has not been published yet.

cases below. The projections of the e-mobility market penentration by Angerer, et al. (2009b) is divided into two scenarios, a Pluralistic Scenario and Dominant Scenario. Both scenarios consider three vehicle concept groups: City-BEVs including mainly passenger vehicles, but also motor scooters and small pick-up trucks (20kWh), Hybrid-electric passenger vehicles (1,4kWh) and Battery-electric passenger vehicles/Plug-In hybrid-electric passenger vehicles (20kWh). In both scnarios, the city-BEVs group plays a minor role, which is why these vehicles are integrated into the third group as it has also been done by Konietzko & Gernuks (2011). The energy requirements chosen by Angerer, et al. (2009b) have been checked against other literature and found to be representative for the group of City-BEVs and BEVs/PHEVs. Tie & Tan (2012, p.89), for example give ranges between 6 and 20kWh for PHEVs and 20 to 40kWh for BEVs. 20kWh for a combined group thus seems to be reasonable. However, for HEVs 1,4kWh appear to neglect slightly higher energy requirements for FHEVs compared to Mild- and Micro Hybrid concepts (cf. sub-chapter 5.2). For FHEVs, Tie & Tan (2012, p.89) state energy requirements between 1,4 and 4kWh, the Toyota Prius FHEV mentioned by Ernst, et al., (2011, p.5872) requires even 5,2kWh. Hence the average energy requirement for the HEV group will be slightly lifted to 2,5kWh, this way representing the entire range of HEV concepts. Accordingly, the scenarios will, in this study, reproduce the following vehicle concepts and energy requirements :

Table 9: Considered vehicle concepts and respective energy requirements

Vehicle concepts	Group 1 HEVs	Group 2 City-BEVs, BEVs and PHEVs
Average energy requirements	2,5kWh	20kWh

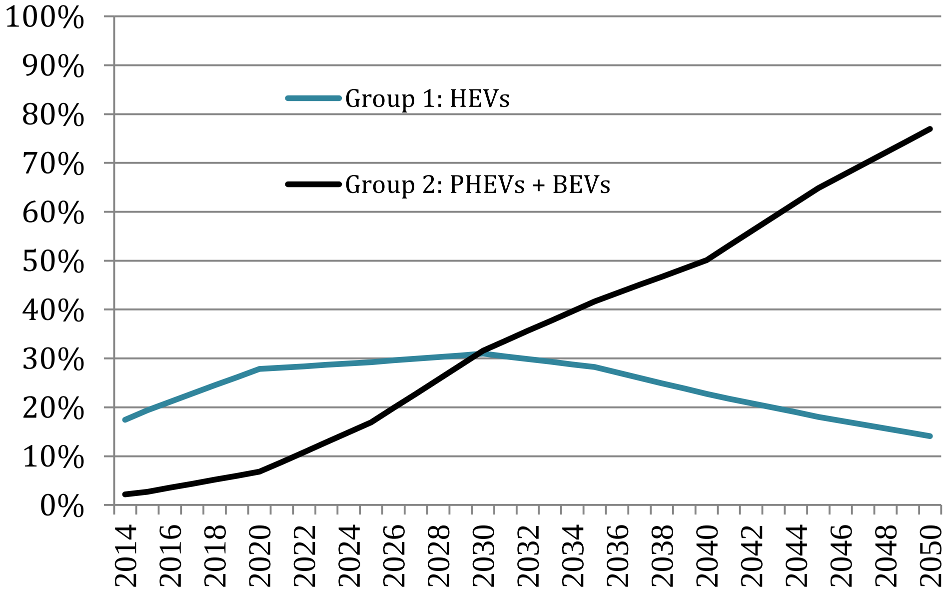
Source: own table based on Angerer, et. al. (2009b); Konietzko & Gernuks (2011); Tie & Tan (2012)

In the very optimistic Dominant Scenario, hybrid concepts will be widely accepted, while electrified vehicles in general will almost entirely replace conventional internal combustion engine vehicles. The emphasis of this scenario lies on the second group. BEVs and PHEVs will continuously gain market shares and replace the HEVs in its market leader position by 2030, as it is illustrated in Figure 11.

The pluralistic scenario represents a more restrictive, moderate market development of e-mobility. In this scenario it is particularly group 1 that is able to gain relevant market shares (cf. Figure 12). The second group can only partially establish itself within the urban commercial transportation sector. For a more detailed list on the underlying assumptions for each scenario refer to Annex A-15. (Angerer, et al., 2009b)

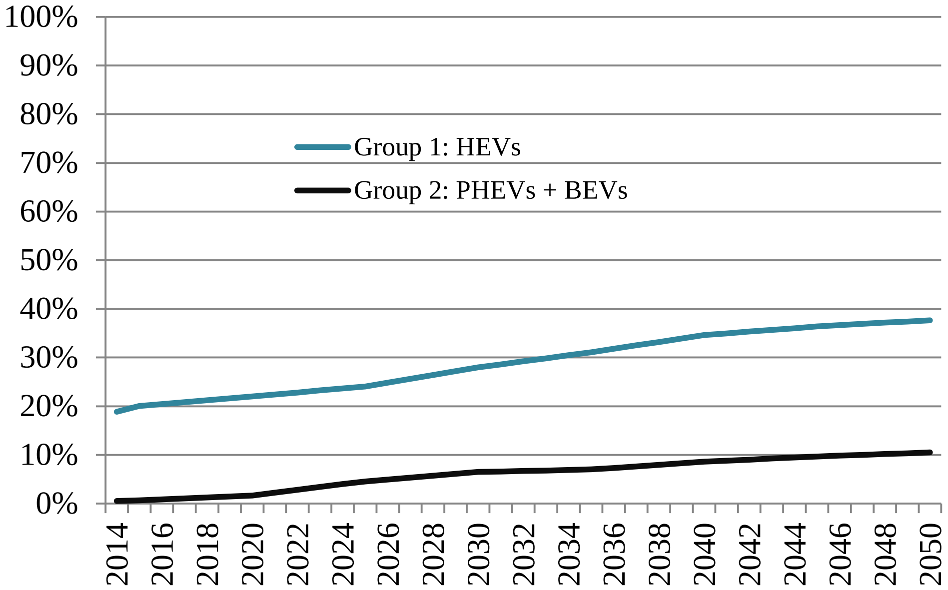
In order to obtain absolute numbers of annual electric vehicle registrations from the ratios provided by Angerer, et al (2009b), annual vehicle registrations were prescribed for the base year 2013, adopting the figure given by statistics of the International Organization of Motor Vehicle Manufacturers. (cf. OICA, 2014) The OICA documented a number of 62,644,460 global passenger vehicle sales or registrations in 2013. Even though Group 2 of the e-mobility scenarios is principally designed to contain also electric motor scooters and small pick-up trucks, it has been argued before that their share is negligibly low, which is why the figure for passenger vehicles only is found to be acceptable. Besides, passenger vehicles represent the greatest vehicle group today and show the highest growth rates. (cf. Peters, et al., 2013; Pavoni & Bernhart, 2012) It shall be mentioned that the chosen *real* figure is only slightly lower than the one forecasted by Konietzko & Gernuks (2011) for 2013: 66,831,428 (a difference of approx. 4 Mio vehicles). For the years 2014 to 2050 an annual growth rate of 2,18%, expected by the World Business Council on Sustainable Development (WBCSD), is adopted. (cf. Fulton & Eads, 2004; Annex A-6: calculation step 2) Its application by Konietzko & Gernuks (2011) has proven its prevailing accuracy so far (see above). Before relating the battery materials with the e-mobility projections, a differentiation of the market penetration of the three considered cathode materials related to the vehicle concept groups is conducted, complementing the differentiation made by Angerer, et al. (2009b) regarding the market penetration of the two different vehicle concept groups. However, for simplification and due to high uncertainties, the market penetration shares of the different cathode types are assumed to be static over the analysed time horizon, i.e. they do not change in time. Again, the respective assumptions made by Konietzko & Gernuks (2011), are adapted, i.e. their assumptions on the market penentration of NMC and LFP cathodes are amended by the addition of the LMO cathode type (cf. Table 10).

Figure 11: E-mobility market penetration as share of annual vehicle registrations: **Dominant Scenario**



Source: own figure based on Angerer, et al. (2009b, Annex A-14)

Figure 12: E-mobility market penetration as share of annual vehicle registrations: **Pluralistic Scenario**



Source: own figure based on Angerer, et al. (2009b, Annex A-14)

The final assumptions for both studies are primarily based on the technical differences of the cathode materials and their state-of-the-art. As LFP provides relatively lower energy densities but higher power densities, it is the preferred cathode material for HEV concepts. Accordingly, its share for FHEV concepts is assumed to be much higher compared to NMC and LMO technologies. LMO is considered to be primarily competing with NMC, while the market share of LMO in general is assumed to be slightly lower than that of both other cathode materials.

Table 10: Assumed cathode material distribution per vehicle concept in per cent

	Group 1		Group 2	
Assumptions by/for	Konietzko & Gernuks	Present analysis	Konietzko & Gernuks	Present analysis
NMC	20%	10%	65%	35%
LFP	80%	80%	35%	35%
LMO	X	10%	X	30%

Source: own table based on Konietzko & Gernuks (2011, p.14)

6.4.2 Battery component specifications

For each battery type, respectively cathode type, an inventory of the relevant material inputs and outputs is gathered from the literature upon which the relevant production processes and flows are reproduced. All three inventories are extracted from LCA studies on particular Li-ion technologies. For the LMO-based battery, the data stems from a study conducted by Notter, et al. (2010a, 2010b). The respective data for NMC- and LFP-based batteries is largely gathered from a study by Majeau-Bettez, et al. (2011a, 2011b) and complemented in part with data from Notter, et al. (2010a, 2010b). Both studies provide the most transparently available data sets on the production chains and flows of differentiated cathode materials. Inputs for particular production processes are either directly provided as percentage of the output or indirectly as mass ratios (kg input per 1kg output), which allows to calculate backwards; parting from a certain battery pack weight to the initial input masses (cf. Annex A-11: calculation steps Prep Calc_6 NMC, LFP, LMO). With view on the Material Flow Model in the software STAN, which requires each process to be mass balanced (input equals output), flows that are of no interest for the present study or that are unknown are considered either as ‘other inputs’ (output>input) or ‘residues and losses’ (input>output).

Unfortunately in most ‘residues and losses’ cases, no further differentiation regarding their composition is possible due to missing data.

In the case of LMO-based batteries, available data – provided by Notter, et al, (2010b) – showed an inconsistency with regard to lithium contents. This became evident in the presented production process of the active electrode material. In order to obtain lithium manganese oxide ($LiMnO_4$), lithium carbonate (Li_2CO_3) is reacted with manganese oxide. For both, the (lithium containing) output, $LiMnO_4$, and the (lithium containing) input, Li_2CO_3, lithium contents can be calculated based on the atomic weight of each contained element. However, adopting the data from Notter, et al. (2010b, p.12), less lithium entered the process than leaving it. Hence, the input mass of lithium carbonate is raised to the extend that its lithium content is equal (minimum condition, assuming no losses) to the lithium content in the output.

In the case of LFP- and NMC-based batteries, the available data was found to be incomplete for a comprehensive model of all three battery types. The process chains – presented by Majeau-Bettez, et al., (2011b) –reached back to the input of lithium hydroxide (LiOH). Thus, data on upstream processes are adopted from Notter, et al. (2010b). In order to connect both partial production chains, lithium carbonate requirements for LiOH production are determined based on the reaction equation and atomic mass shares of the elements (cf. A-13).

With the aforementioned adjustments a combined mass flow model for the production of the three battery types is modelled as displayed in Annex A-16 to A-20. However, in order to be able to relate the battery materials to the annual vehicle registrations respectively the annual energy requirements, it is necessary to determine the material intensity I_B (kg/kWh) for the each battery based on a particular cathode material. The material intensity is crucial when it comes to a critical comparison of different battery technologies (cathode materials) with regard to their resource requirements. Unfortunately, data availability is very poor, which results in high uncertainties. In other words, due to missing primary data, the required figures have to be calculated. The calculation approach is parting from the approach used by Andersson & Råde (2001) who conducted a study on the resource intensity of different battery technologies (different to the ones considered in this study). Based on their approach, in a first step, the material intensity of each active cathode material I_A (kg/kWh) can be calculated from the theoretical specific capacity C (mAh/g) and the theoretical voltage U (V) of the respective active material, as well as

> "(…) *the practical material utilisation, η_m, that is the share of the metal in the practical battery that is actually used in the electrochemical reaction, and the voltage utilisation, η_u, that is the average discharge voltage divided by the theoretical voltage* (…)" (Andersson & Råde, 2001, p.299f).

Hence, the mathematical equation reads as follows:

$$I_A = \frac{1000}{\eta_m \eta_u CU}$$

(Andersson & Råde, 2001, p.299f).

Figures for C and U for each cathode material are given in the literature as listed in Table 11. For C (mAh/g), Doeff (2013) provides ranges that are averaged for this study; this seems acceptable since the ranges are rather small.

Table 11: Theoretical specific capacity and voltage for considered cathode materials

Cathode material	U (V)	C (mAh/g)	*average* C (mAh/g)
NMC	3.8	160-170	165
LFP	3.45	150-170	160
LMO	4.1	100-120	110

Source: own table based on Doeff (2013, p.10).

For the utilisation ratios (η_m and η_u) no specific data for the considered cathode materials is found in the literature. However, the factors for the material utilisation, η_m, of all three Li-ion chemistries considered by Andersson & Råde (2001, p.301) account for 0,5 for the high material intensity case and 0,7-0,8 for the low intensity case, while the voltage utilisation factor, η_u, ranges from 0,9 to 0,95. Thus, for all three Li-ion cathode materials under consideration in this study, an average material utilisation factor of 0,65 and an average voltage utilisation factor of 0,925 are assumed. Accordingly, taking both values into account, the practical specific energy (U x C) is a fraction of approx. 60% of its theoretical value (0,65 x 0,925 = 0,60125/ approx. 60%). The accordingly calculated values for I_A are shown in Table 12. The last missing step is the calculation of the battery material intensity I_B. According to the inventories from Notter, et al., (2010b) and Majeau-Bettez, et al. (2011b), each active material makes up for a certain mass share of 1kg final battery pack. Accordingly, each I_A is divided by its respective mass share to obtain the material intensity of the battery pack, I_B (see Table 12). The values for I_B can now be multiplied with the annual energy requirements, obtaining battery mass flows within the system. (compare Annex X, calculation step 4)

Table 12: Material intensities of active cathode materials

	NMC	LFP	LMO
I_A (kg/kWh)	2,65	3,01	3,69
share in battery	0,202	0,216	0,163
I_B (kg/kWh)	13,14	13,96	22,66

Source: own table based on Notter, et al., (2010b); Majeau-Bettez, et al. (2011b).

Unfortunately, data availability and quality at the substance level was insufficient to reproduce all the material flows contained in the model, especially the flows of the battery production chain. Calculations in STAN can thus solely be conducted at the ‘goods’ layer. However, with the objective to reveal recycling potentials, substance flows for the second half of the model (battery flows) are traced in EXCEL. As the second half of the material flow model provides flows as in terms of ‘tons battery’, average concentrations per ton battery are used (calculated) for lithium and cobalt, based on the chemical composition of the active electrode material and its respective mass shares in the batteries (cf. Table 13, Annex A-23) In the literature, metal concentrations are generally given as g/kWh, which is why the figures given in Table 13 are transformed into metal contents per kWh, based on the material intensity I_A (cf. sub-chapter 6.4.2). Table 14, hence, allows for comparison.

Table 13: Metal concentrations per manufactured kg battery

Cathode-type	LFP	NMC	LMO
Chemical Compound	$LiFePO_4$	$LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$	$LiMnO_4$
Lithium	9,49 g/Kg	14,57 g/kg	8,98 g/kg
Cobalt	X	2,474%	X

Source: own calculations

The here presented metal contents do solely refer to the electrode materials, while the metal demand that is calculated in the MFA model includes lithium requirements for the electrode as well as for the electrolyte. Thereby, the lithium used for the electrolyte makes up for only 5-7% of the total lithium content in the battery, as calculations show. For the projection of recycling potentials (based on the contents in Table 13), the lithium contained in the electrolyte is neglected, since different recycling channels are likely.

Table 14: Lithium and cobalt contents* in g/kWh for different electrode materials

Cathode-type	LFP	NMC	LMO
Lithium	133 g/kWh	191 g/kWh	203 g/kWh
Cobalt	X	325 g/kWh	X

* contents in manufactured battery. Source: own calculations

In comparison to other studies (cf. Annex A-23 and Table 14), the lithium contents in g/kWh appear to be slighty higher but comparable. One reason for higher in-use contents could be owed to the material intensity calculations (cf. sub-chapter 6.4.2) that foresee an average material use of only 60%, but also to a differing consideration of losses among the studies. Note also, that the lithium contents in g/kg are (generally) independent from the battery production chains, i.e. they are calculated independently instead of being retrieved as output from a reproduction of substance flows from the primary input to the use-phase. Hence, there are inconsistencies that cannot be eliminated at this point. For LFP-based batteries the ‘in-use content’ is almost the same as the lithium concentration in the lithium carbonate required for the production of the electrode material. The case of LMO-based batteries is a particular one, since the contents were aligned (cf. sub-chapter 6.4.2). However, in the case of LFP-based batteries there is a difference of 19g, i.e. 19g appear to be lost in the production process of lithium iron phosphate. It cannot be confirmed though that these are actually losses, nor that the LiOH input provided by Majeau-Bettez, et al., (2011b, p.12) should be revised, that the calculated ‘in-use content’ is too optimistic (low), and neither that the correct figures lie somewhere in between.

6.4.3 Recirculation

With the objective to include possible recirculation flows, i.e. end of life (EoL) fates of battery flows and the therein-contained valuable metals, assumptions are made, respectively adopted from prior studies, regarding the useful life of a traction battery, a second-life (reuse) option and their EoL collection efficiency (quota). Concerning the useful life of traction batteries, 10 years are found to be most representative after reviewing the literature. (cf. for example Konietzko, et al., 2011; Brandl, et al., 2012; Evans, 2014; Abraham, et al., 2007, Broussely, et al., 2011) Even though the useful life of the vehicle might exceed that of the battery, replacement flows are not (explicitely) included in the model.

The useful life of a traction battery for automotive application is primarily tied to the battery’s capacity that decreases, based on numerous exo- and endogenous interconnected factors along the batteries life. It commonly accepted that batteries no longer serve the automotive requirements when the capacity falls below 80% of its nominal (initial) capacity. After having reached this threshold value, the capacity losses occur at much higher rates. (cf. for example Konietzko & Gernuks, 2011; Ramoni & Zhang, 2013; Wolfs, 2010)

Nevertheless, spent EV batteries may still offer a storage opportunity for alternative markets (secondary-markets). The use of ‘retired’ EV batteries for grid support, for example, is being considered as one option. Wolfs (2010) who conducted an economic assessment of seconf-life EV batteries for grid-support concludes its economic feasibility especially with regard to small scale applications (e.g. solar rooftop systems). However, he also states that there are still not sufficient studies regarding the technical feasibility, respectively the potential secondary useful life-span. Similarly, Konietzko & Gernuks (2011) assert that potential secondary-life options are still at a conceptual level of developement, and Ramoni & Zhang (2013) point out that there are still numerous issues that require further research before adequate EoL strategies and infrastrcutures, especially with regard to required remanufacturing processes, can be established. Hence, with view on these insights, initially intended reuse flows are discarded for the assed time horizon (until 2050) owing to the high uncertainties combined with an expected low added-value to the informative value of the model and the results.

Regarding the collection efficiency of EoL traction batteries, there is still little knowledge about collection rates, especially on a global level. In this study, a very high, optimistic collection quota of 90% is assumed, for three major reasons. First of all, as Konietzko & Gernuks (2011) have argued before, the very high volume and mass of traction batteries, as well as their high-voltages generally require professional removal from the vehicle. Additionally, traction batteries are of high value, as learned before, which is an important incentive for a high collection rate. The last reason is related to the objective and approach of this study: recirculation flows within the MFA are solely aimed to determine recycling potentials. Assuming a high collection rate of 90% can thus be considered as best-case, respectively maximum potential. Thereby, the risk of distorting primary metal requirements based on a too optimistic collection quota can be considered as irrelevant, since no secondary metal flows back into the supply chain are being modelled.

6.5 Critical reflection

Despite the careful preparation of the analysis, it should be noted that the results must be interpreted with circumspection. As any prospective assessment of new technologies, the results are subject to numerous assumptions, which adds up to the inherent uncertainty of the data used. Data availability, accessibility and quality have been perceived as one of the most particular challenges in the execution of the present analysis, which has also been one of the reasons for the partially close alignment to the data used by Konietzko & Gernuks (2011). Adequate data availability was especially perceived as limitation with view on the battery specifications and battery production chain material/substance flows. Two important motivations for a further analysis on Li and Co flows related to traction batteries, were on one hand the consideration of different current state-of-the-art battery types and secondly, a transparent and complete reconstruction of their production chains. However, latter has been particularly challenging and subject to numerous adjustments.

As it has been laid open in sub-chapter 6.4.2, data on specific processes of the production chain had to be commingled. Subsequently, in order to link the production chains with the e-mobility scenarios, the material-intensity for each battery type was required. The material-intensity is thus *the* decisive link, and consequently determining factor, for the quantification of material flows to both ends – in terms of required input and recycling potential (output). However, no such data could be found in the literature. While the use of average values for Li/Co contents of certain cathode types, as for example used by Konietzko & Gernuks, 2011, were found inadequate (not applicable) for the reconstruction of the battery production chains, average values for Li/Co contents of Li-ion batteries in general (e.g in Angerer, et al., 2009) would have implied the outright negligence of different battery types. Hence, the ultimately chosen approach is, owing to numerous assumptions and the integration of data sets from different studies, highly afflicted with uncertainties, which are passed down to the results.

In general, the commingling of data from different sources is highly questionable and inconsistencies can hardly be eliminated completely.

Also critical and disputable are the assumptions/ data regarding the useful life-span of the batteries, which highly influences the availability of recycling or reuse flows at certain points in time. The life-expectancy of batteries is, itself, a function of numerous factors for which no real-world long-term studies are available yet. (cf. Majeau-Bettez, et al., 2011a) Equalizing the battery useful life-span and vehicle lifespan, is also an assumption that should be kept in mind when evaluating the results of required inputs and recycling potentials. The possible necessity for more than one battery per vehicle life could substantially increase overall resource requirements.

The uncertainties related to the aforementioned assumptions and data could, in principle, be further analysed and/or reduced by applying statistical tests, ranges and/or different scenarios for each value of question. This would, however, substantially increase the complexity and dimensions of the analysis, which goes beyond the scope of this study. Also, such an approach would likewise require massive data describing the uncertainties in order to maintain its validity, respectively the informative value of the results.

A further shortcoming has been the lack of adequate data, respectively data quality regarding (dissipative) life cycle losses of materials, especially on substance level. As it has been mentioned before, most similar, prior studies have been using average Li/Co contents to assess resource requirements and/or recycling potentials, whereby life-cycle losses are largely neglected. This is one of the major reasons why the battery production chains could not be reproduced on substance level: the number of unknown values exceeds that of known values, thus the mathematical equations cannot be solved.

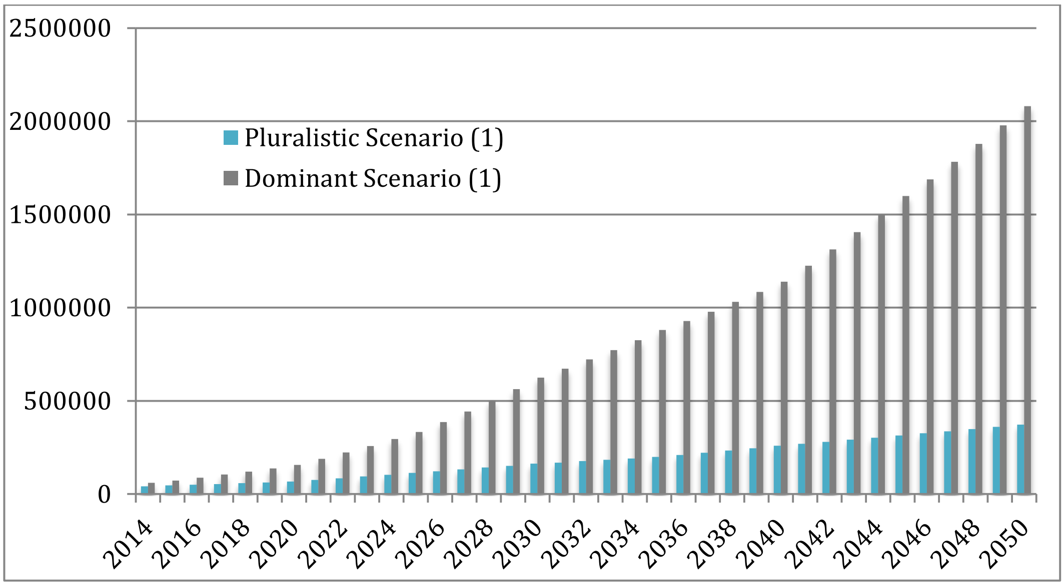
6.6 Quantitative results

The final material flow model in the software STAN integrates all relevant (available) material flows for all three battery, respectively cathode types (cf. Annex A-16ff). There are two (digital) files – one for each scenario – with each containing 1848 equations and 3812 variables (cf. Annex A-21f). Based on the before described assumptions and a lithium content of 6,7% in concentrated lithium brine (Notter, et al., 2010b, p.7), results indicate a development of annual lithium requirements (inputs/ 'imports'), as illustrated in Figure 13. However, these figures appear dubiously high. An examination of the major drivers for the lithium demand, reveals that 70% of the lithium input is 'lost' in the first process. This loss rests on the input-output ratio provided by Notter, et al., (2010b, p.8), who indicate that 9,38kg concentrated lithium with a content of 6,7% lithium are required to produce 1kg lithium carbonate with a content of 18,787% (deduced from the atomic mass shares of the elements). This information could not be confirmed, since lithium carbonate generally serves as equivalent to determine lithium inputs. Consequently, this information is afflicted to high uncertainties. Basically, there are three options: the losses are generally neglected by skipping the production process of lithium carbonate, the information is 'mistaken', or has been misinterpreted. Of course, in case that the information is correct, but generally neglected, this would be utterly devastating with view on a sustainable resource management. Since this question cannot be solved at this point it appears reasonable to consider two cases, whereat case (1) can be considered as the worst-case: (1) lithium requirements based on concentrated lithium brine with a lithium content of 6,7% and (2) lithium requirements based on lithium carbonate with a lithium content of 18,787%.

In case (1), the lithium demand for EV-batteries would rise up to 370.000t (Pluralistic Scenario) and 2Mt (Dominant Scenario), in 2050 (Figure 13).

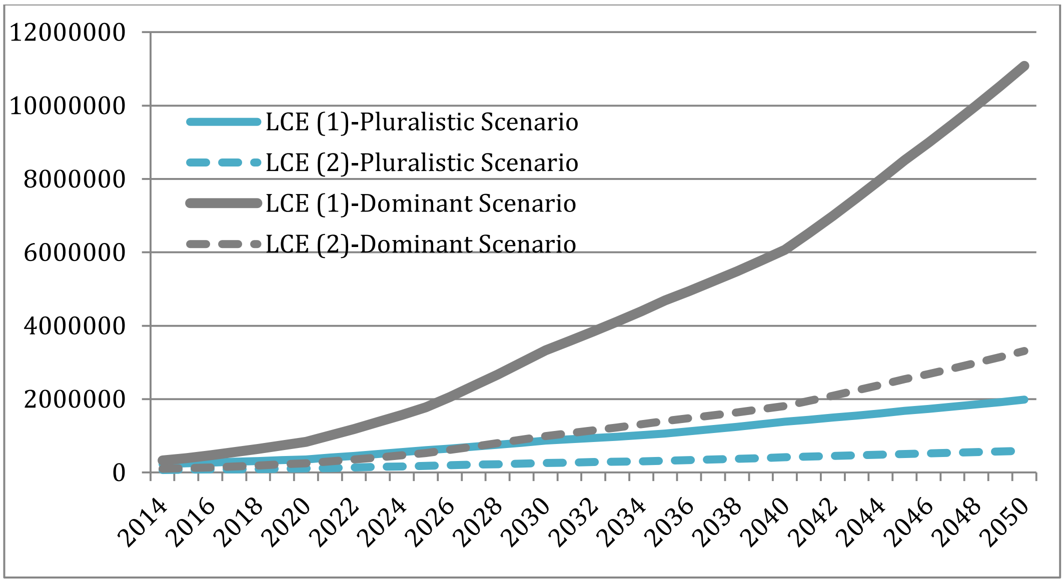
In case (2), the lithium demand for EV-batteries would lie between 112.000t (Pluralistic Scenario) and 622.000t (Dominant Scenario), in 2050. Figure 14 shows a comparison of the demand trajectories given as lithium carbonate equivalent (LCE). For comparison, current annual lithium production is approx. 35.000t/a. (USGS/Jaskula, 2014)

Figure 13: MFA results – annual lithium (metal) requirements 2014-2050



Source: own calculations.

Figure 14: MFA results – lithium demand trajectory in LCE 2014-2050

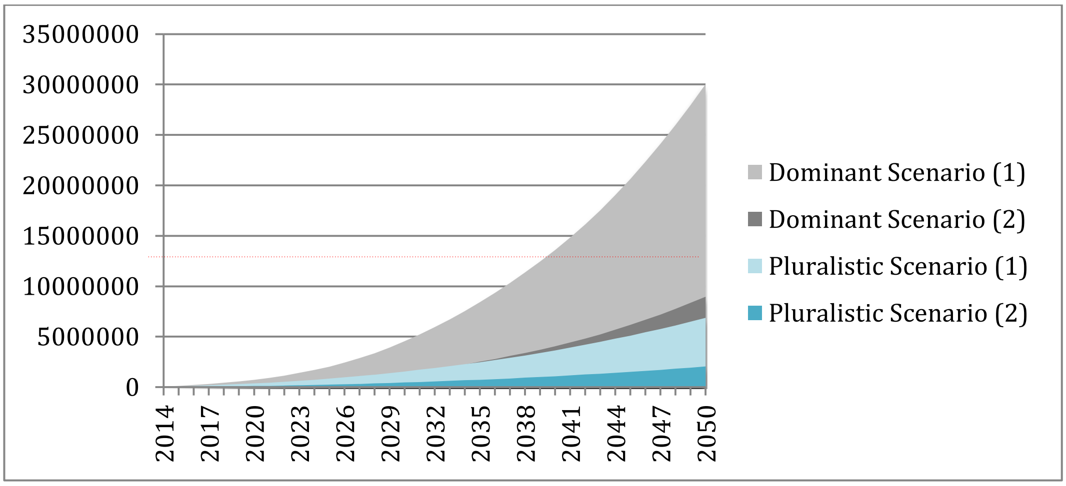


Note: LCE (1) = lithium carbonate equivalent calculated with lithium demand based on concentrated lithium brine; LCE (2) = actual lithium carbonate demand calculated in STAN.

Source: own calculations.

It should also be noted that the amounts in tons show a significant difference between the scenarios, independent from the cases. The trajectory of the first case Dominant Scenario (1), however, steps out by far. Nevertheless, even in case (2), the lithium demand in the Dominant Scenario is more than 5 times the lithium demand in the Pluralistic Scenario 2050. This wide range of possible lithium requirements can be considered as symptomatic for the uncertainty regarding the development of e-mobility and consequently resource requirements. Figure 15 shows the cumulative lithium requirements against current (minimum) reserves (also cf. Annex A-32f). Even though the second case scenarios, as well as the first case Pluralistic Scenario (1) seem to be moderate in comparison to the first case Dominant Scenario (1), between 57-74% of the reserves would be ‘consumed’ by 2050.

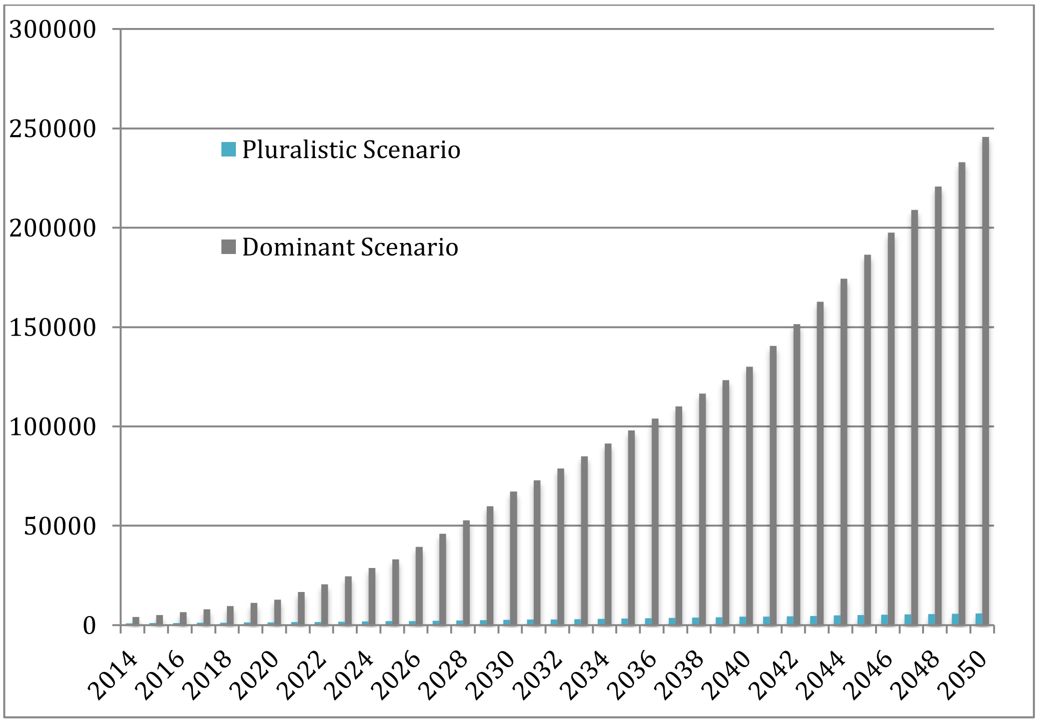
Figure 15: MFA results – cumulative lithium requirements versus lithium reserves



Source: own calculations; reserves: ⋯ 12.1Mt Lithium (Vikström, et al., 2013, p.256)

A high discrepancy between the scenarios is even more visible in the case of cobalt, as Figure 16 shows: the required quantities of cobalt in the Pluralistic Scenario in fact almost disappear against the quantities required in the Dominant Scenario. However, cobalt requirements are – in absolute terms – much less than lithium requirements. This is not surprising with view on the considered battery chemistries (only NMC-chemistry contains cobalt) and the fact that lithium is contained in the electrodes, as well as in electrolyte. According to the calculations, cobalt requirements would lie between almost 6.000t (Pluralistic Scenario) and 246.000t (Dominant Scenario) in 2050. In comparison, current cobalt production reached levels of 103.000t in 2012, and estimated 120.000t in 2013. (USGS/Shedd, 2014)

Figure 16: MFA results – annual cobalt requirements

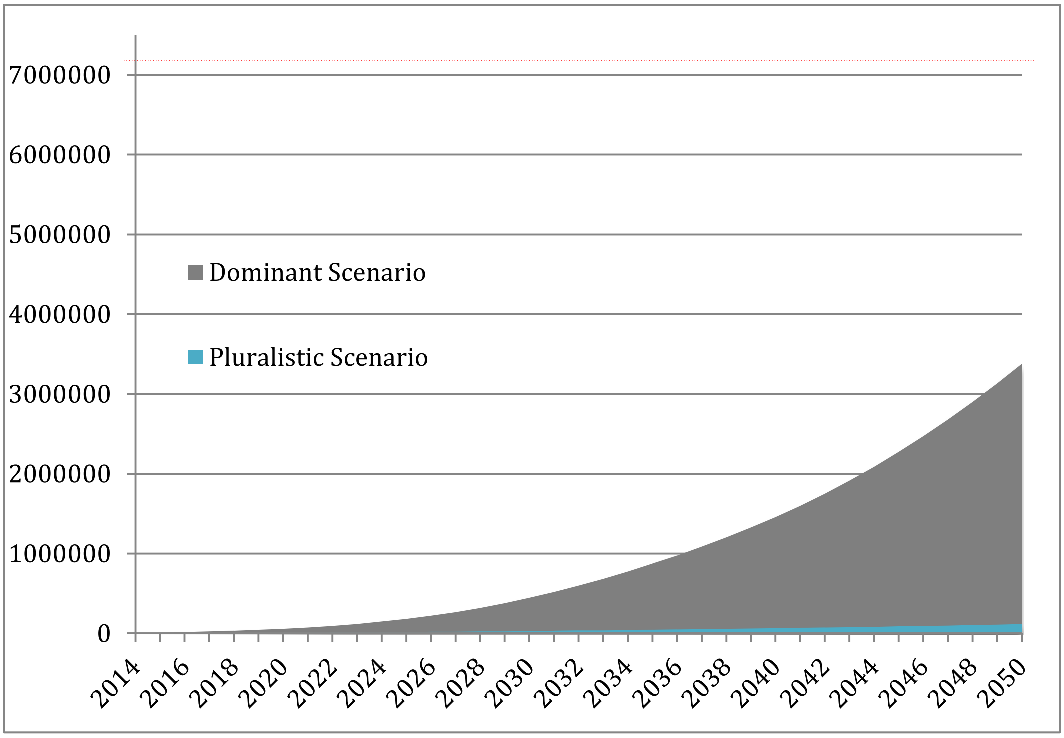


Source: own calculations.

The respective development of recycling potentials (cumulative) for each metal is shown in Figures 18 and 19. In order to follow the contribution of each electrode material to the lithium recycling potential refer to Annex A-29f. Figure 17 illustrates the cumulative cobalt requirements against current (minimum) reserves. As for the annual cobalt requirements, the cumulative cobalt demand in the Pluralistic Scenario is hardly perceivable against the Dominant Scenario, and in the scale necessary to depict the ‘reserve boundary’. In the Dominant Scenario almost half of the reserve stock would be ‘consumed’ by 2050.

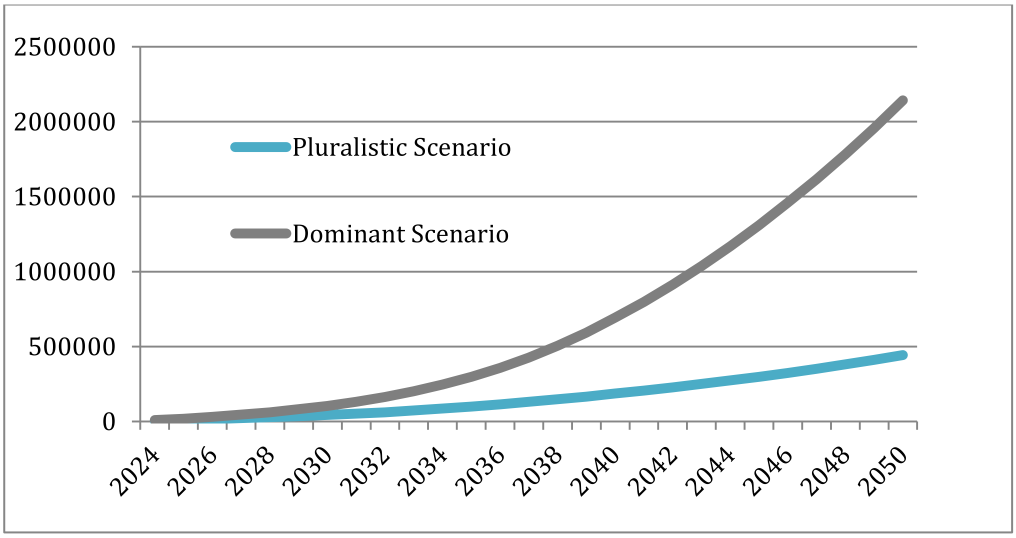
Note, that in neither of the scenarios and cases presented for both, lithium and cobalt, potential supply of secondary/recycled metals is included, respectively deducted. The ‘independent’ development of recycling potentials (cumulative) for each metal is shown in Figures 18 and 19. In order to follow the contribution of each electrode material to the lithium recycling potential refer to Annex A-29f.

Figure 17: MFA result - cumulative cobalt requirements versus cobalt reserves



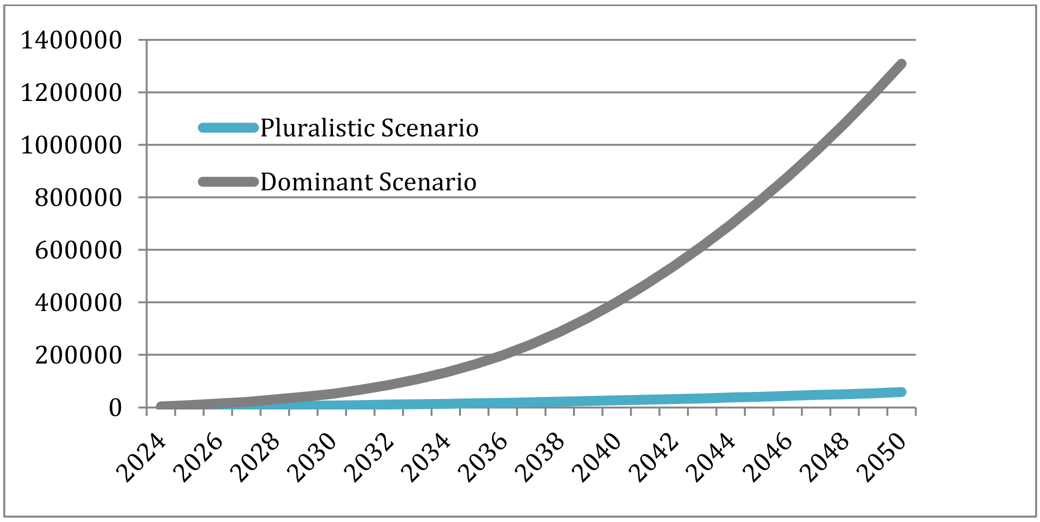
Source: own calculations; reserves: 7.2Mt Cobalt (Shedd, 2014, p.47).

Figure 18: MFA results - cumulative recycling potential for lithium



Source: own calculations.

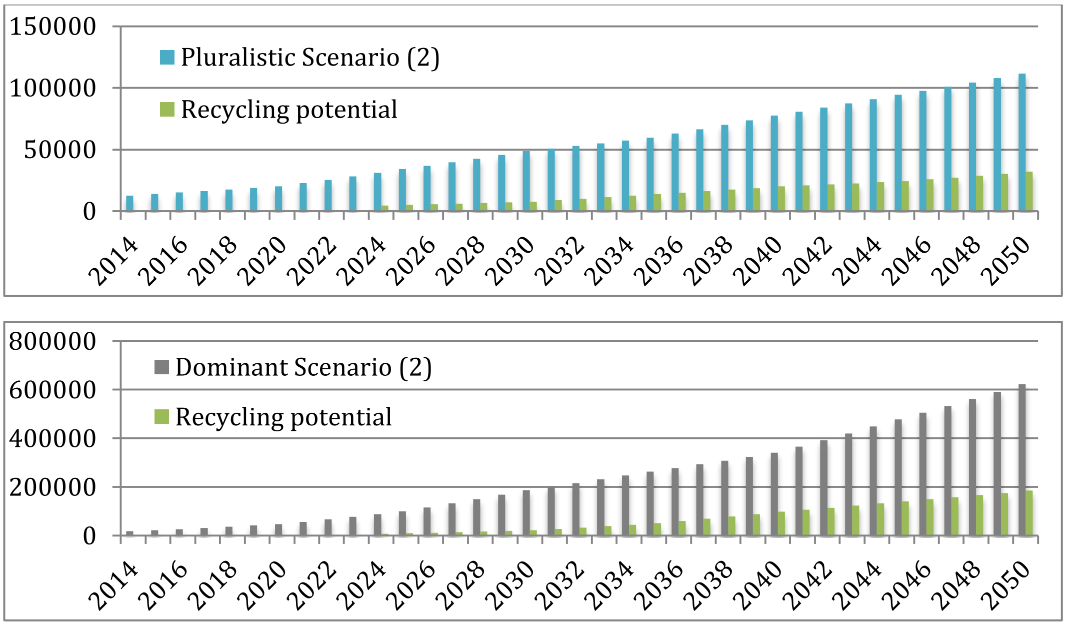
Figure 19: MFA results - cumulative recycling potential for cobalt



Source: own calculations.

Figure 20 indicates that in the case of lithium, even with a 100% technical recycling quota and 100% closed loop recycling, secondary supply could only cover a small fraction of the required quantities – a maximum of around 30% for both second case scenarios in 2050. As it can be expected from previous comparisons, secondary supply potentials look even much worse in the first case scenario, with a maximum of 9% for both second case scenarios in 2050.

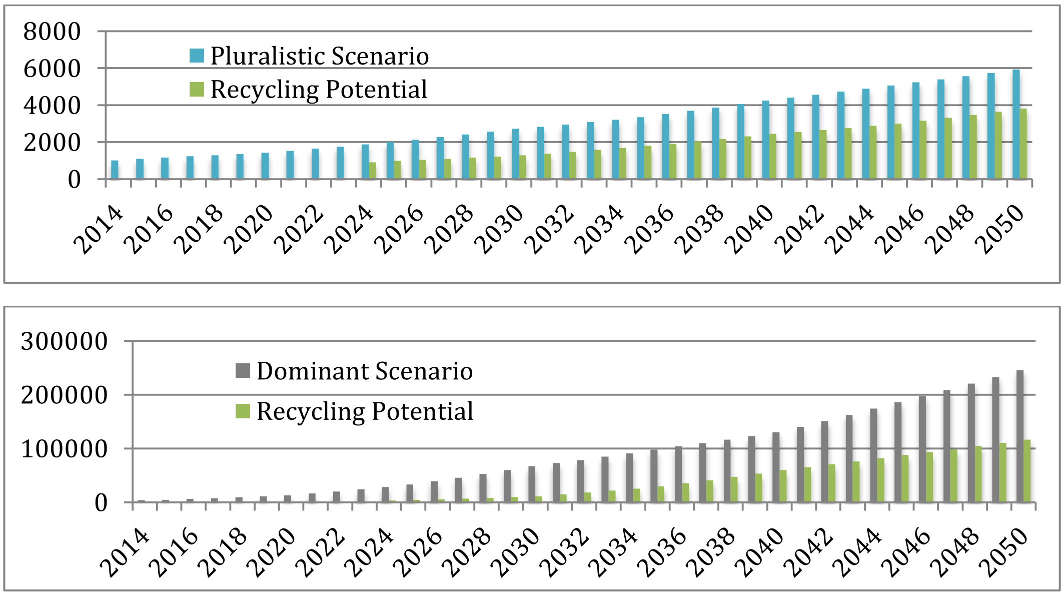
Figure 20: MFA results – Annual lithium demand versus annual recycling potential, case(2)



Source: own calculations.

For cobalt the situation looks relatively more promising according to the results. With a 100% technical recycling quota and 100% closed loop recycling, the secondary supply could cover up to 48% (2050) in the Dominant Scenario and up to 65% (2050) in the Pluralistic Scenario.

Figure 21: MFA results – Annual cobalt demand versus annual recycling potential



Source: own calculations.

7 Discussion

Results from the MFA indicate that, despite a significant difference between the scenarios, e-mobility will be an increased driver for lithium and cobalt demand in the future. Especially in the case of lithium increased quantities and high growth rates with regard to the demand can be expected from traction batteries.

Exact increases in demand for both metals, however, are difficult to predict, which can be seen in the results from this study (difference between scenarios and cases) but also in comparison with findings from other studies (compare Annex A-24). These differences among estimations can hardly be eliminated since each projection is based on numerous assumptions, which are seldom consistent.

The only way to approximate actual future developments and to ‘separate the wheat from the chaff’ is by discussing major assumptions (if transparently laid open) and conclusions, and to identify common trends. Especially with view on the objective of this study, the identification of challenges for a sustainable resource management, the interpretation of trends is of major importance. In fact, the uncertainty itself that becomes visible by comparing estimations on future resource requirements constitutes a major challenge for a sustainable resource management.

An important assumption, particularly in the case of lithium, that has often lead to the overall optimistic appraisal of lithium availability in the future is that of possible recycling rates (cf. for example Kushnir & Sandén, 2012; Gruber, 2011; Konietzko & Gernuks, 2011; Kesler, et al., 2012). However, optimistic recycling rates in the short- and medium term are questionable. The significance of the contribution of secondary lithium production through recycling to satisfy global lithium demands is still highly uncertain. As stated in sub-chapter 6.2.1, lithium recycling has been insignificant historically, and still appears to remain almost non-existent. Even though initiatives and projects aimed to enhance lithium recycling exist, especially from spent EV batteries (cf. Linder, 2010; BMU, 2009, 2012; Umicore, 2014), a number of challenges still impede (sufficiently) large investments. These challenges are dominated by uncertainties regarding required capacities and economical viability. (cf. Kushnir & Sandén, 2012) The commonly argued significant growth of recycling rates and secondary materials is largely based on uncertainty afflicted assumptions on e-mobility market penetration and collection rates. Even if e-mobility develops at estimated rates and coverage, substantial delays in the build-up of recycling capacities are most likely. As mentioned earlier, recycling economies are currently still unsatisfactory and they could even become more challenging, according to Kushnir & Sandén (2012).

Hence, those estimates of future lithium demand for traction batteries that are based on optimistic recycling rates should be interpreted with circumspection, especially under sustainability aspects. As long as high recycling rates are afflicted to high uncertainties it is reasonable and necessary to consider the consequences, respectively additional pressure, of low recycling rates on primary production. Besides, the results from the present study (cf. Figure 20) indicate that even high recycling rates cannot ‘keep up’ with the growth rates in demand. This means that higher production of lithium in the future, under any scenario, will most certainly be required.

Commonly, the evaluation of primary production enhancement potentials is solely based on the comparison of required quantities against geologically available resources or reserves, which has been reason enough for many researchers to conclude that future lithium demands can be met and that there is no need for concern. Furthermore, these conclusions are underpinned with the argumentation that reserves, as dynamic figure, tend to increase over time. (e.g. Konietzko & Gernuks, 2011)

In principle, this approach and argumentation is not wrong, when used as reference point in terms of resource intensity, criticality, and depletion. However, it is highly questionable as sufficient condition to give the 'all-clear' – not in terms of resource economics (i.e. especially short- and medium term supply security), as argued by Vikström, et al. (2013) and Kushnir & Sandén (2012), and certainly not with regard to sustainability (i.e. particularly ecological and social considerations, and time horizons). Especially with regard to the time dimension, demand trajectories as for example the one estimated in this study for the rather moderate second case Dominant Scenario (2) (cf. Figure 15 and Annex A-32), which indicate a possible consumption of approx. 74% of today's reserves by only one sector in less than 40 years, clearly require attention – not only under the premise of a sustainable resource use. Besides, the resource base of a non-renewable resource cannot just be taken as inventory, it is much more complicated than that.

Vikström, et al. (2013, p.253), as well as others (cf. Andersson & Råde, 2001; Kushnir & Sandén, 2012), argue that geological availability and the pace of realizable flow rates into society are to be seen as "*two fundamentally different things*". Even if known resources and reserves indicate the availability of 'sufficient' (for a certain scenario) quantities, "*the scale of material use implied by some scenarios for mass production of vehicle batteries is sufficiently large that resource scarcity in the medium and long term cannot be ruled out outright* (…)" (Kushnir & Sandén, 2012, p.93).

Possible future production quantities are similarly afflicted to uncertainties as the quantities that will be demanded in the future. Kesler, et al. (2012, p.57) alerts that only a small portion of the known deposits (types) is actually in production at present, which is why "(…) *information on geologic factors, such as lithium content and mineralogy, continuity and size, relation to enclosing rocks, and* *location, all of which might affect their economic development, is relatively sparse and scattered*". Numerous of the deposits have not sufficiently, if at all, been evaluated yet. This does especially apply to the supposedly known resources, whose conversion into actually recoverable reserves is, accordingly, still highly uncertain. Brine deposits, which are bearing the greatest resources and thus the greatest capacity potentials in the future compared to other deposit types, differ considerably from one deposit to another e.g. with regard to the lithium content, among many other factors. Consequently, the successful extraction from one deposit does not automatically guarantee the successful production from another deposit. The accessibility, volumes and concentrations of deposits, the degree of zoning feasibility of the reservoirs, the recovery efficiency and processing restrictions owing to by-products are all factors that decide upon a successful conversion of resources into reserves. (cf. Kesler, et al., 2012, p.55, 64) At this point it shall be noted that "(…) *only two of the brine deposits in the top ten are currently producing*; [while] *all others are* [still] *in various stages of evaluation*" (Kesler, et al., 2012, p.66). Local conditions are also crucial for mining activities. These may refer to local processing amenability, appropriate land areas, which are required to offer eligible flow gradients, adequate construction materials for the required ponds, favourable weather and climate conditions. (cf. Kesler, et al., 2012, p.64, Vikström, et al., 2013)

Vikström, et al. (2013, p.261) have made an attempt to model possible future global lithium production until 2100 based on three different methods. The modelled annual production volumes for 2050 are likely to meet neither of the herein projected demands (considering that EV batteries only make up for a share of around 27%, cf. sub-chapter 6.2.1). Even if EV-batteries would make up for 50% of the lithium demand, only the more moderate, second case Pluralistic Scenario (2) could be met.

Furthermore, there are other relevant factors that ultimately might even become more crucial than the size of the reserve or the resource base and thus they should be considered as serious challenges. Among these challenges are social factors, for example, as well as legal frameworks and increasing environmental standards. (cf. Kesler, et al., 2012, p.64, Vikström, et al., 2013) These aspects are not only additional factors of particular interest with regard to sustainability, respectively SRM, but they can also directly affect resource availability. Vikström, et al.

(2013, p.254) explicitly allude to the possibility that "(…) *public outcries against surface mining or concerns for the environment in lithium producing will lead to restrictions* [regarding] *the reserves*". Water consumption of brine production, for example, is a major challenge and threat with regard to the environment and resident population. According to Tahil (2007), water consumption at the currently largest brine deposit, the Salar de Atacama (Chile), accounts for 65% of the region's fresh water. Estimations for the water consumption for industrial scale lithium production at the Salar de Uyuni (Bolivia) – which is currently receiving attention being the largest known salar worldwide (10,000km^2), but which is not yet producing – would surpass the possible water flows from the Rio Grande. Phreatic waters would be required, which, however, would need up to 1000 years to replenish. Consequences for the environment and resident population could thus be dramatic. (cf. Kesler, et al., 2012, p.62; Ammitzboell & Hug, 2012) Further challenges and constraints with regard to lithium supply from brines are the slow response times to changes in lithium demand and the geographical distribution of deposits. Since lithium production from brines is primarily based on evaporation processes and thus largely dependant on weather and climate conditions, it can take 1 to 2 years before a final product is obtained. This time might even be prolonged at places that are under the influence of seasonal climate effects. (cf. Vikström, et al., 2013, p. 254) Favourable climate for lithium production from brines is most favourable in South America and China, where at the same time most of the global brine resources are concentrated. Actually, four countries –Argentina, Bolivia, Chile and China– hold approx. 70% of currently identified brine resources. Since brine is currently the major lithium source, more than 90% of lithium reserves are located in only three of these countries (with exception of Bolivia), producing almost 60% of primary lithium in 2013 (cf. Annex A-26f). (cf. Kesler, et. al., 2012, p.64, 67; USGS/Jaskual, 2014) This geographic concentration of brine sources bears substantial risks for supply security.

However, the difference between the abovementioned reserve and production share could be attributed to a relative advantage of pegmatite deposits over brine deposits with regard to geographic concentration: pegmatites are globally widespread. One of the largest deposits is located in Australia, contributing 38% to global lithium production in 2013. The advantage regarding geographic

distribution is considered to be the major reason for pegmatites to remain of interest as source for lithium, despite their comparatively smaller estimated resource. (cf. Kesler, et. al., 2012; USGS/Jaskula, 2014) Nevertheless, even though their widespread distribution and short processing time (5 days to final product) makes pegmatites less susceptible to supply disruptions, "(...) *about 10 economic pegmatite deposits would have to be found to equal one brine deposit* (…) [placing] *a major challenge on exploration* (…)" (Kesler, et. al., 2012, p.66). (cf. Vikström, et al., 2013) Exploration, however, is generally accompanied with high economic risks and environmental hurdles. (cf. Evans, 2014 and chapter 4.2)
Even for those deposits that have already been identified, their suitability for mining is still afflicted with uncertainties. Especially their amenability to mining, which is "(…) *a function of the form of the pegmatites and their position and attitude relative to the surface*" (Kesler, et al., 2012, p.61), constitutes a major concern. In order to produce sufficient quantities, open pit mining would be necessary in most of the cases. However, this is not always realizable. Kesler, et al, 2012 (p.67) concludes that "*pegmatite deposits* (…) *have not yet been shown to be amenable to the type of large-scale mining that will most certainly be required*". The production from unusual deposits, different to brines and pegmatites, will remain of interest based on the numerous challenges and concerns examined. However, in order to benefit from these unusual sources, new processing methods will be required first. (cf. Kesler, et al., 2012) Investments in exploration and new processing methods could become quite risky though if the hitherto mentioned challenges drive production costs and consequently, which would consequently reduce the profitability of mining operations. (cf. Prior, et al., 2011)

Cobalt supply has been considered to be the relatively more constraining, respectively critical, resource than lithium with regard to EV batteries. (cf. Konietzko & Gernuks, 2011; Peters, et al., 2013, Angerer, et al. 2009a) Konietzko & Gernuks (2011, p.24f), for example, conclude that the cumulative cobalt demand will reach (moderate scenario) or even surpass (optimistic scenario) current reserves (used figure: 7,3Mt) in 2050. In the dominant scenario, even the quantities of the currently identified cobalt resource base (used figure: 15Mt) are reached. With regard to a SRM these conclusions appear more than alarming, particularly with view on the time horizon.

The fact that the MFA conducted in this study does not confirm these findings is not necessarily a contradiction. It must be noted that the MFA exclusively assesses the cobalt demand development for traction batteries (NMC-based batteries), while Konietzko & Gernuks (2011, p.23) consider NMC-based traction batteries plus 6 other cobalt demanding market segments in their analysis. Furthermore, the estimations by Konietzko & Gernuks (2011) are based on a higher material intensity (higher cobalt concentration) and in addition NMC-based batteries have a much higher market share. Table 15 gives an overview on these different assumptions that are likely to contribute to the differences between the results.

Table 15: Comparison of assumptions on major cobalt demand determinants

	Konietzko & Gernuks (2011)	MFA in present study
Material intensity	490 g /kWh	325 g/kWh
Required kWh	1,4 kWh (HEV)	2,5 kWh (HEV)
	20 kWh (PHEV + BEV)	20 kWh (PHEV + BEV)
Market share NMC	65%	35%

Source: see table.

The lower market share of NMC-based batteries in the present analysis is owed to the additional consideration of LMO-based batteries – a battery chemistry that is assumed to compete with NMC-chemistry. Besides, as it has been examined in sub-chapter 5.5.2, cobalt is in general loosing its prior predominance in battery chemistries. Among the reasons for substitution are, in fact, environmental risks and availability concerns. (cf. Scrosati, 2000; Wagner, et al., 2013; Hayner, et al., 2012; Peters, et al., 2013; Roberts & Gunn, 2014)

Therefore, the case of cobalt could be considered as an example for the possible effects that the acknowledgement of resource constraints may have on material development, even though material performance issues might have been the dominant drivers. Either way, there is a trend towards decreasing use of cobalt for traction batteries, which translates into a relief of the cobalt demand from this sector (while increasing the demand for the substitutes, as e.g. manganese and nickel!). Nevertheless, even the relatively more conservative projection of the cobalt demand development in this study indicates an increasing demand. In contrast to the case of lithium, cobalt recycling is fortunately already in practice (cf. sub-chapter 6.2.2) and the recycling potentials estimated in this study (compare Figure 21, p.94) could, if completely exploited, cover a considerable share of the required cobalt quantities. However, as in the case of lithium, the demand for primary resources would still increase and translate into comparable challenges as the once described before for lithium.

A particular challenge for the case of cobalt, however, is its relatively low abundance and consequently its nature of being a by-product in mining activities of other elements. The implications and consequently the challenges for a SRM of by-product metals have been described earlier, in chapter 4.4.

A further challenge with regard to cobalt supply is its high economic importance for other economic sectors, and the fact that production is currently dominated by the large Copper Belt in the Democratic Republic, with a share of almost 50% of global primary production (compare Annex A-27). This geographic concentration of production is further exacerbated by the fact that the region is generally considered as politically unstable. (cf. Peters, et al., 2013)

8 Conclusions & Outlook

The examination of material development for traction batteries and the forecast of potential lithium and cobalt requirements in the future reveal that the implementation of e-mobility will substantially influence the demand for these elements, which poses numerous challenges on their sustainable management. To meet these challenges, improvements at different levels will be necessary.

At first, it must be recognized that even though the magnitude of demand increases is highly uncertain, as it has been discussed, challenges for a sustainable resource management will not just arise in the future. Quite the contrary, many challenges are already present and demand our attention today. They commence with the estimation of potential demands, the assessment and evaluation of possible consequences and the formulation of strategies to encounter these consequences. Thereby, the estimation of absolute demand quantities is not sufficient to meet information requirements. The reproduction and control of material flows along the entire life cycle is an important precondition to identify leakages and inefficiencies, as well as potentials for optimization. However, the assessement approach in this study has shown that such analyses face challenges and failure risks even in the initial stages based on insufficient data availability and quality. Sustainable resource management is not just a ‘real time’ follow up, nor does it start with the realization, evaluation and processing of early recognition analyses, as the one conducted in this study. It should likewise make sure that communication and information systems function in order to make assessments more comprehensive and reliable. Thereby, information on unintended, respectively inexpected material flows (losses) should be as important as the intended and expected ones. This is also a necessary precondition to propel the development and use of vital analytical tools and assessment methods for life cycle losses and resource ‘consumption’, as the ones mentioned in chapter 4.3 – such tools and methods do particularly suffer from information/data deficits.

The identification and ‘management’ of dissipative losses, for example, is not only important with view on resource efficiency, but also with regard to other consequences that should be considered from a sustainability perspective. Cobalt for example is an important trace-element in vitamin B_{12}, and as such vital for life. Both, cobalt deficiencies and overexposures, can have substantial health effects for animals and humans. (cf. Roberts & Gunn, 2014)

At the same time, it is important to make sure that entire life cycles are considered. The results from the MFA, for example, indicate that there are substantial losses of 70% at the very beginning of the supply chain. More information and accordingly more studies on this issue would be required to either confirm or correct this finding. Thereby, definitions should play an important role. Since lithium, as many other elements, does not occur freely in nature, and is generally extracted in other than its metal form, it must be unequivocably clear what is meant when referring to lithium demand, production, recycling, reserves and the resource base.

Material flow assessments in general are also essential for both, the consistency and efficiency strategy, with regard to recycling.

As the MFA in this study has revealed, there are significant potentials for recycling of lithium and cobalt. The recycling of stocks in the anthroposphere can be an important means of a sustainable resource management, however, especially in the case of lithium, recycling of traction batteries is almost non-existant yet.

One of the identified hurdles are based on economic factors. Here, material flow analyses can provide important information on recirculating quantities and time horizons to lower investment risks but also to determine required infrastructures and capacities.

Even though lithium recycling from traction batteries is not yet implemented on an industrial scale, it must be understood that its future success does largely depend on today’s decisions. It has become clear that battery technology/material R&D is still highly dynamic, which bears the chance to consider already today the requirements for future recycling systems, as well as reuse options. As argued in chapter 3, the material choices and the design of a good can be a determining factor for an efficient and consistant life cycle managament. Nevertheless, it must also be noted that even if efficient recycling systems can be implemented, the results of the MFA and those of the studies examined, point out that there are clear limiations with regard to a sustainable use/management of non-renewable resources through the exploitation of recycling potentials. Recycling can postpone the problem of exhaustion but surely not solve it. (cf. Kesler, 2010)

Accordingly, in an ideal situation recycling would largely cover the basic demand for a non-renewable resource, while primary production would serve to replace inevitable losses. Thereby, especially social and ecological impacts of mining activities would be reduced to a minimum.

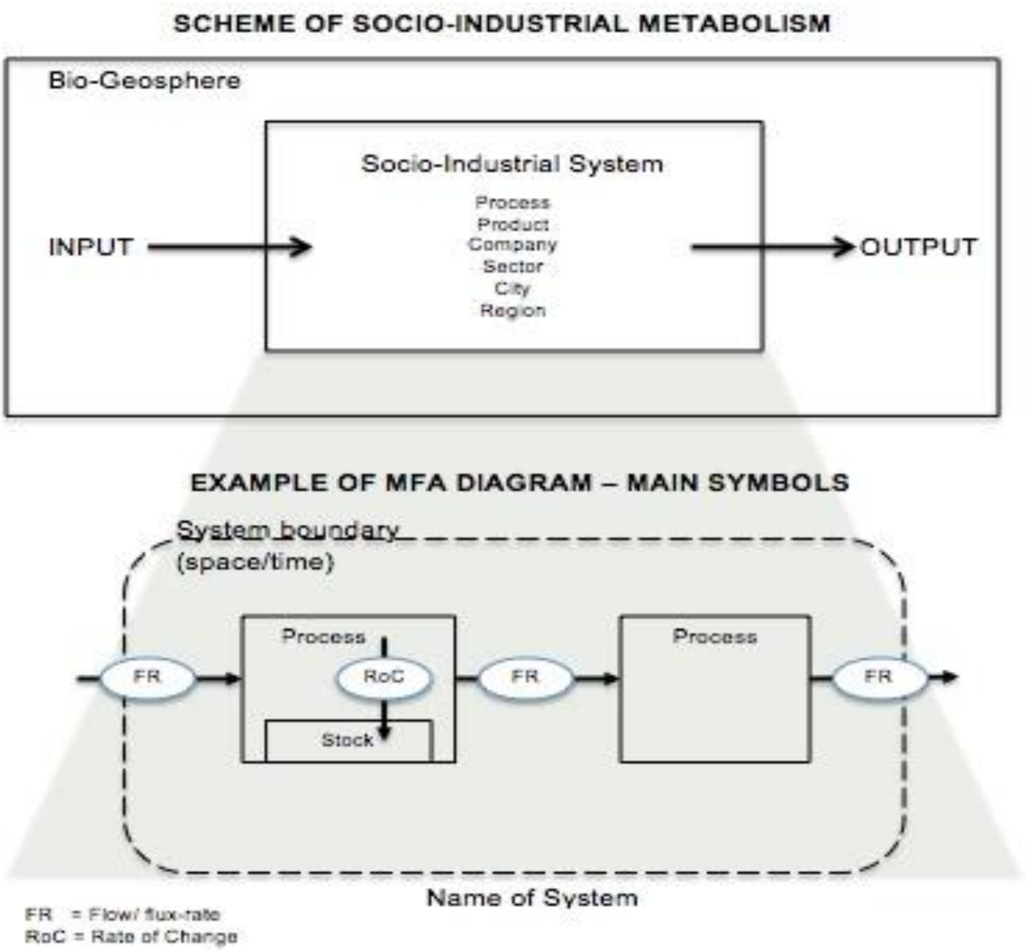
The projections in this and other studies, however, indicate that primary production will increasingly have to cover the basic demand for lithium and cobalt, which means that impacts of mining activities are likely to increase. To reduce the social and environmental loads of mining activities and metal cycles, standards and new policy instruments must be implemented. Additionally, incentives should be set to stimulate more efficient mining operations and technological innovation along the entire life cycle.

Nevertheless, a sustainable management of non-renewable resources solely based on the efficiency and consistency strategy is unlikely in light of the projected demand trajectories for lithium and cobalt. In the case of non-renewable resources, answers to the challenges should not be seeked on a purely physical and technological level, especially if the initial driver for such critical resource demands – in this case e-mobility – is culturally influenced. (cf. Graedel & van der Voet, 2010) A transformation towards e-mobility is with no doubt an important step towards a more sustainable future, especially when considering that the sink function of Earth’s carrying capacity (for example in terms of GHG emissions) appears to be at more risk than its source function. As vonGleich, et al. (2006, p.14) state: “*The limits of the carrying capacity of the sinks, in this case the consequences of* CO_2 *accumulation in the athmosphere, could become the limiting factor much earlier than the possible depletion of* (…) [re]*sources*”. However, a transformation towards e-mobility is also largely based on societies’ nonrestrictive demand for mobility, which is both a driver but also a challenge (conveniance requirements) for e-mobility. Much more research on how to motivate sufficiency and alternative and/or complementary solutions to meet the demand for (individual) mobility will be required in the future to mitigate trade-offs with view on sustainability, and to ensure a sustainable use of resources while reducing impacts on the intake capacity of the Earth.

Therefore, assessment approaches and methods, which are instrumental for sustainability management, need to be enhanced in order to not only capture physical, quantitative metrics but also cultural/sociological, qualitative ones. As mentioned before this will also require enhanced, interdisciplinary, as well as transparent communication and information provision.

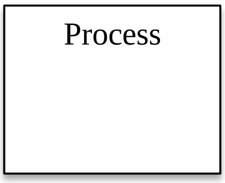
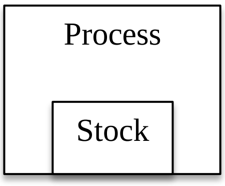
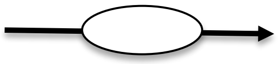
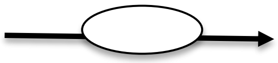
Appendix

A- 1: Scheme of the socio-industrial metabolism in relation to MFA methodology



Source: own figure based on Brunner & Rechberger (2004, p.38); Bringezu & Bleischwitz (2009, p.12,14).

A- 2: Most important MFA elements, definitions and symbols

MFA Elements		**Definition** (& symbolic representation in diagram)
Material	**Substance**	“(…) *any (chemical) element or compound composed of uniform units.*”[1] p.35
	Good	“ (…) *economic entities of matter with a positive or negative value. (...) made up of one or several substances.*”[2] p.36
System boundary (time & space)		Time: “(…) *time span over which the system is investigated and balanced.*”[3] Space: “(…) *usually* (…) *the geographical in which the processes are located.*”[3] p.43 
Process		– Transformation, transport or storage of materials. – Black-box, only inputs and outputs are of interest. 
Stock (& final sink)		– special type of process: only exemption to black-box approach – “(…) *total amount of materials stored in a process.*”[4] p.38 
Flow		Mass flow rate (e.g. t/year) 
Flux		Mass flow rate per cross section (e.g. kg/month * m^2) 
System		Object of investigation “(…) *defined by a group of elements, the interactions between these elements, and the boundaries between these and other elements in space and time*”[3]

Source: based on Brunner & Rechberger (2004, p.[2]36, [4]38, [3]43); [1]Sax & Lewis (1987) in: Brunner & Rechberger (2004, p.35).

A- 3: Battery performance parameters in the literature

Parameter	**Measured in**	**Notes**	**Mentioned in**
Specific energy (also: gravimetric energy density)	Wh/kg (Wh kg $^{-1}$)	Cell and system level[a)]	(Pollet, et al., 2012, p.236); [a)] (Thielmann & Isenmann, 2010, p.10, 16)*; (Peters, et al., 2013, p.35); (Hawkins, et al., 2012, p.5); (Winter & Brodd, 2004, p.4246); (Huggins, 2009, p.vi); (Kaiser, et al., 2008, p.31); (Gaines & Cuenca, 2000, p.6)
Energy density (also: volumetric energy density)	Wh/L (Wh L $^{-1}$)	Cell and system level[a)]	(Pollet, et al., 2012, p.236); [a)] (Thielmann & Isenmann, 2010, p.10,16)*; (Peters, et al., 2013, p.35); (Hawkins, et al., 2012, p.5); (Winter & Brodd, 2004, p.4246); (Huggins, 2009, p.vi); (Kaiser, et al., 2008, p.31); (Gaines & Cuenca, 2000, p.6)
Range	km	[e)] Performance measure, determined particularly by energy	[e)] (Hayner, et al., 2012, p.446); (Gaines & Cuenca, 2000, p.6)
Specific power (also: gravimetric powery density)	W/kg (W kg $^{-1}$)	Cell and system level[a)] [f)] power density defines realizable acceleration behaviour	(Pollet, et al., 2012, p.236); [a)] (Thielmann & Isenmann, 2010, p.10, 16)*; (Peters, et al., 2013, p.35); (Winter & Brodd, 2004, p.4246); [f)] (Kaiser, et al., 2008, p.31); (Löser, R., 2012)
Power density (also: volumetric power density)	W/L (W L $^{-1}$)	Cell and system level[a)] [f)] power density defines realizable acceleration behaviour	(Pollet, et al., 2012, p.236); [a)] (Thielmann & Isenmann, 2010, p.10, 16)*; (Peters, et al., 2013, p.35); (Winter & Brodd, 2004, p.4246); [f)] (Kaiser, et al., 2008, p.31); (Löser, R., 2012)
Maximum and acceleration speed		[e)] Performance measure, determined particularly by power	[e)] (Hayner, et al., 2012, p.446); (Huggins, 2009, p.vi)
Cold start-up performance			(Thielmann, et al., 2012a, p.7)
Energy Quality	V		(Huggins, 2009, p.11ff); (Peters, et al., 2013, p.35)
Volume	L		(Pollet, et al., 2012, p.236); (Peters, et al., 2013, p.29)
Mass	kg		(Pollet, et al., 2012, p.236); (Peters, et al., 2013, p.29)

A -3.1: Battery performance parameters in the literature

Stored energy	Wh	h) capacity proportional to discharge current; capacity x average discharge voltage = energy stored (Wh)	(Pollet, et al., 2012, p.236); (Peters, et al., 2013, p.29); h) (Tie & Tan, 2013, p.88)
Dis/charge rate**		d) Duration of charging process h) max. discharge current in the index of C; 1C = battery is depleted in 1h	(Pollet, et al., 2012, p.236); d) (Peters, et al., 2013, p.35); h) (Tie & Tan, 2013, p.88)
Surrounding requirements		a) tolerated temperatures, max. in both directions c) sensitivity to heat e) temperature effects	c) (Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10); e) (Hawkins, et al., 2012, p.5)
Response time			(Pollet, et al., 2012, p.236)
Efficiency (conversion)	a) %		(Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10); (Peters, et al., 2013, p.29); (Winter & Brodd, 2004, p.4247); (Huggins, 2009, p.9f)
Reliability			(Pollet, et al., 2012, p.236); e) (Hayner, et al., 2012, p.446)
Cycle life & cycling behaviour		b) Durability a) Operating life span g) use-phase efficiency g) Cycling behaviour, Coulombic efficiency= contrary to %-loss of available capacity per cycle	b)(Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10, 16)*; (Peters, et al., 2013, p.35); g) (Huggins, 2009, p.9, 15); g) (Majeau-Bettez, et al., 2011a, p.4549)
Calendric life		b) Durability a) Operating life span d) Limitations due to degradation effects; km performance 8influence cost)***	b)(Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10, 16)*; d) (Peters, et al., 2013, p.30,35); (Hawkins, et al., 2012, p.5)

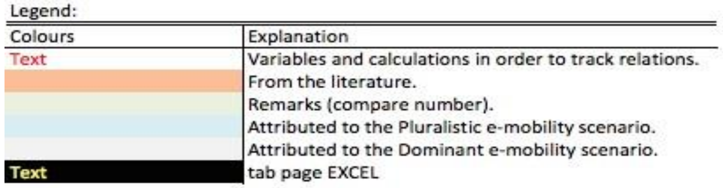
A -3.2: Battery performance parameters in the literature

Safety		a) in terms of EUCAR-Level d) Exclusion criterion e) consequence of battery rapture, especially in crash	(Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10, 16)*; d) (Peters, et al., 2013, p.35); e) (Hayner, et al., 2012, p.446)
Specific charge (battery capacity)	mAh/g (mAh g^{-1})	g) Charge capacity e) rate capability vs. storage capacity	(Wagner, et al., 2013, p.486f); g) (Huggins, 2009, p.13, 15); e) (Hayner, et al., 2012, p.446); h) (Tie & Tan, 2013, p.88)
Cost	a) €/kWh	a) Cell and system *** d) influenced by calendric life (km performance)	(Pollet, et al., 2012, p.236); a) (Thielmann & Isenmann, 2010, p.10, 16)*; d) (Peters, et al., 2013, p.30, 35) e) (Hayner, et al., 2012, p.446); (Hawkins, et al., 2012, p.5); (Huggins, 2009, p.9)
Recyclability			(Pollet, et al., 2012, p.236)
Environmental impact			(Pollet, et al., 2012, p.236); (Hawkins, et al., 2012, p.5)
Maintenance			(Pollet, et al., 2012, p.236)
**Convenience		e) Performance measure (not parameter) → space limitations due to battery and charging time	e) (Hayner, et al., 2012, p.446)
Self-discharge			(Huggins, 2009, p.16)

*Thielmann & Isenmann (2010, p.16): Characteristics to describe cell-types by the Innovationsallianz.

Sources: see table.

A- 4: Legend MFA calculations



Legend:

Colours	Explanation
Text	Variables and calculations in order to track relations.
🟧	From the literature.
🟨	Remarks (compare number).
🟦	Attributed to the Pluralistic e-mobility scenario.
⬜	Attributed to the Dominant e-mobility scenario.
Text	tab page EXCEL

A- 5: MFA calculation step 1

E-mobility market penetration (%) - anually 2013 – 2050		**(Calc_1-3,5)**				
Vehicle Concept	**Group 1**		**Group 2**		**TOTAL EVs**	
Measured in	% of new registrations		% of new registrations		% of new registrations	
Scenario	**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**
2013	A					
2014						
…						
2050						

A- 6: MFA calculation step 2

E-mobility market penentration (absolute) - anually 2013 – 2050				**(Calc_1-3,5)**			
Vehicle concept	**Passenger vehicle**	**Group 1**		**Group 2**		**TOTAL EVs**	
Measured in	**No.** new registrations	**No.** new registrations		**No.** new registrations		**No.** new registrations	
Scenario		**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**
2013*	C	D=A*C					
2014	C*1+B	Absolute Number of vehicles					
…							
2050	Absolute Number of vehicles						
Annual growth rate:	B						

Sources A-4 to 6: own tables.

A- 7: MFA calculation step 3

E-mobility energy requirements (kWh) - anually 2013 - 2050 (Calc_1-3,5)						
Vehicle concept	**Group 1**		**Group 2**		**TOTAL EVs**	
kWh per vehicle	average kWh of battery pack E		average kWh of battery pack			
Measured in	kWh		kWh		kWh	
Scenario	**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**	**Pluralistic**	**Dominant**
2013	F=D*E	G=D*E				
2014						
...						
2050						

Source: own tables.

A- 8: MFA calculation step 4

Material intensity of different cathode active materials: required kg battery per kWh based on specific cathode material (Calc_4)							
	U(V)	C(mAh/g)	ηm	ηu	I_A (kg/kWh) Active electrode material mass	Active material mass share in battery	I_B (kg/kWh) Battery mass
NMC	H	I	J	K	L=1000/(H*I*J*K)	M	N=L/M
LFP							
LMO							

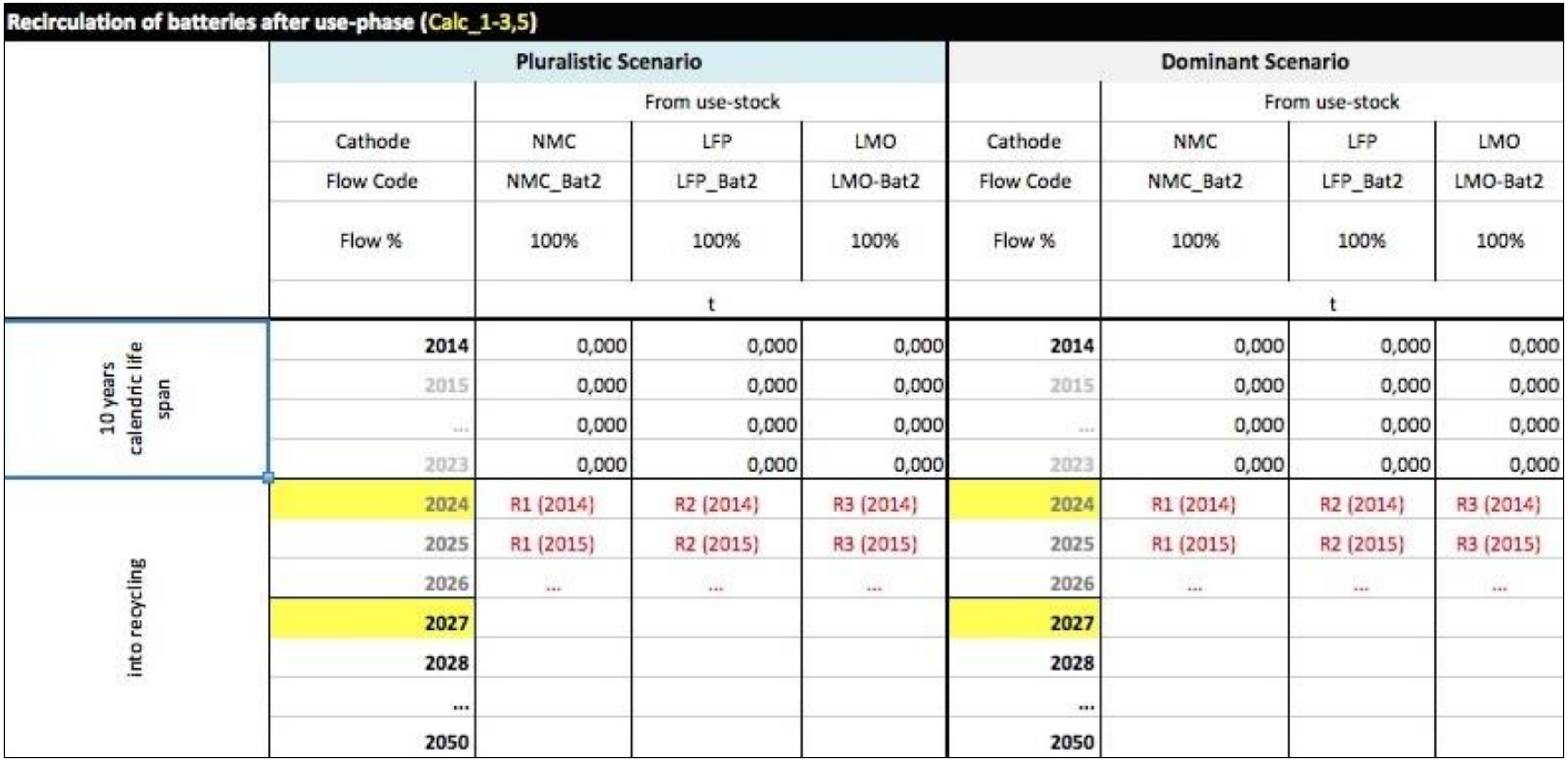
Source: own table.

A- 9: MFA calculation step 5.1

Annually required battery mass for each battery type and vehicle group (Calc_1-3,5)									
Pluralistic Scenario									
Vehicle concept	**Group 1**			**Group 2**			**TOTAL EVs**		
Cathode material	NMC	LFP	LMO	NMC	LFP	LMO	NMC	LFP	LMO
kg per kWh	N								
Distribution in %	P *(2)*								
Measured in	kg			kg			kg		
2013	R=G*N*P								
2014									
...									
2050									
Dominant Scenario									
Vehicle concept	**Group 1**			**Group 2**			**TOTAL EVs**		
Cathode material	NMC	LFP	LMO	NMC	LFP	LMO	NMC	LFP	LMO
kg per kWh	N								
Distribution in %	P *(2)*								
Measured in	kg			kg			kg		
2013	R=G*N*P						R1	R2	R3
2014									
...									
2050									
Remarks									
(2) assumed									

Source: own table.

A- 10: MFA calculation step 5.2

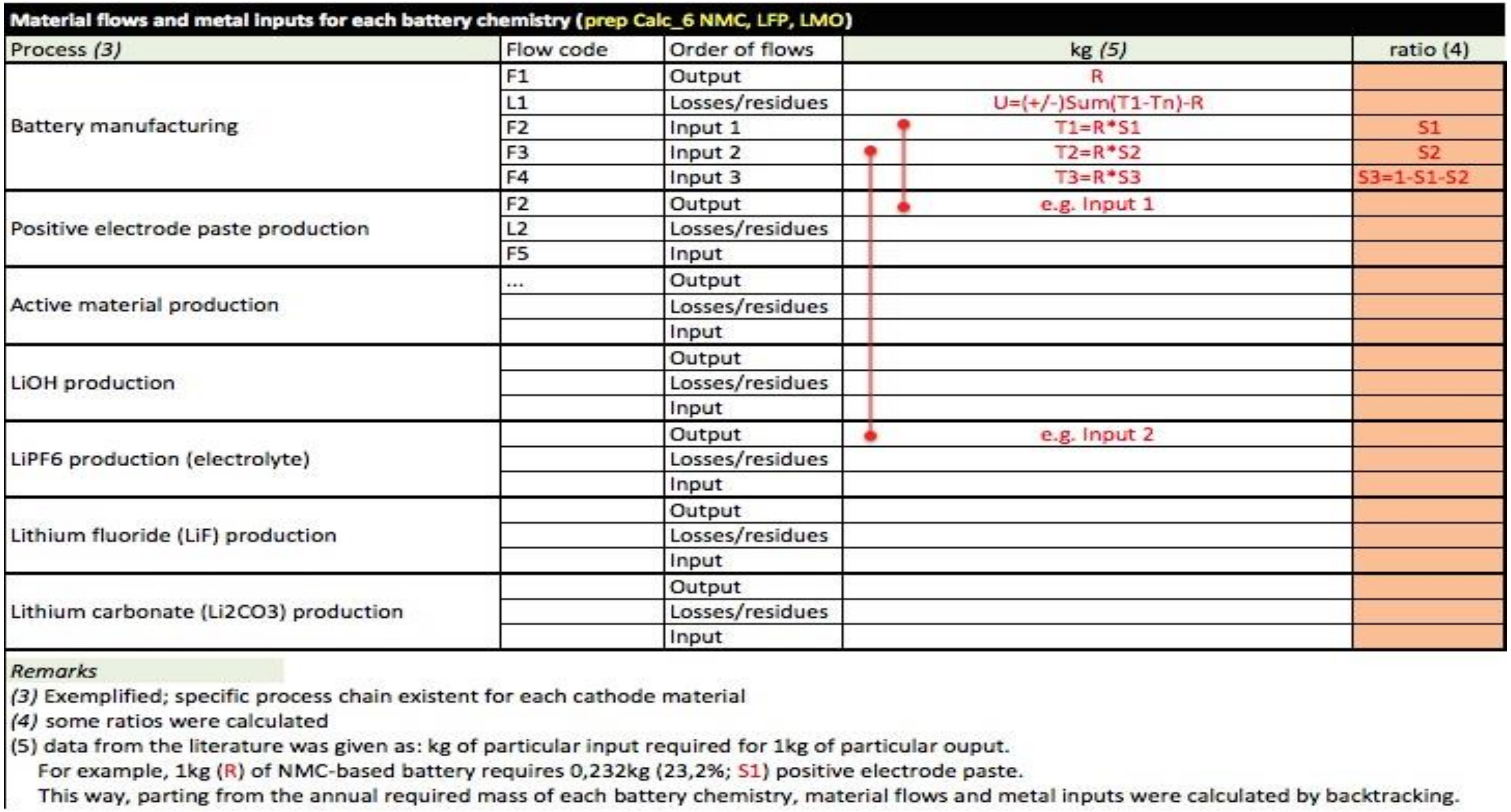


Recirculation of batteries after use-phase (Calc_1-3,5)

	Pluralistic Scenario				Dominant Scenario			
		From use-stock				From use-stock		
	Cathode	NMC	LFP	LMO	Cathode	NMC	LFP	LMO
	Flow Code	NMC_Bat2	LFP_Bat2	LMO-Bat2	Flow Code	NMC_Bat2	LFP_Bat2	LMO-Bat2
	Flow %	100%	100%	100%	Flow %	100%	100%	100%
		t				t		
10 years calendric life span	2014	0,000	0,000	0,000	2014	0,000	0,000	0,000
	2015	0,000	0,000	0,000	2015	0,000	0,000	0,000
	...	0,000	0,000	0,000	...	0,000	0,000	0,000
	2023	0,000	0,000	0,000	2023	0,000	0,000	0,000
into recycling	2024	R1 (2014)	R2 (2014)	R3 (2014)	2024	R1 (2014)	R2 (2014)	R3 (2014)
	2025	R1 (2015)	R2 (2015)	R3 (2015)	2025	R1 (2015)	R2 (2015)	R3 (2015)
	2026	...	...	...	2026	...	...	...
	2027				2027			
	2028				2028			
	...				...			
	2050				2050			

Source: own table.

A- 11.1: MFA calculation step 6



Material flows and metal inputs for each battery chemistry (prep Calc_6 NMC, LFP, LMO)

Process *(3)*	Flow code	Order of flows	kg *(5)*	ratio (4)
Battery manufacturing	F1	Output	R	
	L1	Losses/residues	U=(+/-)Sum(T1-Tn)-R	
	F2	Input 1	T1=R*S1	S1
	F3	Input 2	T2=R*S2	S2
	F4	Input 3	T3=R*S3	S3=1-S1-S2
Positive electrode paste production	F2	Output	e.g. Input 1	
	L2	Losses/residues		
	F5	Input		
Active material production	...	Output		
		Losses/residues		
		Input		
LiOH production		Output		
		Losses/residues		
		Input		
LiPF6 production (electrolyte)		Output	e.g. Input 2	
		Losses/residues		
		Input		
Lithium fluoride (LiF) production		Output		
		Losses/residues		
		Input		
Lithium carbonate (Li2CO3) production		Output		
		Losses/residues		
		Input		

Remarks

(3) Exemplified; specific process chain existent for each cathode material

(4) some ratios were calculated

(5) data from the literature was given as: kg of particular input required for 1kg of particular ouput.
For example, 1kg (R) of NMC-based battery requires 0,232kg (23,2%; S1) positive electrode paste.
This way, parting from the annual required mass of each battery chemistry, material flows and metal inputs were calculated by backtracking.

Note: continue next page.

A-11.2: MFA calculation step 6

Material Flows combined, transferable to STAN Software (Calc_6 combined)

		ratio *(4)*	S1	S2	...
	Total battery mass required	Flow code	F1	L1	F2
2013	R		T1=R*S1		
2014					
...					
2050					
2013					
2014					
...					
2050					

A- 12: MFA calculation step 7

Material flows and metal inputs for each battery chemistry (Calc_7 Metal concentrations)

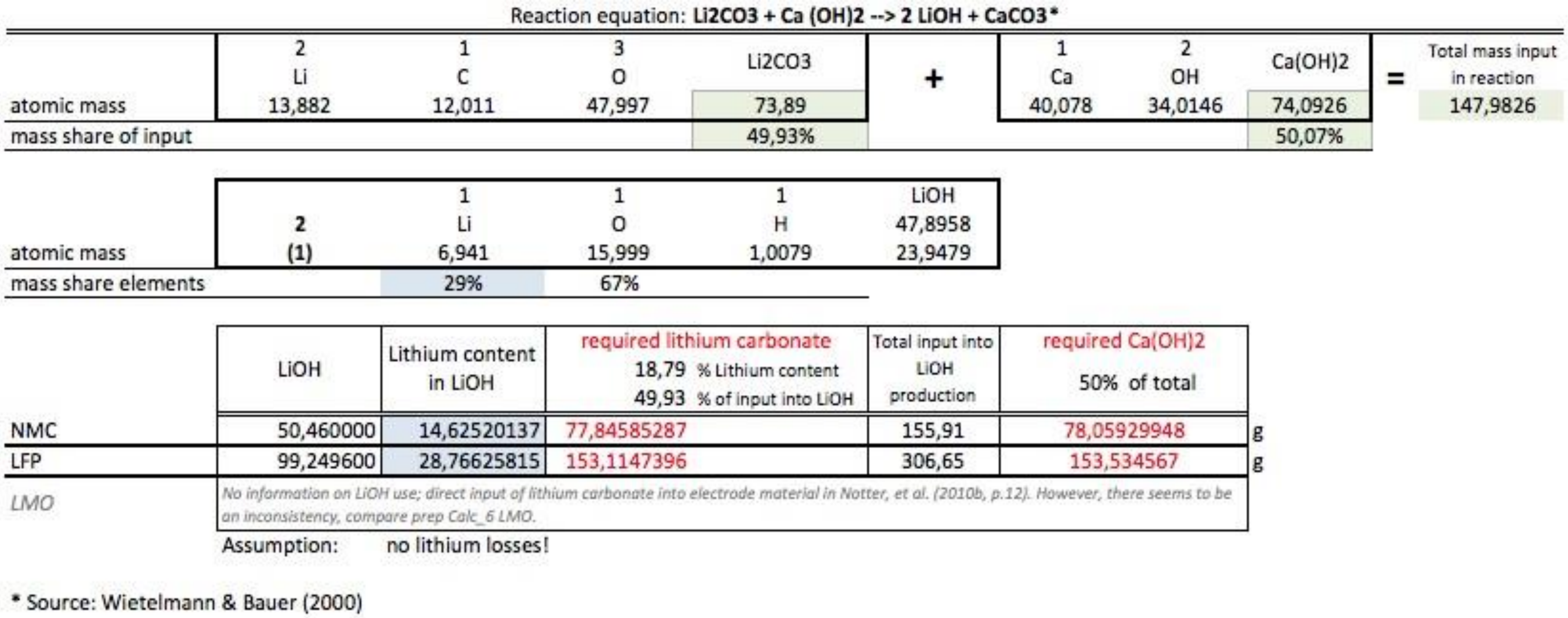
	NMC-electrode *(6)* **$LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$**						
	1	0,4	0,2	0,4	2	TOTAL	
Element	**Li**	Ni	**Co**	Mn	O		
relative atomic mass	V					W=(Summe V)	
relative mass distribution	X=V/W					100	%
absolute mass distribution	Z=M*X					M	g

Remarks

(6) Example; same procedure for LFP and LMO electrode, as well as the lithium containing electrolyte LiPF6

Sources A-11, A-12: own tables.

A- 13: LiOH production adjustments



Reaction equation: **Li2CO3 + Ca (OH)2 --> 2 LiOH + CaCO3***

	2 Li	1 C	3 O	Li2CO3	+	1 Ca	2 OH	Ca(OH)2	=	Total mass input in reaction
atomic mass	13,882	12,011	47,997	73,89		40,078	34,0146	74,0926		147,9826
mass share of input				49,93%				50,07%		

		1	1	1	LiOH
	2	Li	O	H	47,8958
atomic mass	**(1)**	6,941	15,999	1,0079	23,9479
mass share elements		29%	67%		

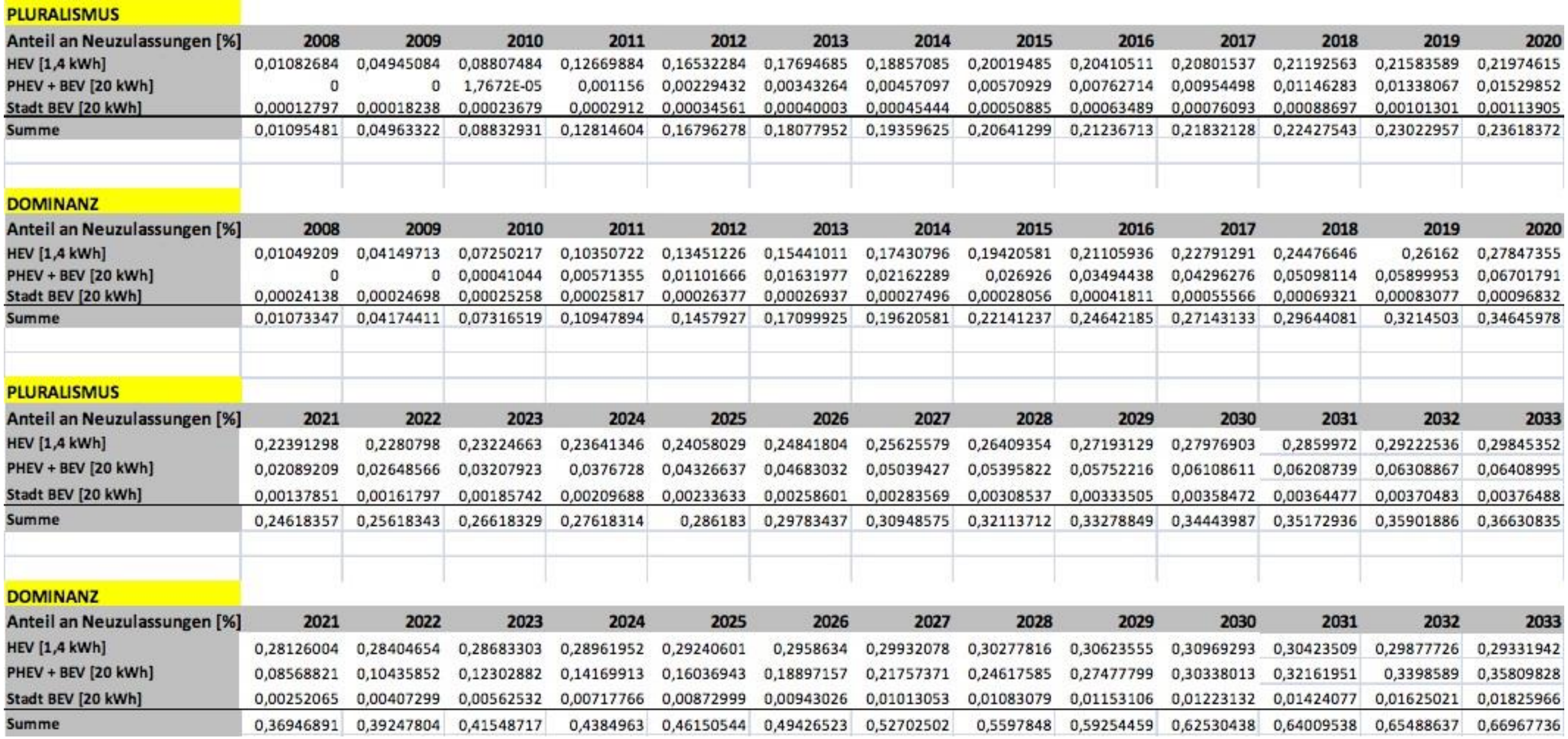
	LiOH	Lithium content in LiOH	required lithium carbonate 18,79 % Lithium content 49,93 % of input into LiOH	Total input into LiOH production	required Ca(OH)2 50% of total	
NMC	50,460000	14,62520137	77,84585287	155,91	78,05929948	g
LFP	99,249600	28,76625815	153,1147396	306,65	153,534567	g
LMO	*No information on LiOH use; direct input of lithium carbonate into electrode material in Notter, et al. (2010b, p.12). However, there seems to be an inconsistency, compare prep Calc_6 LMO.*					

Assumption: no lithium losses!

* Source: Wietelmann & Bauer (2000)

Source: own calculations.

A- 14.1: Fraunhofer ISI e-mobility Scenarios – new vehicle registrations 2008-2050



PLURALISMUS

Anteil an Neuzulassungen [%]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
HEV [1,4 kWh]	0,01082684	0,04945084	0,08807484	0,12669884	0,16532284	0,17694685	0,18857085	0,20019485	0,20410511	0,20801537	0,21192563	0,21583589	0,21974615
PHEV + BEV [20 kWh]	0	0	1,7672E-05	0,001156	0,00229432	0,00343264	0,00457097	0,00570929	0,00762714	0,00954498	0,01146283	0,01338067	0,01529852
Stadt BEV [20 kWh]	0,00012797	0,00018238	0,00023679	0,0002912	0,00034561	0,00040003	0,00045444	0,00050885	0,00063489	0,00076093	0,00088697	0,00101301	0,00113905
Summe	0,01095481	0,04963322	0,08832931	0,12814604	0,16796278	0,18077952	0,19359625	0,20641299	0,21236713	0,21832128	0,22427543	0,23022957	0,23618372

DOMINANZ

Anteil an Neuzulassungen [%]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
HEV [1,4 kWh]	0,01049209	0,04149713	0,07250217	0,10350722	0,13451226	0,15441011	0,17430796	0,19420581	0,21105936	0,22791291	0,24476646	0,26162	0,27847355
PHEV + BEV [20 kWh]	0	0	0,00041044	0,00571355	0,01101666	0,01631977	0,02162289	0,026926	0,03494438	0,04296276	0,05098114	0,05899953	0,06701791
Stadt BEV [20 kWh]	0,00024138	0,00024698	0,00025258	0,00025817	0,00026377	0,00026937	0,00027496	0,00028056	0,00041811	0,00055566	0,00069321	0,00083077	0,00096832
Summe	0,01073347	0,04174411	0,07316519	0,10947894	0,1457927	0,17099925	0,19620581	0,22141237	0,24642185	0,27143133	0,29644081	0,3214503	0,34645978

PLURALISMUS

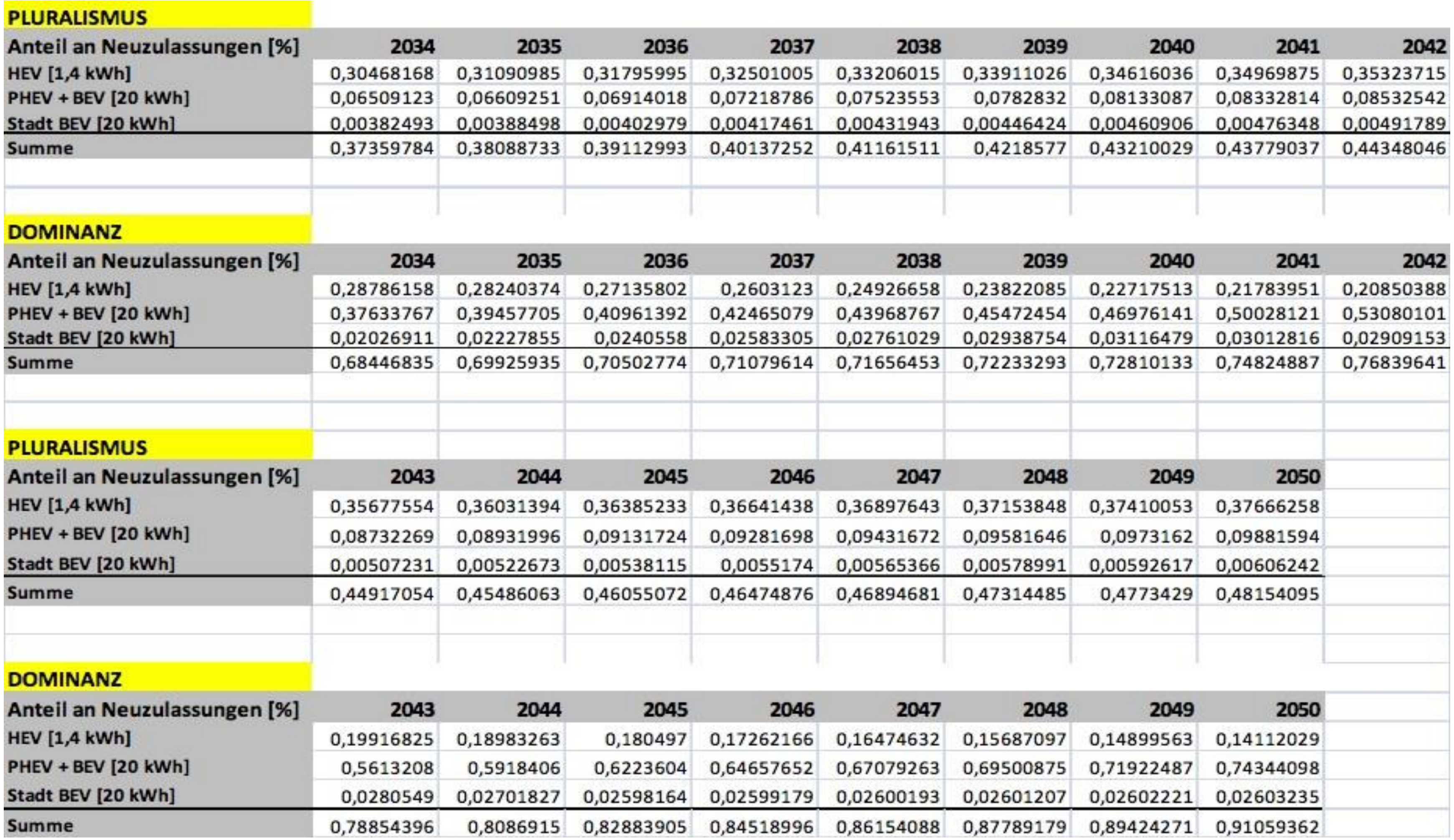
Anteil an Neuzulassungen [%]	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
HEV [1,4 kWh]	0,22391298	0,2280798	0,23224663	0,23641346	0,24058029	0,24841804	0,25625579	0,26409354	0,27193129	0,27976903	0,2859972	0,29222536	0,29845352
PHEV + BEV [20 kWh]	0,02089209	0,02648566	0,03207923	0,0376728	0,04326637	0,04683032	0,05039427	0,05395822	0,05752216	0,06108611	0,06208739	0,06308867	0,06408995
Stadt BEV [20 kWh]	0,00137851	0,00161797	0,00185742	0,00209688	0,00233633	0,00258601	0,00283569	0,00308537	0,00333505	0,00358472	0,00364477	0,00370483	0,00376488
Summe	0,24618357	0,25618343	0,26618329	0,27618314	0,286183	0,29783437	0,30948575	0,32113712	0,33278849	0,34443987	0,35172936	0,35901886	0,36630835

DOMINANZ

Anteil an Neuzulassungen [%]	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
HEV [1,4 kWh]	0,28126004	0,28404654	0,28683303	0,28961952	0,29240601	0,2958634	0,29932078	0,30277816	0,30623555	0,30969293	0,30423509	0,29877726	0,29331942
PHEV + BEV [20 kWh]	0,08568821	0,10435852	0,12302882	0,14169913	0,16036943	0,18897157	0,21757371	0,24617585	0,27477799	0,30338013	0,32161951	0,3398589	0,35809828
Stadt BEV [20 kWh]	0,00252065	0,00407299	0,00562532	0,00717766	0,00872999	0,00943026	0,01013053	0,01083079	0,01153106	0,01223132	0,01424077	0,01625021	0,01825966
Summe	0,36946891	0,39247804	0,41548717	0,4384963	0,46150544	0,49426523	0,52702502	0,5597848	0,59254459	0,62530438	0,64009538	0,65488637	0,66967736

Note: continue next page.
Source: Angerer, et al., (2009b, Annex).

A- 14.2: Fraunhofer ISI e-mobility Scenarios – new vehicle registrations 2008-2050



PLURALISMUS

Anteil an Neuzulassungen [%]	2034	2035	2036	2037	2038	2039	2040	2041	2042
HEV [1,4 kWh]	0,30468168	0,31090985	0,31795995	0,32501005	0,33206015	0,33911026	0,34616036	0,34969875	0,35323715
PHEV + BEV [20 kWh]	0,06509123	0,06609251	0,06914018	0,07218786	0,07523553	0,0782832	0,08133087	0,08332814	0,08532542
Stadt BEV [20 kWh]	0,00382493	0,00388498	0,00402979	0,00417461	0,00431943	0,00446424	0,00460906	0,00476348	0,00491789
Summe	0,37359784	0,38088733	0,39112993	0,40137252	0,41161511	0,4218577	0,43210029	0,43779037	0,44348046

DOMINANZ

Anteil an Neuzulassungen [%]	2034	2035	2036	2037	2038	2039	2040	2041	2042
HEV [1,4 kWh]	0,28786158	0,28240374	0,27135802	0,2603123	0,24926658	0,23822085	0,22717513	0,21783951	0,20850388
PHEV + BEV [20 kWh]	0,37633767	0,39457705	0,40961392	0,42465079	0,43968767	0,45472454	0,46976141	0,50028121	0,53080101
Stadt BEV [20 kWh]	0,02026911	0,02227855	0,0240558	0,02583305	0,02761029	0,02938754	0,03116479	0,03012816	0,02909153
Summe	0,68446835	0,69925935	0,70502774	0,71079614	0,71656453	0,72233293	0,72810133	0,74824887	0,76839641

PLURALISMUS

Anteil an Neuzulassungen [%]	2043	2044	2045	2046	2047	2048	2049	2050
HEV [1,4 kWh]	0,35677554	0,36031394	0,36385233	0,36641438	0,36897643	0,37153848	0,37410053	0,37666258
PHEV + BEV [20 kWh]	0,08732269	0,08931996	0,09131724	0,09281698	0,09431672	0,09581646	0,0973162	0,09881594
Stadt BEV [20 kWh]	0,00507231	0,00522673	0,00538115	0,0055174	0,00565366	0,00578991	0,00592617	0,00606242
Summe	0,44917054	0,45486063	0,46055072	0,46474876	0,46894681	0,47314485	0,4773429	0,48154095

DOMINANZ

Anteil an Neuzulassungen [%]	2043	2044	2045	2046	2047	2048	2049	2050
HEV [1,4 kWh]	0,19916825	0,18983263	0,180497	0,17262166	0,16474632	0,15687097	0,14899563	0,14112029
PHEV + BEV [20 kWh]	0,5613208	0,5918406	0,6223604	0,64657652	0,67079263	0,69500875	0,71922487	0,74344098
Stadt BEV [20 kWh]	0,0280549	0,02701827	0,02598164	0,02599179	0,02600193	0,02601207	0,02602221	0,02603235
Summe	0,78854396	0,8086915	0,82883905	0,84518996	0,86154088	0,87789179	0,89424271	0,91059362

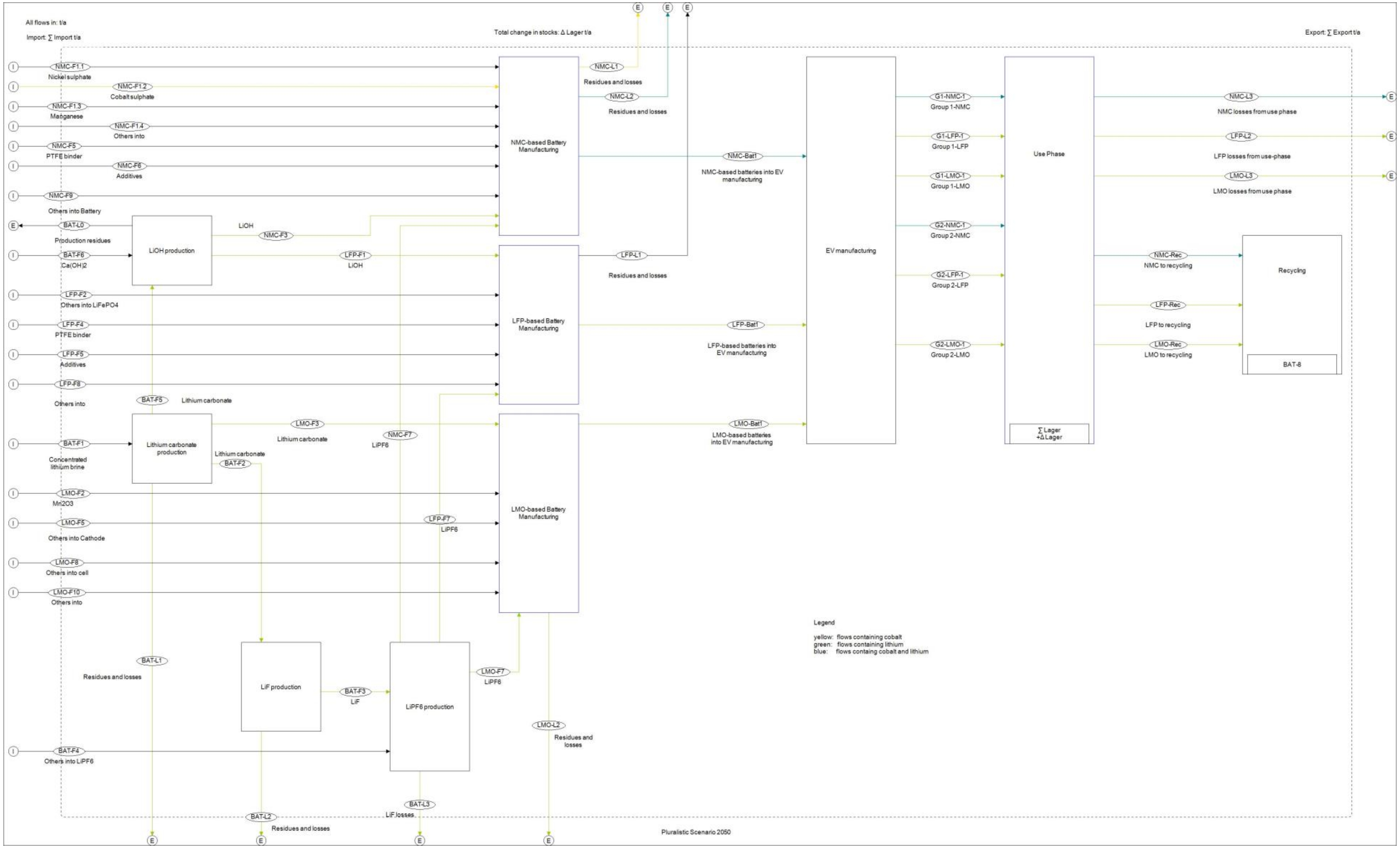
Source: Angerer, et al., (2009b, Annex).

A- 15: Fraunhofer ISI e-mobility scenarios – underlying assumptions

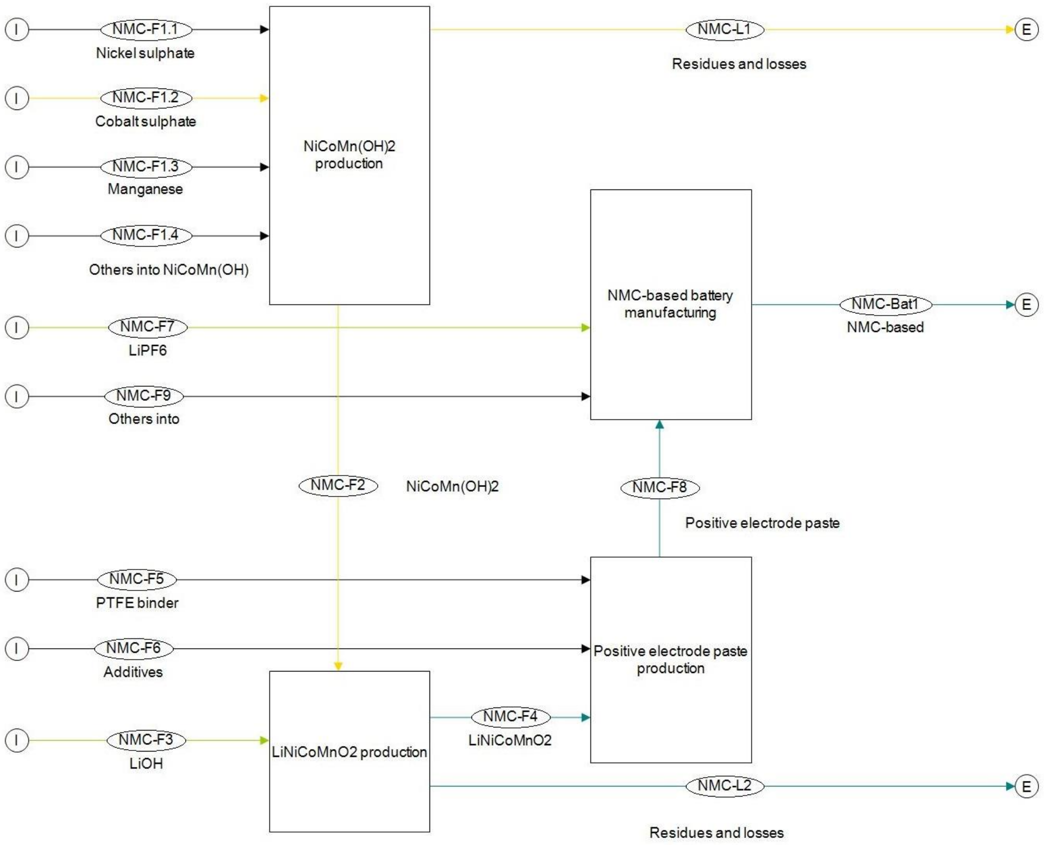
Dominant Scenario	- Hybridization becomes widely established - Technical and economic objectives are achieved - safety issues are resolved - the gravimetric energy density is significantly increased - very high prices for crude oil (above 180$/bbl) - Vehicle-to-Grid (feed-back of excess energy from the traction battery tot he grid) services and arbitrage activities are contributing to the cost effectiveness - the majority of the consumers assumes the additional acquisition costs - e-mobility dominates individual mobility - PHEVs and BEVs for urban uses become established from mid-2015; BEVs in general from mid-2025
Pluralistic Scenario	- e-mobility as one of many options to enhance the efficiency of individual mobility (diversification of fuels and powertrains) - hybridization gains relevant market shares - Technical and economic objectives are achieved - safety issues are resolved - the gravimetric energy density is increased - high prices for crude oil (above 130$/bbl) - PHEVs are used by a small share of consumers - the majority of small inner-city vehicles are BEVs - Group 2 can only partially position itself in the inner-city commercial transport sector

Source: Angerer, et al., (2009b), p.26ff.

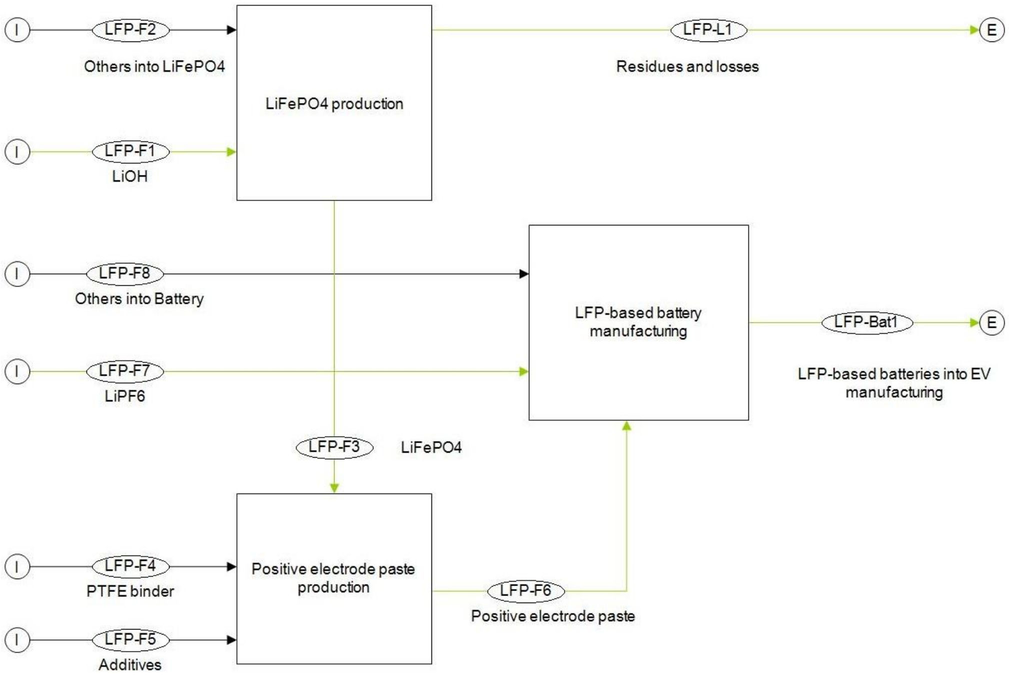
A- 16: Material Flow Model (in STAN) with Flow Codes



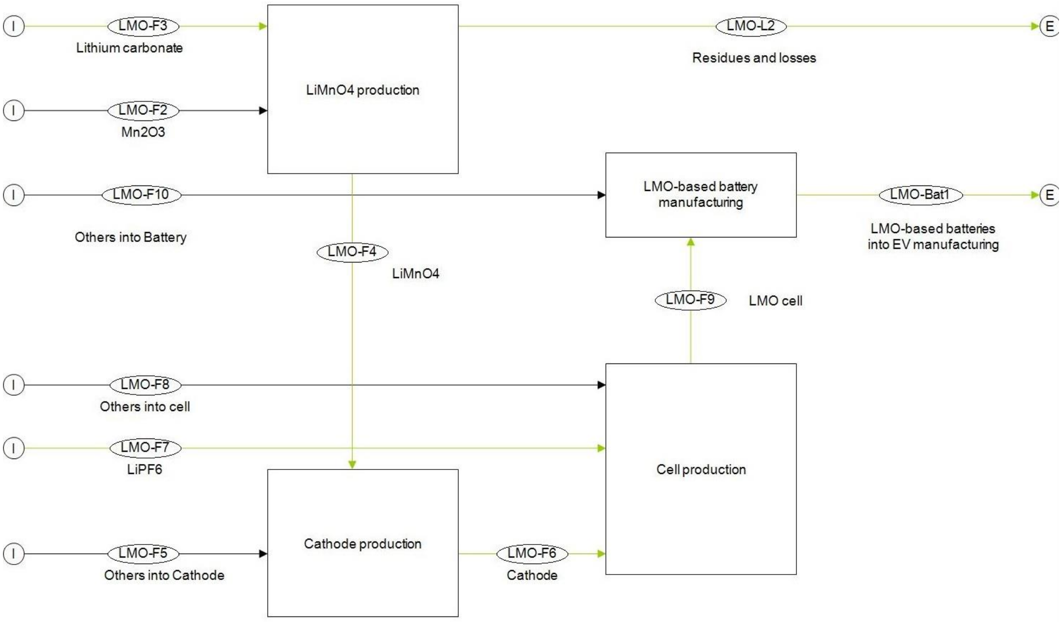
A- 17: Subsystem 1 – NMC-based battery manufacturing



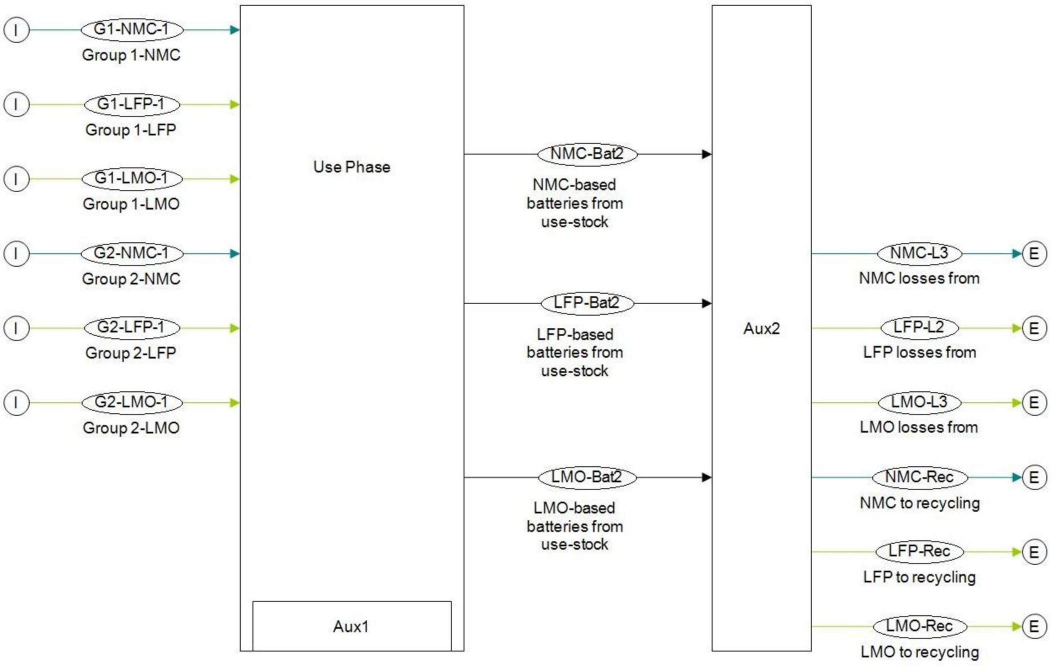
A- 18: Subsystem 2 – LFP-based battery manufacturing



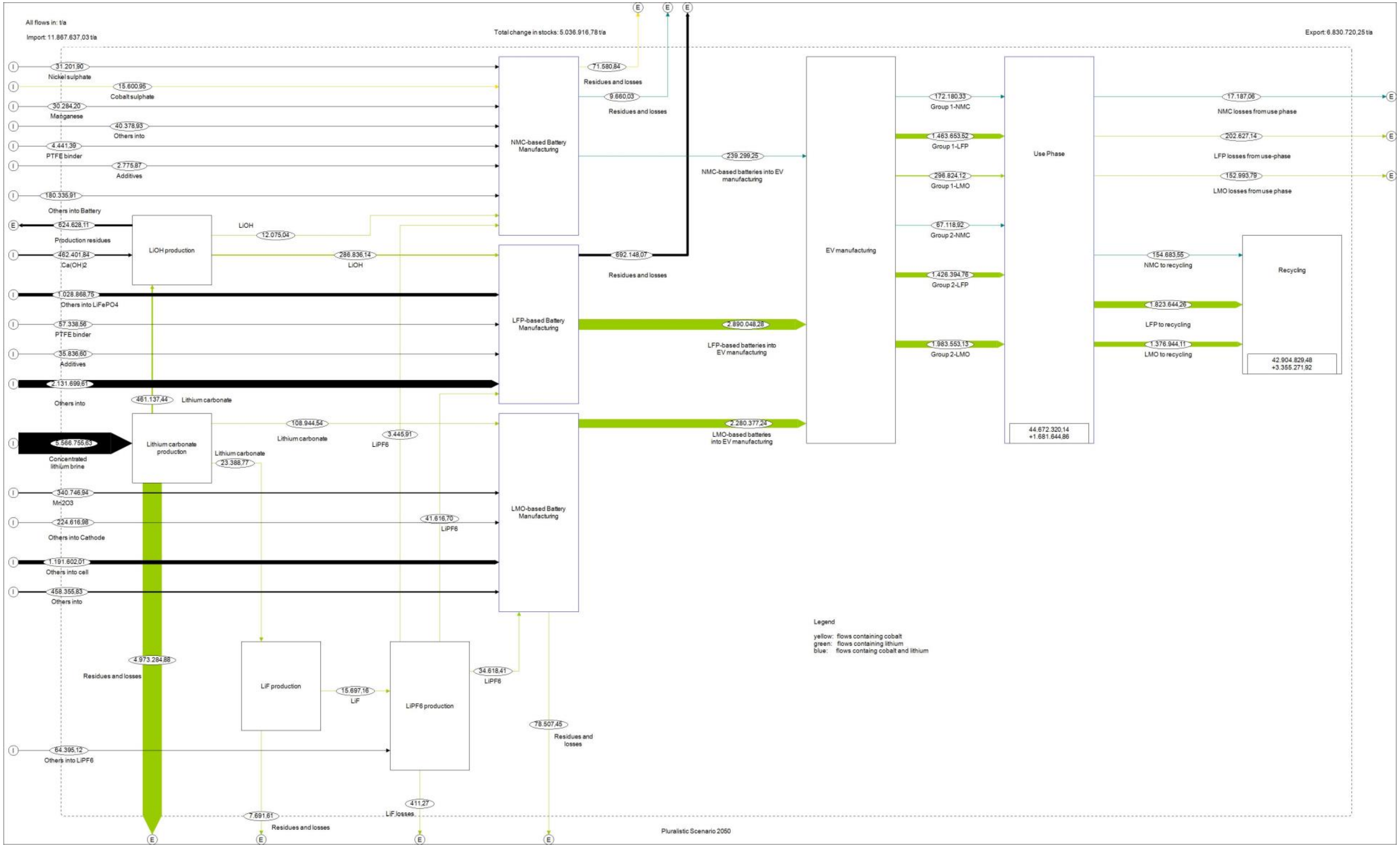
A- 19: Subsystem 3 – LMO-based battery manufacturing



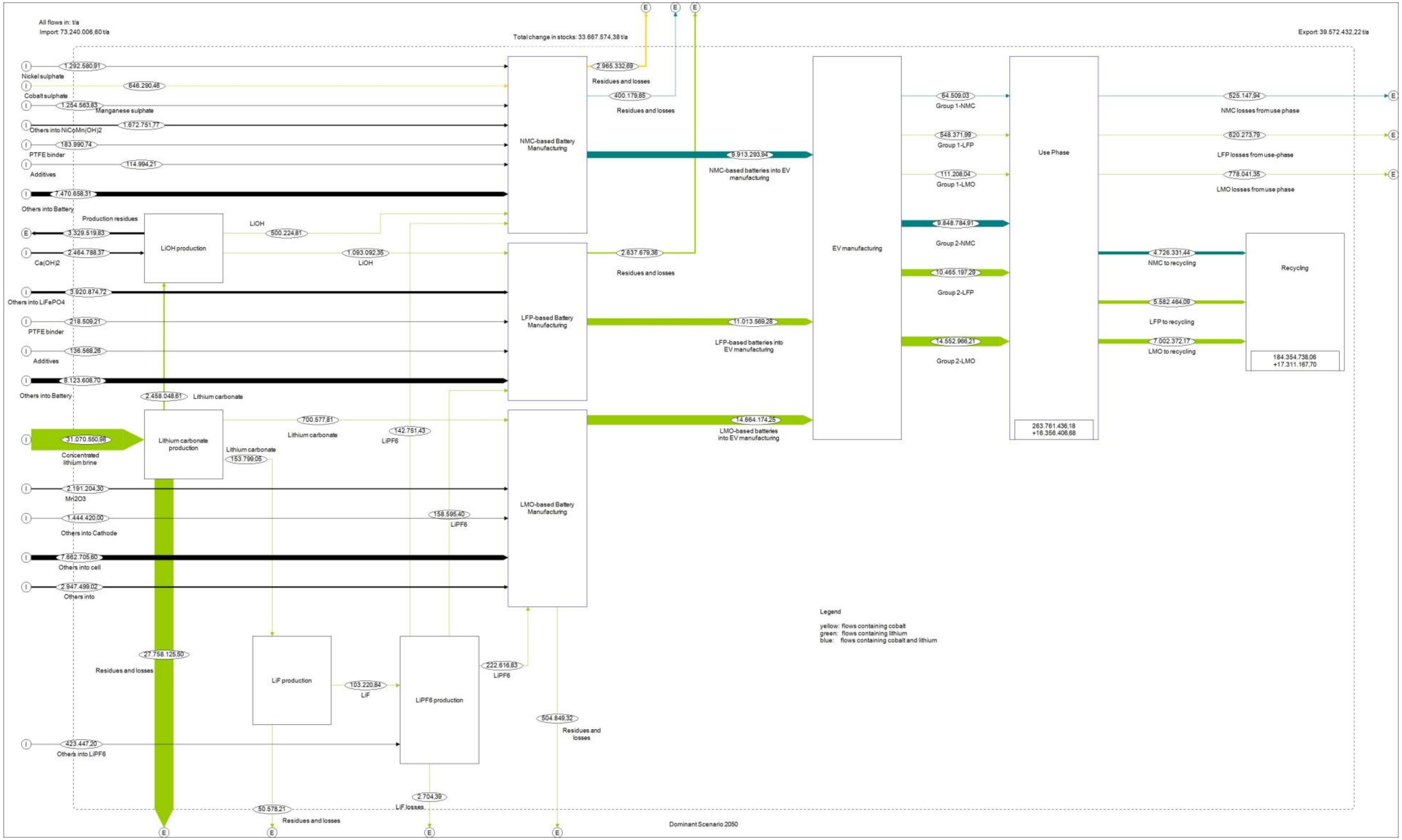
A- 20: Subsystem 4 – use phase



A- 21: STAN file – Pluralistic Scenario in 2050



A- 22: STAN file – Dominant Scenario in 2050



A- 23: Lithium contents in g/kWh from different sources

Source	Li-content (g Li/kWh)	Remarks
Konietzko & Gernuks (2011, p.13,22)	157	NMC
	101	LFP
DGS (2008) in: Angerer, et al. (2009a, p.170)	50	
Buchmann (2006) in: Angerer, et al. (2009a, p.170)	83	
Thail (2006) in: Angerer, et al. (2009a, p.170)	300	
Angerer, et al. (2009a, p.171)	180	cobalt mixed oxides
Angerer, et al. (2009a, p.171)	120	LFP
Angerer, et al. (2009a, p.172)	150	average of mix of cobalt systems and LFP in 2030
Kushnir & Sandén (2012)	140	average
Andersson & Råde (2001, p.301)	110 – 140	lithium-cobalt
Andersson & Råde (2001, p.301)	85 – 140	lithium-manganese
Andersson & Råde (2001, p.301)	100 – 140	lithium-nickel

Source: see table.

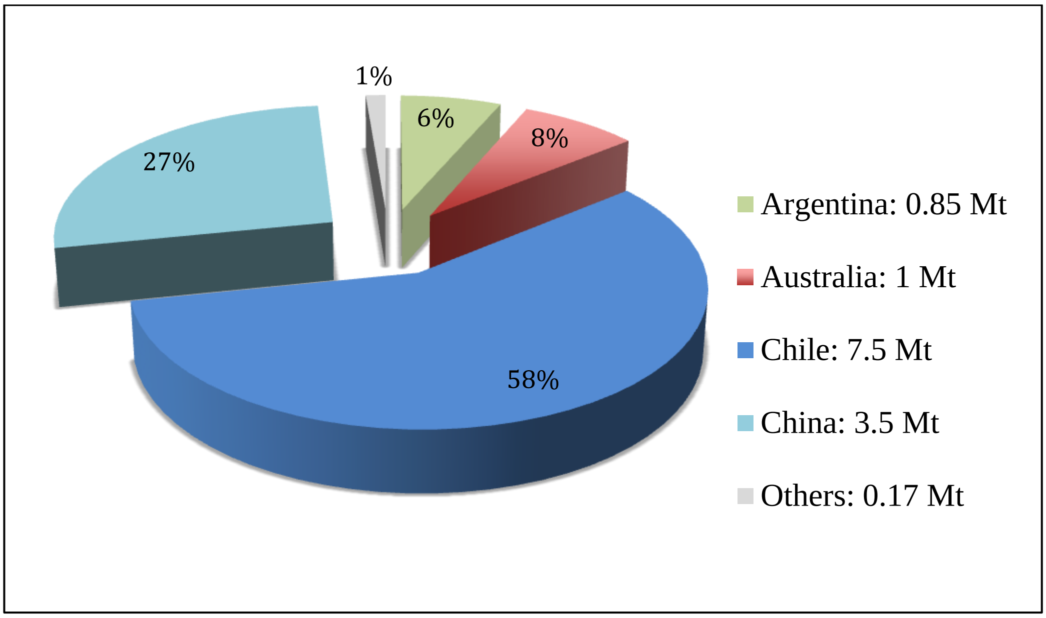
A- 24: Future lithium and cobalt demand estimations in the literature

	Lithium			**Cobalt**	
	Max. annual lithium requirements	Cumulative Li demand	Recycling potential	Max. annual cobalt requirements	Recycling potential
This study	112.000t – 622.000t[A] 370.000t – 2Mt[B] (2050)	2Mt – 9Mt[A] 7Mt – 30 Mt[B] (2050)	30%[A,C] 9%[B,C]	6.000t – 246.000t (2050)	48 – 65%[C]
Konietzko & Gernuks (2011)	150.000t – 450.000t[D, E] (2050)		17-19%[E]	400.000t – >1Mt[D, E] (2050)	20 – 34% [E]
Angerer, et al. (2009)	7.500t (2030)			20.400t – 40.800t (2030)	
Kushnir & Sandén (2012)		4 - 7Mt[F] 18 - 30.Mt[G] (2050)	ca. 25% -29%[F] <30%[G]		

Note: [A]case (2), solely traction batteries; [B]case (1), solely traction batteries; [C] both scenarios, in case of 90% resource recycling quota; [D]traction batteries and other market sectors; [E]moderate and optimistic scenario; [F]9kWh battery adoption; [G]36kWh battery adoption.

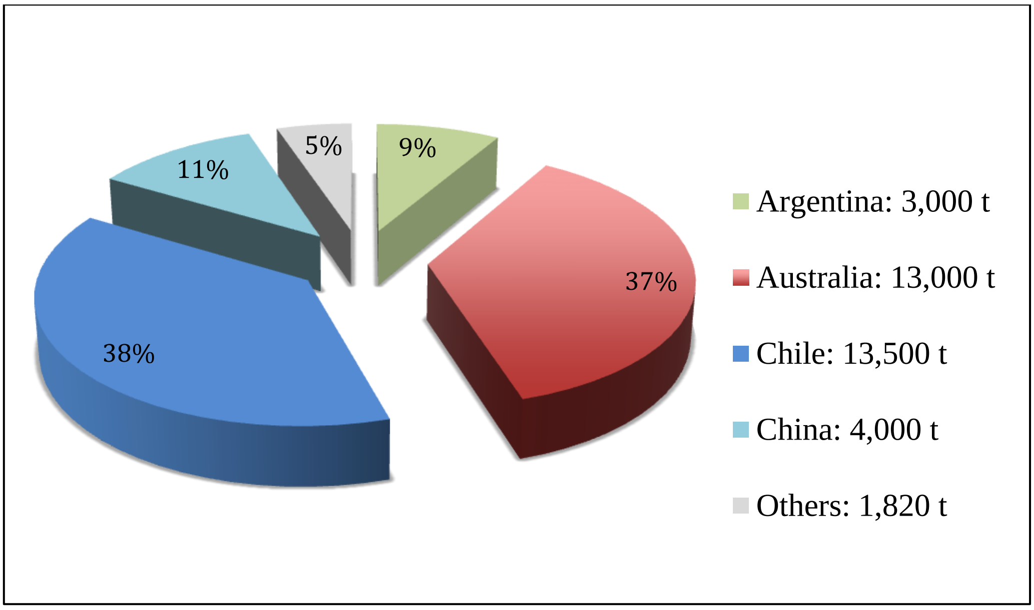
Sources: see table.

A- 25: Latest USGS lithium reserves estimates (rounded)



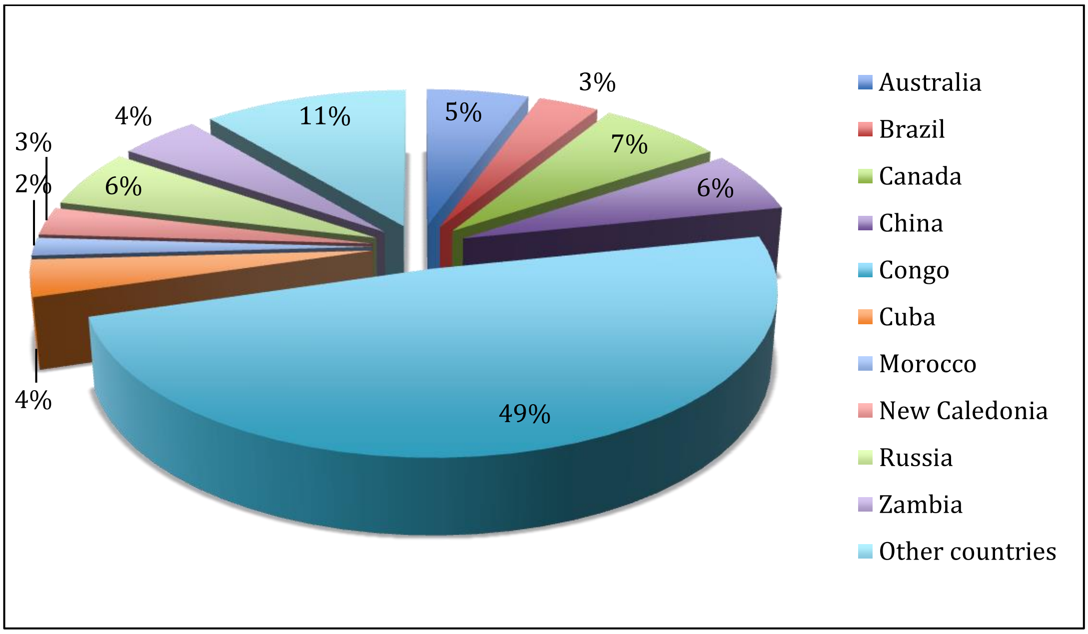
Source: based on USGS (Jaskula, 2014).

A- 26: Latest USGS lithium production estimates for 2013 (rounded)



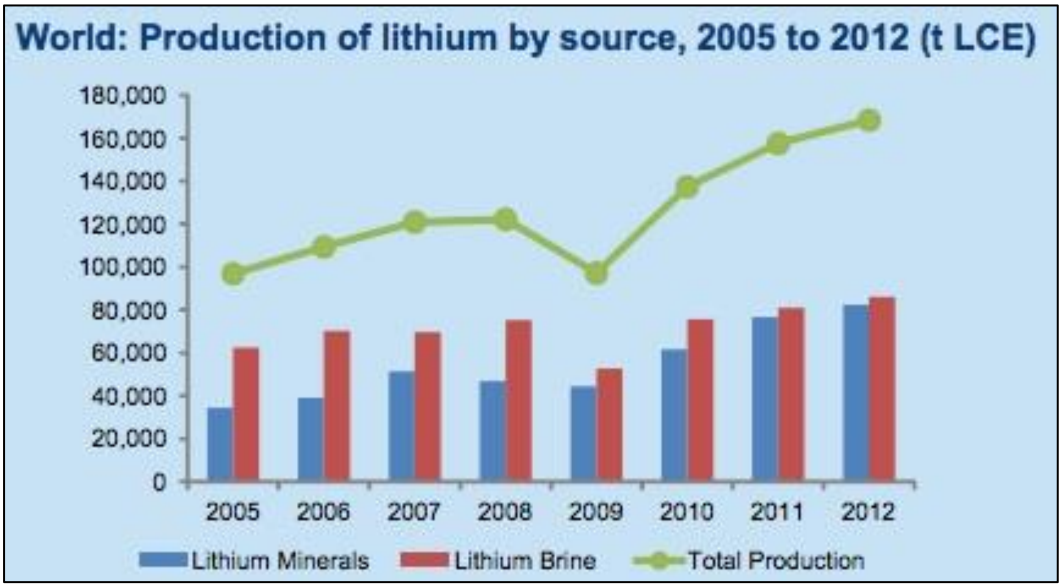
Source: based on USGS (Jaskula, 2014).

A- 27: Latest USGS cobalt production estimates for 2013 (rounded)



Source: based on USGS/Shedd, 2014.

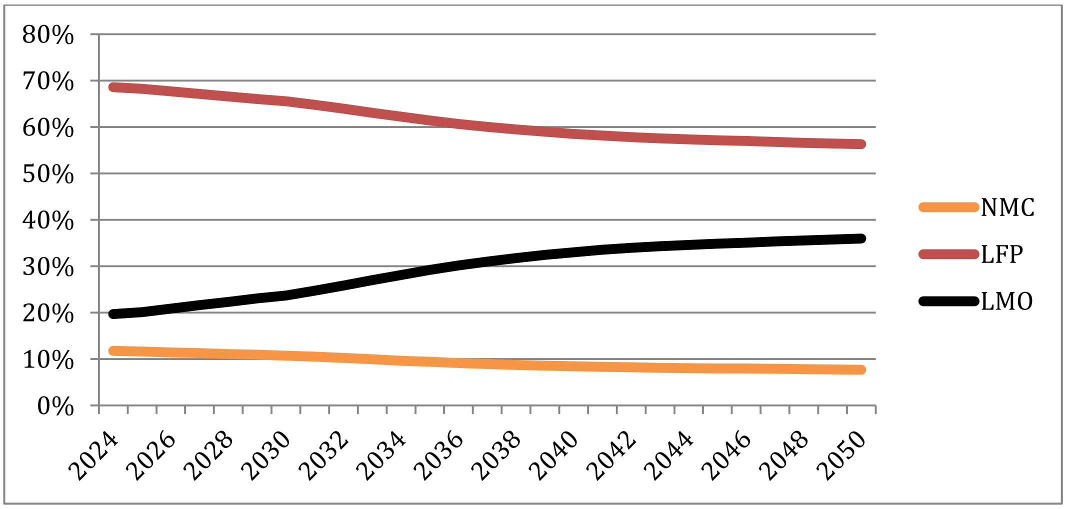
A- 28: Global production of lithium by source, 2005 to 2012 in t LCE*



* Lithium carbonate equivalent (LCE) with a lithium content of 18.9% (Vikström, et al., 2013, p.258)

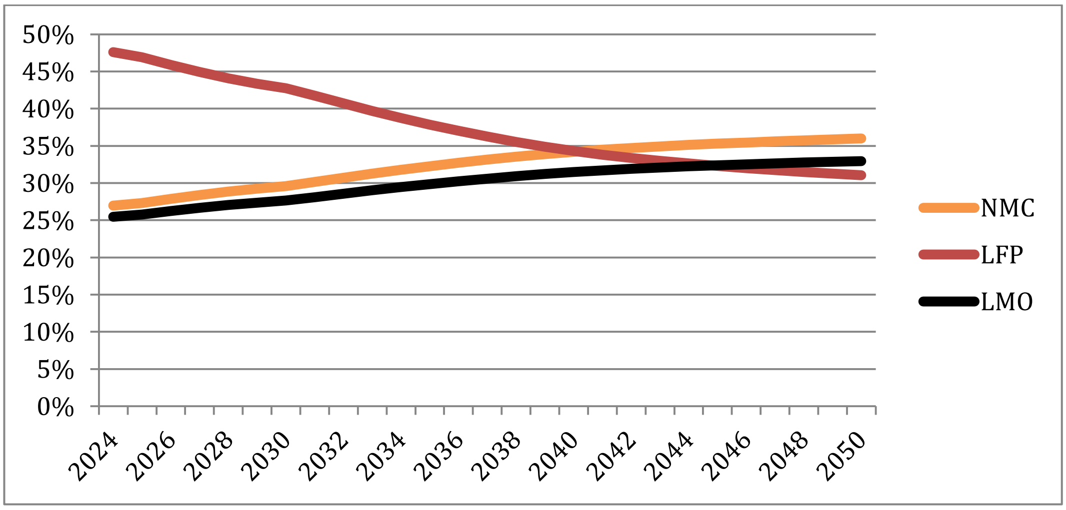
Source: Roskill (2013, p.3)

A- 29: MFA results – contribution of the three electrode materials to the lithium recycling potential in the Pluralistic Scenario



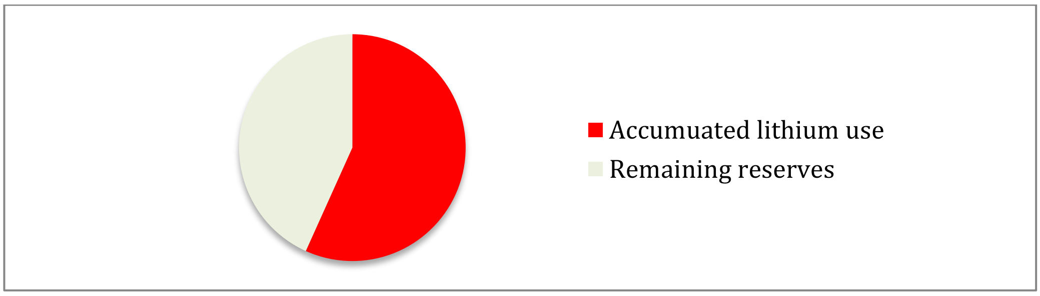
Source: own calculations.

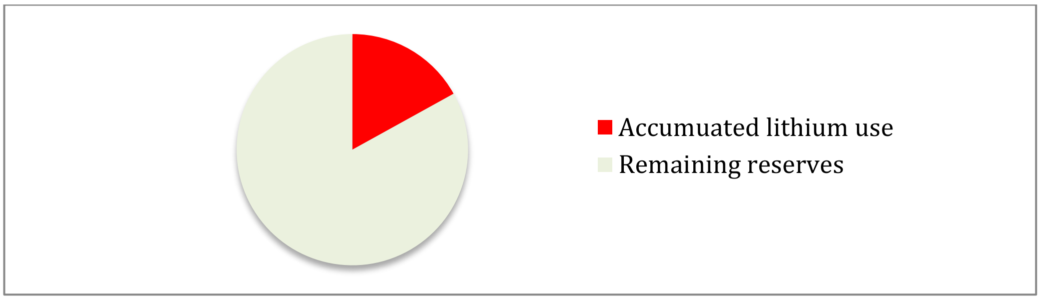
A- 30: MFA results – contribution of the three electrode materials to the lithium recycling potential in the Dominant Scenario



Source: own calculations.

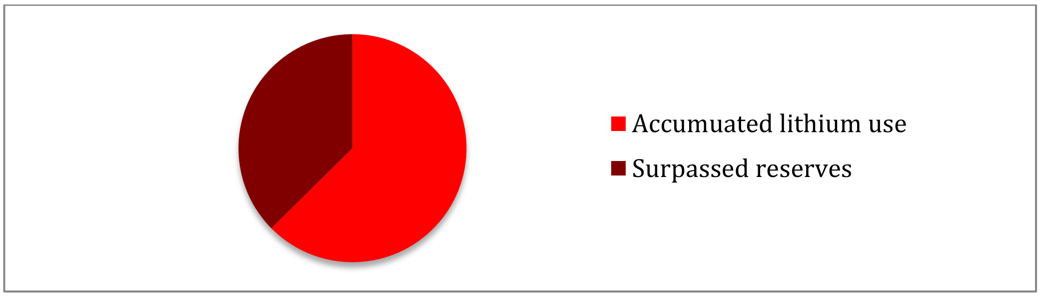
A- 31: MFA results – accumulated lithium use Pluralistic Scenario (1)/(2) against minimum lithium reserves

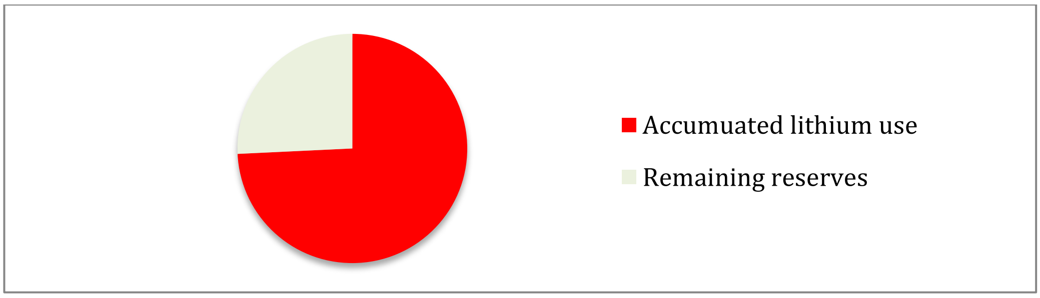




Source: own calculations; reserves of 12.1Mt lithium based on Vikström, et al. (2013, p.256)

A- 32: MFA results – accumulated lithium use Dominant Scenario (1)/(2) against minimum lithium reserves





Note: in case (1) the accumulated lithium use would be 248% of the reserves!

Source: own calculations; reserves of 12.1Mt lithium based on Vikström, et al. (2013, p.256)

Literature

Abraham, D., Knuth, J., Dees, D., Bloom, I., & Christophersen, J. (2007). Degradation of high-power lithium-ion cells – Electrochemistry of harvested electrodes. *Journal of Power Sources, 170* (2), pp. 465-475.

Allen, F., Halloran, P., Leith, A., & Clare Lindsay, M. (2009). Using Material Flow Analysis for Sustainable Materials Management. *Journal of Industrial Ecology , 13* (5), pp. 662-665.

Ammitzboell, N., & Hug, B. (2012, September 3). *Ein Land sucht seine eigenen Regeln: Sanfte Lithium-Gewinnung - das Lithium des Salar de Uyuni in Bolivien*. Retrieved May 24, 2014 from Wochenzeitung: Zeit-Fragen: http://www.zeit-fragen.ch/index.php?id=1052

Anderberg, S. (1998). Industrial metabolism and the linkages between economics, ethics and the environment. *Ecological Economics , 24,* pp. 311-320.

Andersson, B., & Råde, I. (2001). Metal Resource constraints for electric-vehicle batteries. *Transportation Research Part D , 6,* pp. 297-324.

Angerer, G., Marscheider-Weidemann, F., Lüllmann, A., Erdmann, L., Scharp, M., Handke, V., et al. (2009a). *Rohstoffe für Zukunftstechnologien.* Fraunhofer Institut für System- und Innovationsforschung (ISI); Institut für Zukunftsstudien und Technologiebewertung (IZT). Stuttgart: Fraunhofer IRB Verlag.

Angerer, G., Marscheider-Weidemann, F., Wendl, M., & Wietschel, M. (2009b). *Lithium für Zukunftstechnologien - Nachfrage und Angebot unter besonderer Berücksichtigung der Elektromobilität.* Fraunhofer ISI, Fraunhofer Systemforschung Elektromobilität (FSEM) & Innovationsallianz-Lithium-Ionen-Batterie (LIB2015), Karlsruhe.

Ayres, R. (1995). Life cycle analysis: a critique. *Journal of Resource Conservation and Recycling , 14* (199).

Ayres, R., Ayres, L., McCurley, J., Small, M., Tarr, J., & Ridgery, R. (1985). *A Historical Reconstruction of Major Pollutant Levels in the Hudson-Raritan Basin: 1880-1980.* Pittsburgh: Variflex Corp.

Baccini, P., & Brunner, P. (1991). *Metabolism of the Anthroposphere.* New York: Springer.

Baccini, P., & Brunner, P. (2012). *Metabolism of the Anthroposphere: analysis, evaluation, design.* Cambridge: MIT Press.

Baitz, M., & Wolf, M.-A. (2006). Metals and plastics - competition or synergy? In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 519-534). Dordrecht, The Netherlands: Springer.

Battery Blog . (2010, June 10). *Lithium Ion Anode Materials - Ordered and Disordered Carbon*. Retrieved April 20, 2014 from Battery Blog - Battery News, Views, and Education: http://batteryblog.ca/2010/06/lithium-ion-anode-materials-ordered-and-disordered-carbon/

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., et al. (2007). *Climate Change 2007: Synthesis Report.* IPCC, Valencia.

BMU. (2009). *Erneuerbar mobil.* Retrieved July 10, 2014 from LiBRi - Entwicklung eines realisierbaren Recyclingkonzepts für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge: http://www.erneuerbar-mobil.de/de/projekte/foerderprojekte-aus-dem-konjunkturpaket-ii-2009-2011/batterierecycling/libri

BMU. (2012). *Erneuerbar mobil.* Retrieved July 10, 2014 from EcoBatRec - Demonstrationsanlage für ein kostenneutrales, ressourceneffizientes Processing ausgedienter Li-Ionen-Batterien der Elektromobilität: http://www.erneuerbar-mobil.de/de/projekte/foerderung-von-vorhaben-im-bereich-der-elektromobilitaet-ab-2012/forschung-und-entwicklung-zum-thema-batterierecycling/ecobatrec

Brandl, M., Gall, H., Wenger, M., Lorentz, V., Giegerich, M., Baronti, F., et al. (2012). Batteries and Battery Management Systems for Electric Vehicles. *2012 Design, Automation and Test in Europe Conference and Exhibition*, (pp. 971-976).

BRGM. (2008). *Technologies innovantes et metaux High-Tech.*

Bringezu, S., & Bleischwitz, R. (2009). Introduction. In S. Bringezu, & R. Bleischwitz (Eds.), *Sustainable Resource Management* (pp. 1-10). Sheffield, UK: Greenleaf Publishing Limited.

Broussely, M., Herreyre, S., Biensan, P., Kasztejna, P., Nechev, K., & Staniewicz, R. (2011). Aging mechanism in Li ion cells and calendar life predictions. *Journal of Power Sources , 97-98*, pp. 13-21.

Brunner, P., & Rechberger, H. (2004). *Practical Handbook of Material Flow Analysis.* Boca Raton, FL, USA: Lewis Publishers.

Buchert, M., Jenseit, W., Dittrich, S., Hacker, F., Schüler-Hainsch, E., Ruhland, K., et al. (2011). *Ressourceneffizienz und ressourcenpolitische Aspekte des Systems Elektromobilität.* Arbeitspaket 7 des Forschungsvorhabens OPTUM, Öko-Institut e.V.;Umicore; TU Clausthal; Daimler AG, Darmstadt.

Buchert, M., Schüler, D., & Bleher, D. (2009). *Critical Metals for Future Sustainable Technologies and their Recycling Potential.* Öko-Institut e.V.; UNEP; United Nations University.

Burke, A. (2007). Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE, 95 (4),* pp. 806-820.

CDI. (2013). *Cobalt Facts.* Retrieved May 21, 2014 from Cobalt Development Institute (CDI): http://www.thecdi.com/cdi/images/documents/Cobalt%20Facts%20-%20Supply%20%20Demand%20-%2012.pdf

CDI. (2014). *Cobalt-the Technology Enabling Metal*. Retrieved May 21, 2014 from Cobalt Development Institute (CDI): http://www.thecdi.com/about-cobalt

Cencic, O., & Rechberger, H. (2008). Material Flow Analysis with software STAN. *Journal of Environmental Engineering and Management , 18* (1), pp. 3-7.

Cleveland, C., & Ruth, M. (1999). Indicators of dematerialization and intensity of materials use. *Journal of Industrial Ecology , 2*, pp. 15-50.

Darton Commodities Ltd. (2014). *Minor Metals: Co - Cobalt*. Retrieved May 21, 2014 from Minor Metals Trade Association: http://www.mmta.co.uk/metals/Co

Deutsche Bundesregierung. (2009). *Nationaler Entwicklungsplan Elektromobilität der Bundesregierung.* Berlin, Germany.

Dijkema, G., Reuter, M., & Verhoef, E. (2000). A new paradigm in waste management. *Waste Management , 20* (8), pp. 633-638.

Doeff, M. (2013). Battery Cathodes. In R. Brodd, *Batteries for Sustainability: Selected Entries from the Encyclopedia of Sustainability Science and Technology* (pp. 5-49). New York: Springer Science + Business.

Duvigneaud, P., & Denayeyer-de Smet, S. (1975). L'Écosystème Urbain Bruxellois. In P. Duvigneaud, P. Kestemont, & T. d. International (Ed.), *Productivité biologique en Belgique* (pp. 581-597). Bruxelles.

Eatherley, D., & Morley, N. (2008). Strategic Report by the Resource Efficiency Transfer Network. In C. Rea, *Material Security - Ensuring Resource Availability for the UK Economy.* Chester: C-Tech Innovation Ltd.

Ehrenfeld, J. (1997). Industrial ecology: a framework for product and process design. *Journal of Cleaner Production , 5* (1-2), pp. 87-95.

Enquete Kommission "Schutz des Menschen und der Umwelt" - 12. Deutscher Bundestag. (1993). *Verantwortung für die Zukunft - Wege zum nachhaltigen Umgang mit Stoff- und Materialströmen.* Bonn: Economica Verlag.

Erkman, S. (1997). Industrial ecology: a historical review. *Journal of Cleaner Production , 5* (1-2), pp. 1-10.

Ernst, C.-S., Hackbarth, A., Madlener, R., Lunz, B., Sauer, D., & Eckstein, L. (2011). Battery sizing for serial plug-in hybrid electric vehicles: A model-based economic analysis for Germany. *Energy Policy , 39*, pp. 5871-5882.

European Commission. (2014). *Report on critical raw materials for the EU.* Brussels.

European Commission. (2008). *The Raw Materials Initiative - Meeting our Critical Needs for Growth and Jobs in Europe.*

European Parliament and the Council. (2009, April 23). *Decision on the effort of Member States to reduce their GHG emissions to meet Community's GHG emissions reduction commitments up to 2020.* Retrieved January 21, 2014 from Decision No 406/2009/EC : http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0136:0148:EN:PDF#page=12

Evans, K. (2014). Lithium. In G. Gunn, *Critical Metals Handbook* (1. Edition ed., pp. 230-260). Keyworth, Nottingham, UK: John Wiley & Sons Ltd.

Fulton, L., & Eads, G. (2004). *IEA/SMP Model Documentation and Reference Case Projection.* WBCSD. WBCSD.

Gaines, L., & Cuenca, R. (2000). *Costs of lithium-ion batteries for vehicles.* Argonne National Laboratory , Center for Transportation Researcg, Argonne, IL.

Gerssen-Gondelach, S., & Faaij, A. (2012). Performance of batteries for electric vehicles on short and longer term. *Journal of Power Sources , 212,* pp. 111-129.

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., et al., (2011). Methodology of Metal Criticality Determination. *Environmental Science & Technology*, 46 (2), pp. 1063-1070.

Graedel, T. E., & van der Voet, E. (2010). *Linkages of Sustainability.* Cambridge: MIT Press.

Gruber, P., Medina, P., Keoleian, G., Kesler, S. E., & Wallington, T. (2011). Global lithium availability: a constraint for electric vehicles? *Journal of Industrial Ecology , 15,* pp. 760-775.

Hagelüken, C., & Meskers, C. (2010). Complex life cycles of precious and special metals. In T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. 163-197). Cambridge: The MIT Press.

Halada, K., Shimada, M., & Ijima, K. (2008). Forecasting of the consumption of metals up to 2050. (J. I. Materials, Ed.) *Materials Transactions , 49* (3), pp. 402-410.

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Hammer Stromman, A. (2012). *Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles - Supporting Material.* Retrieved March 19, 2014 from Wiley Online Library: http://onlinelibrary.wiley.com/store/10.1111/j.1530-9290.2012.00532.x/asset/supinfo/jiec532-sup-0001-S1.pdf?v=1&s=0ffcfad9015984dae69de3941a663e52dbe475f0

Hayner, C., Zhao, X., & Kung, H. (2012). Materials for rechargeable lithium-ion batteries. *Annual Review of Chemical and Biomolecular Engineering , 3,* pp. 445-471.

Huggins, R. (2009). *Advanced Batteries - Material Science Aspects.* New York, USA: Springer.

Huntzicker, J., Friedlander, S., & Davidson, C. (1975). Material balance for automobile-emitted lead in the Los Angeles Basin. *Environmental Science and Technology , 9* (448).

IEEE . (2014). *Lithium Batteries Take to the Road.* Retrieved April 15, 2014 from IEEE Advancing Technology for Humanity: http://spectrum.ieee.org/images/sep07/images/lithf2.gif

IRP. (2011). *Recycling rates of metals - A status report.* United Nations Environmental Programme, Working Group on the Global Metal Flows.

IRP. (2012). *Responsible Resource Management for a Sustainable World: Findings from the International Resource Panel.* United Nations Environment Programme.

Irrek, W., & Kristoff, K. (2008). Ressourceneffizienz: Warum sie verdient, viel schneller umgesetzt zu werden. (U. u. Wuppertal Institut für Kima, Ed.) *Wuppertal papers* (176).

IWR. (2012). *stan2web*. Retrieved Feburary 03, 2014 from stan2web: http://www.stan2web.net/infos/history

Jaskula, B. (2014, Feburary). *Mineral Commodity Summary: Lithium.* (USGS, Ed.) Retrieved May 20, 2014 from USGS: http://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2014-lithi.pdf

Kaiser, O., Eickenbusch, H., Grimm, V., & Zweck, A. (2008). *Zukunft des Autos.* Zukünftige Technologien Consulting der VDI Technologiezentrum GmbH, Düsseldorf, Germany.

Karlsson, S. (2006). Dematerialization of the metals turnover. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 237-247). Dordrecht, The Netherlands: Springer.

Kesler, S. (2010). Geological stocks and prospects for nonrenewable resources. In T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. 109-131). Cambridge: The MIT Press.

Kesler, S., Gruber, P., Medina, P., Keoleian, G., Everson, M., & Wallington, T. (2012). Global lithium resources: Relative importance of pegmatite, brine and other deposits. *Ore Geology Reviews , 48*, pp. 55-69.

Konietzko, S., & Gernuks, M. (2011). *Ressourcenverfügbarkeit von sekundären Rohstoffen - Potenzialanalyse für Lithium und Kobalt.* LiBRi; LithoRec.

Kushnir, D., & Sandén, B. (2012). The time dimension and lithium resource constraints for electric vehicles. *Resource Policy , 37* (1), pp. 93-103.

Kwade, A., & Bärwaldt, G. (2012). *Recycling von Lithium-Ionen-Batterien (LithoRec).* BMU funded, Braunschweig, Germany.

Linder, E. (2010). *Wohin damit? Elektromobilität und Entsorgung.* Retrieved July 10, 2014 from LithoRec - Recycling von Lithium-Ionen-Batterien: http://www.lithorec.de/fileadmin/lithorec/Dokumente/Berichte_%C3%BCber_Lithorec/Wohin_damit_-_Elektromobilit%C3%A4t_und_Entsorgung__Linder__Eva.pdf

Lipinski, K., Lackner, H., Laué, O. P., Kafka, G., Niemann, A., Raasch, E., et al. (2014). *ITWissen*. Retrieved July 10, 2014 from Memory-Effekt: http://www.itwissen.info/definition/lexikon/Memory-Effekt-memory-effect.html

Müller, T., Bilitewski, B., & Woidasky, J. (2011). Recycling von Lithium-Ionen-Batterien aus Kraftfahrzeugantrieben. *Symposium Rohstoffeffizienz und Rohstoffinnovationen.* Nürnberg, Germany.

Majeau-Bettez, G., Hawkins, T., & Hammer Stromman, A. (2011a). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electrical Vehicles. *Environmental Science and Technology , 45*, pp. 4548-4553.

Majeau-Bettez, G., Hawkins, T., & Hammer Stromman, A. (2011b). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electrical Vehicles. Supporting Information. *Environmental Science and Technology , 45*.

McLean, H., Duchin, F., Hagelüken, C., Halada, K., Kesler, S., Moriguchi, Y., et al. (2010). Stocks, flows, and prospects of mineral resources. In T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. 199-218). Cambridge: The MIT Press.

Mondal, P., Kumar, A., Agarval, V., Sharma, N., Vijay, P., Bhangale, U., et al. (2011). Crititcal Review of Trends in GHG Emissions from Global Automotive Sector. *British Journal of Environment & Climate Change , 1* (1), pp. 1-12.

Moriguchi, Y. (2010). Mineral Resources - Quantitative and Qualitative Aspects of Sustainability. In T. Graedel, E. van der Voet, T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. p. 99 -108). Cambridge: The MIT Press.

Newcome, K., Kalma, I., & Aston, A. (1978). The metabolism of a city: the case of Hong Kong. *Ambio , 7* (3).

NIMS. (2008). *Study on global flow of metals - an example of material recycling.*

Norgate, T. (2010). Deteriorating ore resources. In T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. 131-148). Cambridge: The MIT Press.

Notter, D., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., et al. (2010a). Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environmental Science and Technology , 44*, pp. 6550-6556.

Notter, D., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., et al. (2010b). Contribution of Li-ion batteries to the environmental impact of electric vehicles. Supporting information. *Environmental Science and Technology , 44*.

NPE. (2012). *Fortschrittsbericht der Nationalen Plattform für Elektromobilität (Dritter Bericht).* NPE & GGEMO. Berlin, Germany: BMVBS.

NRC. (2007). *Minerals, Critical Minerals, and the U.S. Economy.* Washington DC: National Academy Press.

OICA. (2014). *New PC registrations or sales 2005-2013*. Retrieved April 27, 2014 from International Organization of Motor Vehicle Manufacturers: http://www.oica.net/wp-content/uploads//pc-sales-2013.pdf

Paroc Group. (2014). *Sustainability* . Retrieved Feburary 28, 2014 from Paroc Group: http://www.paroc.com/knowhow/sustainability

Pasaran, A. (2009a). Battery requirements for plug-in hybrid electric vehicles - analysis and rationale. *23rd international electric vehicle symposium (EVS-232009), National Renewable Energy Laboratory* (p. 18). Anaheim: U.S. Department of Energy.

Pasaran, A., Gonder, J., & Keyser, M. (2009b). Ultracapacitor applications and evaluation for hybrid electric vehicles. *7th annual advanced capacitor world summit conference.* La Jolla: National Renewable Energy Laboratory (NREL).

Pasaran, A. (2006). Energy storage requirements analysis for advanced vehicles (fuel cell, mild hybrid, and plug-in hybrid). *NREL Deliverable Report in Fullfillment of FY2006 August Milestone for Energy Storage Task.* Midwest Research Institute (MRI).

Pavoni, F., & Bernhart, W. (2012). *The Lithium-Ion Value Chain.* Roland Berger Strategy Consultants, Istanbul.

Peters, A., Doll, C., Plötz, P., Sauer, A., Schade, W., Thielmann, A., et al. (2013). *Konzepte der Elektromobilität - Ihre Bedeutung für Wirtschaft, Gesellschaft und Umwelt.* (B. f. (TAB), Ed.) Berlin: edition sigma.

Pollet, B., Staffell, I., & Shang, J. (2012). Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. *Electrochimica Acta , 84*, pp. 235-249.

Prior, T., Guirco, D., Muss, G., Mason, L., & Behrisch, J. (2011). Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change* , pp. 1-11.

Ramoni, M., & Zhang, H. (2013). End-of-life (EoL) issues and options for electric vehicle batteries. *Clean Technologies and Environmental Policy* .

Reuter, M., & van Schaik, A. (2010). Transforming the recovery and recycling of nonrenewable resources. In T. Graedel, & E. van der Voet (Eds.), *Linkages of Sustainability* (pp. 149-162). Cambridge: The MIT Press.

Roberts, S., & Gunn, G. (2014). Cobalt. In G. Gunn, *Critical Metals Handbook* (1. Edition ed., pp. 122-147). Keyworth, Nottingham, UK: John Wiley & Sons.

Rombach, G. (2006). Limits of Metal Recycling. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 295-312). Dordrecht, The Netherlands: Springer.

Roskill. (2013). *Lithium: Market Outlook to 2017 Leaflet.* Retrieved March 27, 2014 from Roskill: http://www.roskill.com/reports/minor-and-light-metals/lithium/leaflet

Sagar, A., & Frosch, R. (1997). A perspective on industrial ecology and its application to a metals-industry ecosystem. *Journal of Cleaner Production , 5* (1-2), pp. 39-45.

Sax, N., & Lewis, R. E. (1987). *Hawley's Condensed Chemical Dictionary* (11th ed. ed.). New York: Van Nostrand Roland.

Schäper, S. (2006). Sustainability-optimised material selection and product design at Audi. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 535-562). Dordrecht, The Netherlands: Springer.

Scrosati, B. (2000). Recent advances in lithium ion battery materials. *Electrochimica Acta , 45*, pp. 2461-2466.

Scrosati, B., & Garche, J. (2010). Lithium batteries: status, prospects and future. *Journal of Power Sources , 195*, pp. 2419-2430.

Shedd, K. (2004). *Cobalt recycling in the United States in 1998.* USGS.

Shedd, K. (2014). *Mineral Commodity Summary: Cobalt.* Retrieved May 21, 2014 from USGS: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2014-cobal.pdf

Stahel, W. (2006). The role of metals for designing products and solutions in the context of a sustainable society. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 593-607). Dordrecht, The Netherlands: Springer.

Steindl-Rast, D., & Lebell, S. (2002) *Music of Silence*. Seastone, Berkeley, CA.

Tabor, R., & Haugerud, R. (2013). *North Cascades Geology*. From USGS: http://geomaps.wr.usgs.gov/parks/noca/nocageol2a.html

Tahil, W. (2007). The trouble with lithium, implications of future PHEV production for lithium demand. *Meridian International Research* .

Thielmann, A., Isenmann, R., & Wietschel, M. (2010). *Technologie-Roadmap Lithium-Ionen-Batterien 2030.* Fraunhofer-Institut für System- und Innovationsforschung (ISI). Karlsruhe, Germany: Fraunhofer Verlag.

Thielmann, A., Sauer, A., Isenmann, R., & Wietschel, M. (2012b). *Technologie-Roadmap Energiespeicher für die Elektromobilität.* Fraunhofer-Institut für System- und Innovationsforschung, Karlsruhe, Germany.

Thielmann, A., Sauer, A., Isenmann, R., Wietschel, M., & Plötz, P. (2012a). *Produkt-Roadmap Lithium-Ionen-Batterien 2030.* Fraunhofer-Institut für System- und Innovationsforschung (ISI). Karlsruhe, Germany: Fraunhofer Verlag.

Tie, S., & Tan, C. (2013). A review of energy sources and energy management system in electric vehicles. *Renewable and Sustainable Energy Reviews , 20*, pp. 82-102.

Treffer, F. (2011). *Entwicklung eines realisierbaren Recyclingkonzepts für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge (LiBRi).* BMU funded, Hanau, Germany.

Umicore. (2014). *Umicore Battery Recycling*. Retrieved July 10, 2014 from Umicore Battery Recycling: http://www.batteryrecycling.umicore.com/UBR/

UNEP. (2010). *Sustainable Lifestyles - Innovations Brief.* Retrieved January 20, 2014 from UNEP: http://www.unep.fr/scp/marrakech/taskforces/downloads/home/english/SLT%20Innovations%20Brief.pdf

Vikström, H., Davidsson, S., & Höök, M. (2013). Lithium availability and future production outlooks. *Applied Energy , 110*, pp. 252-266.

von Gleich, A. (2006b). Outlines of Sustainable Metals Industry. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 4-40). Dordrecht, The Netherlands: Springer.

von Gleich, A., Gottschick, M., Jepsen, D., & Sanders, K. (2006a). Sustainability strategies in field trial. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 249-291). Dordrecht, The Netherlands: Springer.

Wäger, P., Lang, D., Bleischwitz, R., Hagelüken, C., Meissner, S., Reller, A., et al. (2010). Seltene Metalle - Rohstoffe für Zukunftstechnologien. *(41)* . (S. A. Wissenschaften, Ed.) Zürich, Switzerland.

Wagner, R., Preschitschek, N., Passerini, S., Leker, J., & Winter, M. (2013). Current research trends and prospects among the various materials and designs used in lithium-based batteries. *Journal of Applied Electrochemistry , 43*, pp. 481-496.

WCED. (1987). *Our Common Future.* Retrieved January 17, 2014 from UN Documents: http://www.un-documents.net/wced-ocf.htm

Wellmer, F.-W., & Wagner, M. (2006). Metallic raw materials - constituents of our economy. In A. von Gleich, R. Ayres, & S. Gößling-Reisemann (Eds.), *Sustainable Metals Management* (pp. 41-69). Dordrecht, The Netherlands: Springer.

Wietelmann, U., & Bauer, R. (2000). Lithium and Lithium compounds. In *Ullmann's Encyclopedia of Industrial Chemistry.* Wiley-VCH Verlag GmbH & Co. KGaA.

Wietschel, M., & Dallinger, D. (2008). Quo vadis Elektromobilität? *Energiewirtschaftliche Tagesfragen , 58* (12), pp. 8-12.

Winter, M., & Brodd, R. (2004). What are batteries, fuel cells, and supercapacitors? *Chemical Reviews , 104*, pp. 4245-4269.

Wolfs, P. (2010). Economic assessment of "second use" lithium-ion batteries for grid support. *20th Australasian Universities Power Engineering Conference (AUPEC)* (pp. 1-6). IEEE.

Wolman, A. (1965). The metabolism of cities. *Scientific American , 213* (179).

Zackrisson, M., Avellán, L., & Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - critical issues. *Journal of Cleaner Production , 18*, pp. 1519-1529.

Ziemann, S., Mueller, D., Grunwald, A., Schebek, L., & Weil, M. (2014). Rohstoffverfügbarkeit für ein zukünftiges Mobilitäts- und Energiesystem - Was können Untersuchungen der Rohstoffkreisläufe beitragen? In U. Teipel, & A. Reller (Ed.), *3. Symposium Rohstoffeffizienz und Rohstoffinnovationen* (pp. 405-417). Stuttgart: Fraunhofer Verlag.

Statement of Authorship

I hereby declare and certify that this document and the accompanying code have been composed by myself. No other person’s work has been used without due acknowledgement in the main text of the thesis.

I do also certify that I have faithfully followed the guideline of good scientific practice as defined by the Carl-von-Ossietzky University Oldenburg.

Selbständigkeitserklärung

Hiermit versichere ich, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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Sabine Albach