Report on workshop summary for results and implications of the pilot case

Deliverable 4.2

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Table of Contents

List of Tables

List of Figures

List of abbreviations

MFA	Material Flow Analysis
LCA	Life Cycle Assessment
SDU	University Of Southern Denmark
NTNU	Norwegian University of Science and Technology
GEUS	Geological Survey of Denmark and Greenland
BGS	British Geological Survey
TU Vienna	Technische Universität Wien
IAI	International Aluminium Institute
MIT	Massachusetts Institute of Technology
WBMS	World Bureau of Metal Statistics
NGU	Geological Survey of Norway
SSB	Statistics Norway
DIRMIN	Norwegian Directorate of Mining
TNO	Netherlands Organisation for Applied Scientific Research

1 Executive Summary

The conceptual framework of MinFuture is structured as a pyramid with seven components related to Material Flow Analysis (i.e., systems, data, uncertainty, models, indicators, visualisation, and strategy & decision support). The hierarchical structure of components implies that the robustness of upper components largely relies on a good understanding of the lower components. Six material-specific workshop were organised under the umbrella of MinFuture project, aiming to identify gaps that hamper a robust mapping of raw material cycles. In each material-specific workshop, stakeholders from academia, industry, and government were brought together to discuss and comment on the current status of each material cycle. Challenges or issues of each material cycle were identified through interactive sessions. Drawn upon discussions and comments from the six material-specific workshops, we found several common gaps in Material Flow Analysis:

1. The current system definition does not correspond to challenges;
2. Data gaps need to be bridged via data harmonization and improving data reporting;
3. End-of-life management challenges are not always well conceived because some of them are yet to come.
4. Better demand-supply forecasting approaches and methods are needed;
5. Quantitative understanding of drivers and uncertainties are needed to forecast the future demands.

Possible solutions or directions that might fill the gaps were pointed out in the workshops:

1. A high resolution of life cycle stages, especially intermediate processes, is necessary in Material Flow Analysis, in order to reflect the complexity of routes and linkages in material cycles. A good dialogue with industry is of great importance when developing a system.
2. Data gaps are commonly found in output/shipment, market share, and material content at product level. The foremost task is to improve current data reporting system by incorporating material-related information. Even if data are available in some cases, inconsistent commodity code systems for shipment and trade data are still one of the major challenges. Therefore, data should be reported with metadata, which could help map data in a system.
3. To understand the dynamics and feedbacks within a material cycle or across material cycles, stocks (including reserves and societal stocks) should be put emphasis on in demand and supply forecasting models. Quantitative forecasting models and scenarios should refine their resolution on technology development (e.g., design, substitution, market share, and so on).

2 Introduction

Robust knowledge on global material cycles should underpin decisions towards secure and sustainable supply of raw materials. However, such knowledge is currently highly fragmented, dispersed and varies significantly between different commodities, countries or life cycle stages, making the integration of data and information impossible. A common 'language' enabling the assimilation of existing knowledge is missing. The purpose of MinFuture is the development of a common approach to material flow analysis (MFA) and the establishment of international collaboration. MinFuture brings together 16 international partners from universities, public organizations and companies, to provide transparency about existing MFA approaches, identify information gaps concerning global material flows, and develop a framework towards a roadmap to monitor the physical economy of materials.

The conceptual framework of MinFuture is structured in a pyramid (see http://www.minfuture.eu/themes) with seven MFA-related components. The hierarchical structure of the components implies that the robustness of the components on the higher levels depends on the robustness of the components on the lower levels. The system and data form the foundation of the common methodology. Before we go forward to develop models and scenarios, a good understanding of four dimensions (i.e., stages, trade, layers, and time) related to material cycles is needed to guarantee the robustness of models, scenarios, indicators, and decision making based on them. Issues in the four dimensions or challenges that hinder the development of the common methodology are needed to be identified by collaboration between academia, industry, and government.

To do so, six workshops were conducted on specific materials from late April to early May of 2018. These six workshops aimed at bringing together stakeholders (e.g., material producers, end users, recyclers, and policy makers) relevant to each individual material. The workshops were structured around small interactive sessions and presentations which allow all participants to enter into practical discussion.

To frame the discussion of the workshops, the concepts of MinFuture common methodology and seven-component pyramid were presented as an introductory session in workshops to let participants have an overview of the main objectives of MinFuture project. Short presentations on the current status of the individual material in each workshop served as triggers for discussions on major challenges or issues along lifecycle stages of the individual material. In each workshop, we aimed at collecting comments and thoughts on the current status and challenges from different aspects of the individual material cycle. There were inputs from different stakeholders, especially from industries, who provided valuable insights into the main barriers in developing global raw material cycles.

This report provides an overview of the six material-specific workshops with background information and objectives, summaries of the presentations and discussions, and suggestions for the ways forward. The results of these six workshops were used to refine the mapping of the six case materials, guide subsequent case studies, and form the basis of the framework and roadmap for monitoring the physical economy.

3 Neodymium & Platinum Workshops

3.1 Date, Place, and Participants

Table 1 Date, place, and participants of neodymium workshop

@ Benz (Ø31-605-2), SDU / TEK, Odense, Denmark May 3rd 2018, Neodymium	
Name	**Affiliation**
Gang Liu	SDU
Daniel Müller	NTNU
Zhi Cao	SDU
Kasper Rasmussen	SDU
Ciprian Cimpan	SDU
Wu Chen	SDU
Oliver Diehl	Fraunhofer
Per Kalvig	GEUS
Maren Lundhaug	NTNU
Romain Billy	NTNU
Badrinath Veluri	Grundfos
Adriana Cristina Urda	Siemens Gamesa Renewable Energy
Henrik Wenzel	SDU

Table 2 Date, place, and participants of platinum workshop

@ U176 (Ø22-604-1), SDU / TEK, Odense, Denmark May 4th 2018, Platinum	
Name	**Affiliation**
Oliver Diehl	Fraunhofer Institute for Silicate Research, Germany
Daniel Müller	NTNU
Romain Billy	NTNU

Maren Lundhaug	NTNU
Gang Liu	SDU
Kasper Rasmussen	SDU
Zhi Cao	SDU
Henrik Wenzel	SDU
Mikkel Juul Larsen	EWII catalysts
Shuang Ma Andersen	SDU Chemical Engineering
Gus Gunn	BGS
Evi Petavratzi	BGS
Colton Bangs	Umicore
Marcus Berr	SDU
Shehab Elmasry	SDU

3.2 Objectives

3.2.1 Neodymium Workshop

The main objective of the neodymium workshop is to test out the framework we developed in MinFuture towards a roadmap to monitor the physical economy/material stocks and flows of neodymium and especially its use in wind turbines. We aim to bring together active stakeholders and researchers in the field of Neodymium life cycle and wind energy industry. In the neodymium workshop, we will present our conceptual framework and preliminary results on neodymium material flows and demand-supply forecasting associated with the Danish future energy scenarios. Then we would like to ask our stakeholders to give feedback on i) the methodological framework itself, ii) the current mapping of the neodymium material cycle and its dynamics, and (iii) relevance of this knowledge for businesses/industry.

3.2.2 Platinum Workshop

The main objective of the platinum workshop is to test out the framework we developed in MinFuture towards a roadmap of the future of platinum and its use in electrolysis and fuel cells. We aim to bring together active stakeholders and researchers in the field of platinum life cycle and catalyst industry. In the platinum workshop, we will present our conceptual framework and preliminary results on platinum material flows and demand-supply forecasting associated with European energy scenarios. Then we would like to ask our stakeholders to give feedback on (1) the methodological framework itself, (2) the current mapping of the platinum material cycle and its dynamics, and (3) relevance of this knowledge for businesses/industry.

3.3 Contents of Workshops

3.3.1 Neodymium Workshop

Table 3 Contents of neodymium workshop

Time	Theme	Content
12:00-12:30	Around the table	Welcome and around the table with light lunch
12:30-13:10	Introduction	• Introduction to MinFuture and framework (10 mins) • Regional Nd cycle and the materials demand of future Danish wind energy systems (15 mins) • Global Nd demand-supply forecasting and criticality assessment (15 mins)
13:10-14:40	Challenges/issues	• Introduction and an exercise on "ranking of challenges" • Supply constraints (e.g., development of reserves, production technology, and trade/geopolitics) • Demand forecast (e.g., market prospects, substitution, and lifetime) • Recycling and end-of-life management challenges (e.g., EoL collection, recovery, and regulation)
14:40-15:00	Coffee break	
15:00-15:50	System	Interactive session on system definition (30 mins break-out, and 20 mins reporting and plenary)
15:50-16:30	Data	Interactive session on data sources, availability, and quality
16:30-17:15	Wrapping up	Addressing gaps, way forward, and future collaboration

3.3.2 Platinum Workshop

Table 4 Contents of neodymium workshop

Time	Theme	Content
09:00-09:20	Around the table	Welcome and around the table with coffee and bread
09:20-10:00	Introduction	• Introduction to MinFuture and core concepts (10 mins) • Introduction to V-sustain (10 mins) • Preliminary results on global and regional Pt cycle (20 mins)

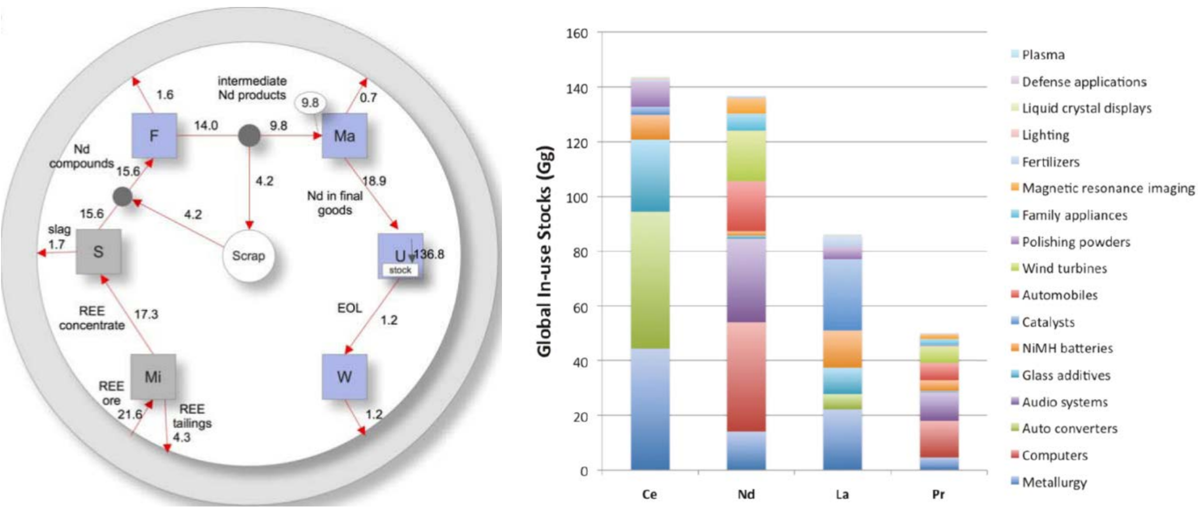
10:00-11:30	Challenges/issues	• Introduction and an exercise on "ranking of challenges" • Supply constraints (e.g., development of reserves, production technology, and trade/geopolitics) • Demand forecast (e.g., market prospects, substitution, and lifetime) • Recycling and end-of-life management challenges (e.g., EoL collection, recovery, and regulation)
11:30-12:20	System	Interactive session on system definition (30 mins break-out, and 20 mins reporting and plenary)
12:20-13:00	Lunch	
13:00-13:40	Data	Interactive session on data sources, availability, and quality
13:40-14:30	Wrapping up	Addressing gaps, way forward, and future collaboration

3.4 Status, Learning Outcomes, and Challenges

3.4.1 Status of Neodymium Cycle

The first estimate on global in-use stocks of the rare earth elements employed a top-down approach to characterise the global neodymium cycle (Figure 1). The global neodymium cycle comprises four stages: production, fabrication and manufacturing (F&M), use, and waste management and recycling (WM&R). Neodymium flows from manufacture into use rely on data for the distribution of neodymium into products.

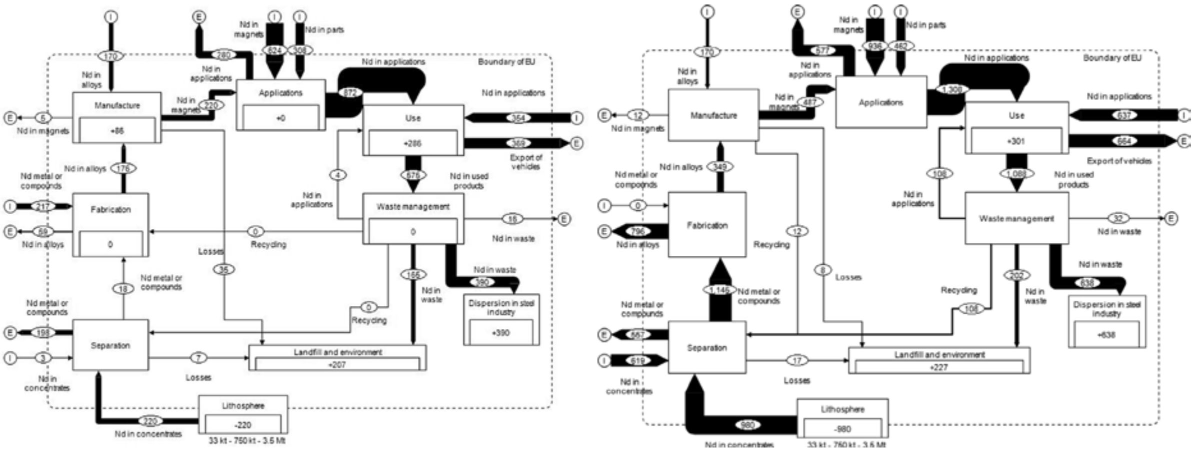
Figure 1: First estimate of global neodymium flow cycle



Sources: (Du and Graedel 2011b, 2011a)

At the regional level, a combination of top-down method and bottom-up data (e.g., production and trade of individual neodymium-contained products) was employed to map the European neodymium cycle (Figure 2). A forecast of European neodymium cycle in 2020 was then conducted based on market outlook of intermediate products.

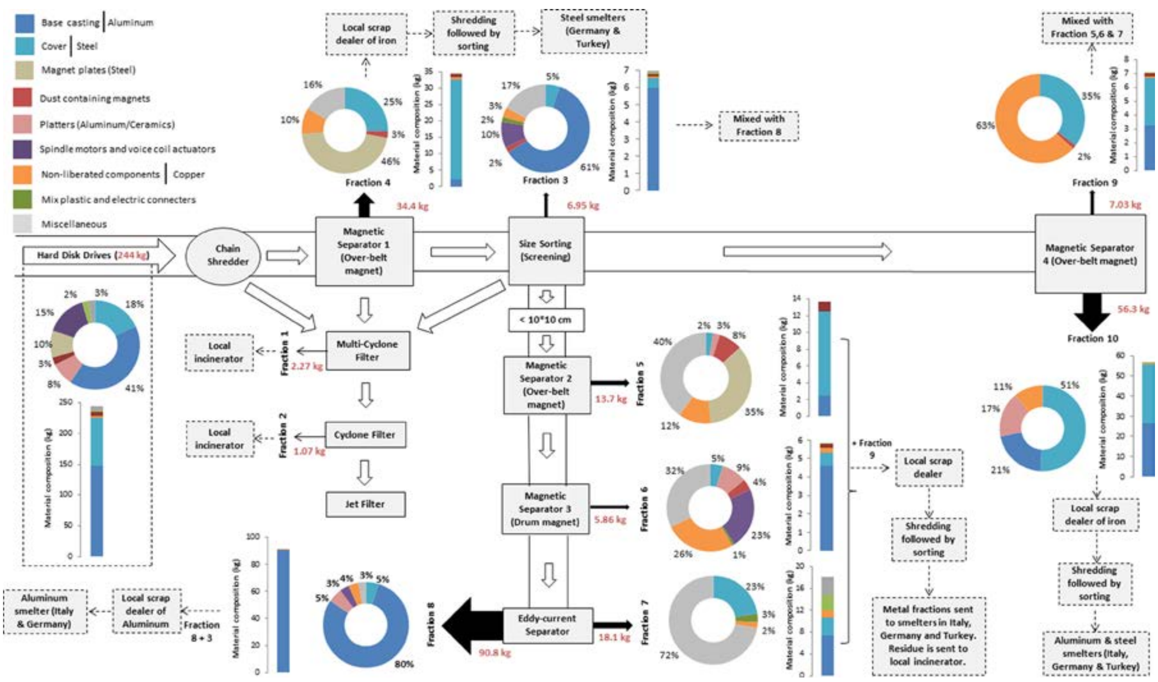
Figure 2: Historical and prospective neodymium flow cycle at regional level (A European case)



Sources: (Guyonnet et al. 2015; Rollat et al. 2016)

Most studies normally simplified the end-of-life stages. A case study on hard disk drives in Denmark gives a good example of how to track neodymium flows in end-of-life stages (Figure 3). Bottom-up data were collected from waste treatment centre. This study found that the shredding-based treatment processes resulted in almost 99% loss of neodymium in end-of-life hard disk drives.

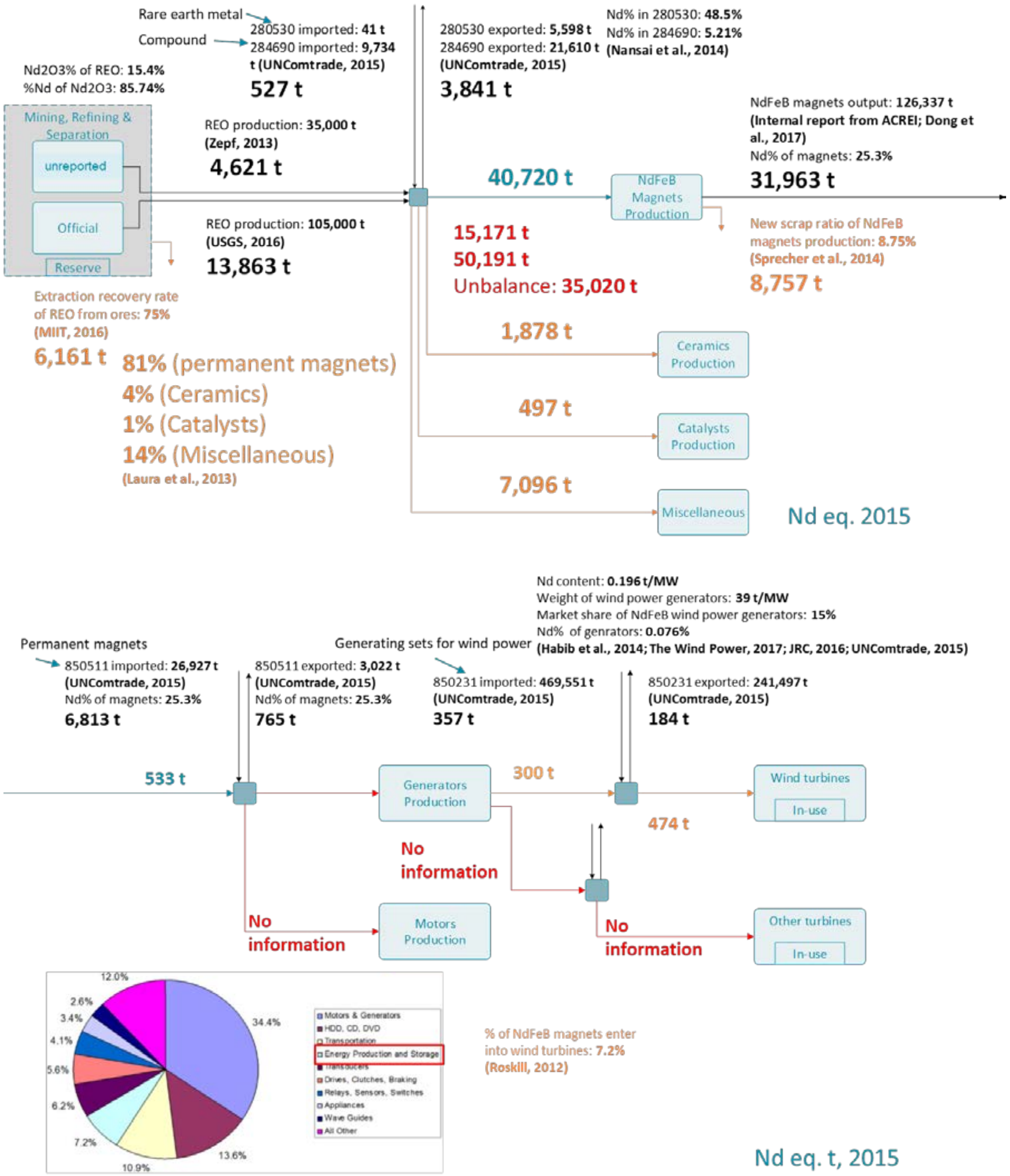
Figure 3: Tacking neodymium flow in end-of-life products in Denmark: A case study on computer hard disk drive



Sources: (Habib, Parajuly, and Wenzel 2015)

The fragmentation of data leads to an enormous imbalance in Chinese neodymium cycle (Figure 4). Large uncertainties remain in neodymium production data and trade data, especially production data that are from USGS. Neodymium production data were estimated based on export quota. However, illegal mining activities and part of legal mining activities might be unreported. At European level, the lack of information on market distribution of neodymium hinders the mapping of neodymium cycle.

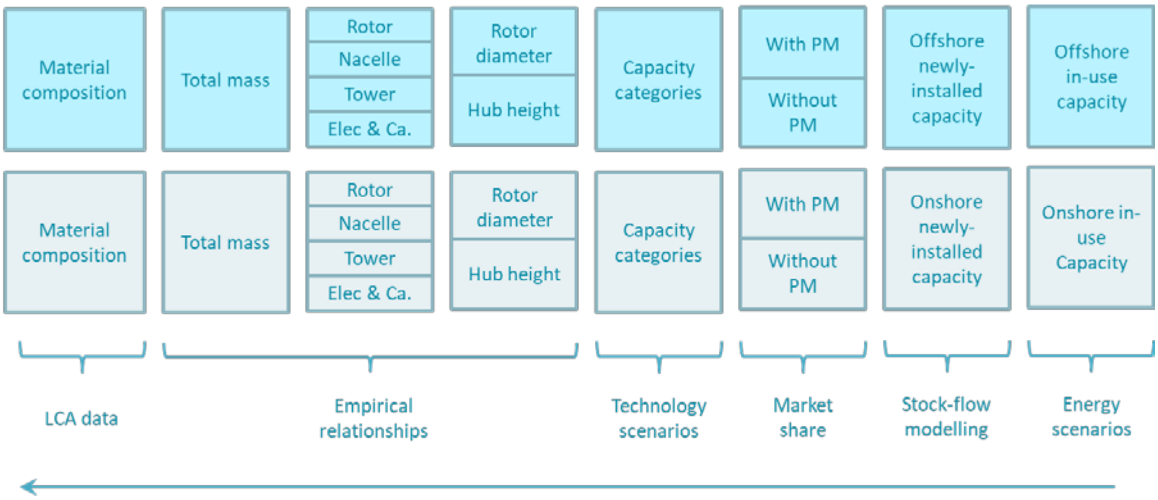
Figure 4: Tracing the neodymium flow related to wind energy system at region level (China and EU28)



Sources: developed by authors

A stock-driven model with bottom-up technology-specific information is developed to forecast the demand and potential secondary supply of neodymium in Danish wind energy system (Figure 5). Energy scenarios are served as the major driver of the stock-driven model. Empirical data (e.g., wind turbine design specification and LCA inventory) are used to transform the capacity of wind turbines to material demands.

Figure 5: Forecasting materials demand of future Danish wind energy system

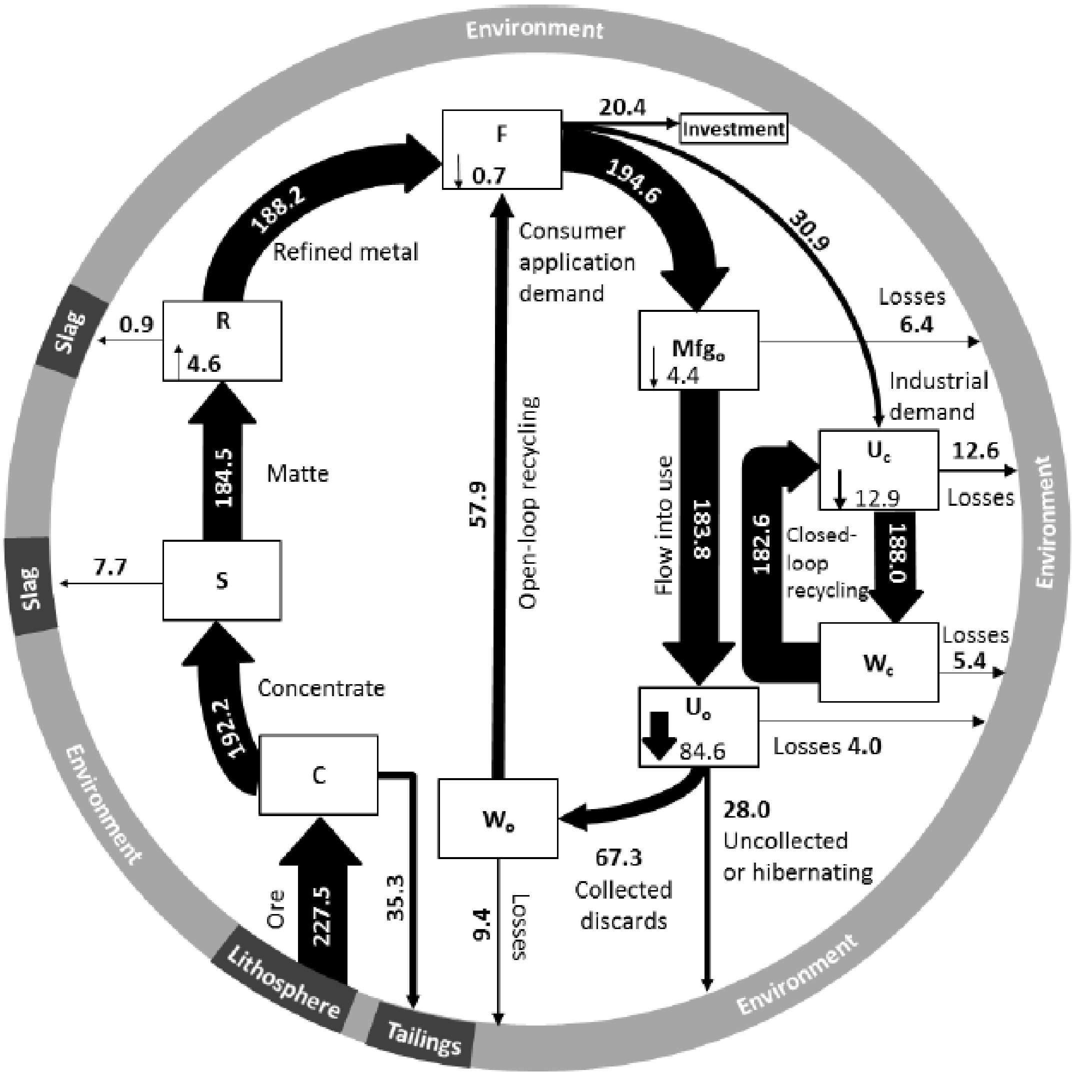


Sources: developed by authors

3.4.2 Status of Platinum Cycle

The Yale Stocks and Flow (STAF) framework was employed to construct a contemporary platinum cycle (Figure 6). This study distinguished “open-loop” recycling and “closed-loop” recycling. The “open-loop” recycling occurs in consumer applications (e.g., auto-catalyst, jewellery, dental, and electronics), while the “closed-loop” recycling occurs in industrial applications (e.g., chemical, petroleum, electrochemical, and glass industries). In the “closed-loop” recycling, the end-of-life platinum is sent for recovery on a toll-basis without a change of ownership.

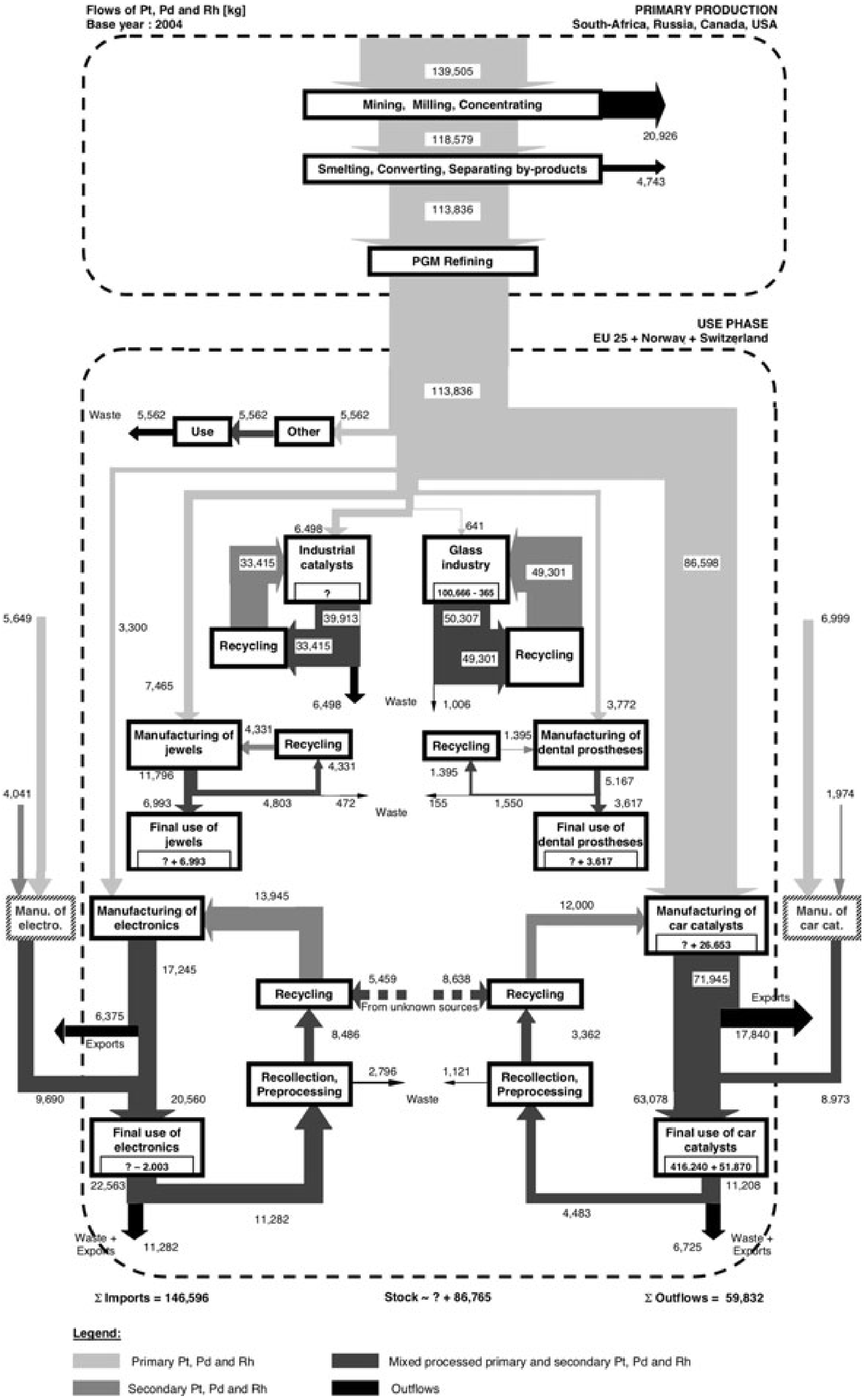
Figure 6: Global anthropogenic flows of Pt in year 2010



Sources: (Nedal 2015)

A European platinum cycle was mapped but focused on environmental impacts related platinum production (Figure 7). Several major platinum users (e.g., automotive, catalyst convertors, chemical and glass industries) are identified in this study. Similar recycling fashions (i.e., closed-loop and open-loop) are presented in this study as well.

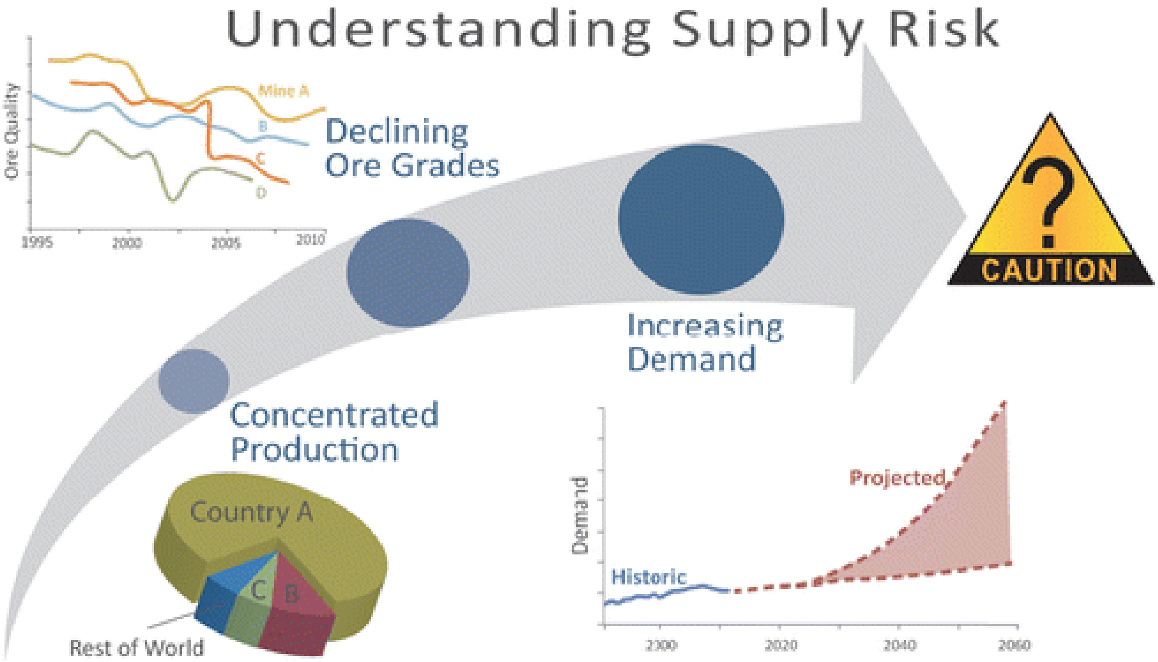
Figure 7: Platinum group metal flows of Europe



Sources: (Saurat and Bringezu 2008)

Drawn upon future automotive industry growth and automotive sales shifts toward new technologies, potential risks for decreased platinum availability were evaluated (Figure 8). Due largely to sales growth in fuel cell vehicles, an automotive fleet that meets 450 ppm greenhouse gas stabilization goals would require within 10% of historical growth rates of platinum supply before 2025. Methodologically, this study does not consider stock dynamics in the demand-forecasting model.

Figure 8: Platinum availability for future automotive technologies



Sources: (Alonso, Field, and Kirchain 2012)

3.4.2 Learning Outcomes and Challenges

Several major learning outcomes and challenges are drawn upon comments from neodymium and platinum workshops.

6. The current system definition does not correspond to challenges yet. For instance, resolution of life cycle stages, especially intermediate processes, is not always high enough. The complexity of end-of-life stages of neodymium or platinum cycle (e.g., repowering of magnets; electrochemical recycling of Pt) is not completely reflected in the current system. Linkages of material cycles are not included (e.g., co-products and shredded waste).
7. Data gaps need to be bridged via data harmonization and improving data reporting. Data gaps are commonly found in output/shipment, market share, and material content at product level. Even if data are available in some cases, inconsistent commodity code systems for shipment and trade data are still one of the major challenges. Misinterpretation of reported data often happens due to the lack of metadata (i.e., system context).
8. End-of-life management challenges are not well conceived because they are yet to come. Demands of Nd/Pt-contained products are still expanding; therefore, end-of-life Nd/Pt-contained products are of low priority. The incompatibility of products between multiple producers and ever-changing quality requirement hinder the recycling of Nd/Pt-contained products.
9. Better demand-supply forecasting approaches and methods are needed. To go beyond indicator-based criticality assessment and LCA studies, dynamics and feedbacks should be included, which requires understanding of stocks. A higher resolution on technology development (e.g., design, substitution, market share, and

so on) is needed in the demand forecasting models. A better understanding of international trade along the whole value chain is needed to develop multiregional models. The definition of reserves should better understood to facilitate the supply forecasting.

10. Quantitative understanding of drivers and uncertainties are needed to forecast the future demands. Proper visualisation is needed as well to communicate results with stakeholders. In-use products stock development (e.g., installed capacity), lifetime, bottom-up mass determination (e.g., technology specific data), market share (e.g., penetration rate of PM wind turbines or fuel cell vehicles), and material substitution (e.g., material content variation) are identified as major challenges in the quantitative analysis.

4 Aluminium & Cobalt Workshop

4.1 Date, Place, and Participants

Table 5 Date, place, and participants of aluminium & cobalt workshop

@ MRC Conference Centre, 13th Floor, One Kemble Street, London WC2B 4AN April 27th 2018	
Name	**Affiliation**
Daniel Müller	NTNU
Romain Billy	NTNU
Maren Lundhaug	NTNU
Evi Petavratzi	BGS
Carolin Kresse	BGS
Teresa Brown	BGS
Gus Gunn	BGS
Astrid Allesch	TU Vienna
Carol-Lynne Pettit	Cobalt Institute
Mark Mistry	Nickel Institute
Bartłomiej Wojdyło	CanPack
Rafal Niemiec	CanPack
Birte Ewers	ifeu Heidelberg gGmbH
Chris Bayliss	IAI

Marlen Bertram	IAI
Jonathan Cullen	Cambridge University
Elsa Olivetti	MIT
Sue Eales	WBMS
Anton Löf	RMG Consulting
Dominic Wittmer	EC Joint Research Centre
Richard Herrington	The Natural History Museum
Ronald Gillner	Hydro Aluminium Rolled Products GmbH

4.2 Objectives

The main objectives of this workshop is to i) find out how to improve the mapping and forecasting of Al and Co cycles, including status, goals, and ways forward; ii) test and improve the MinFuture framework, using Al & Co as examples; and iii) facilitate learning across the supply chain, including countries, metals, and sectors.

4.3 Contents of Workshop

Table 6 Contents of aluminium and cobalt workshop

Time	Content
08:30-09:00	Registration and coffee Al workshop
09:00-09:15	Welcome and introduction (Evi Petavratzi, BGS)
09:15-09:40	Introduction to the MinFuture project (Daniel Müller, NTNU)
09:40-10:05	Status of tracking aluminium (Romain Billy, NTNU)
10:05-10:30	Trends, challenges, and opportunities (Evi Petavratzi, BGS)
10:30-10:45	Break
10:45-11:15	Gaps; vision for tracking Al in 10 years (Daniel Müller, NTNU)

11:15-11:45	Addressing the gaps (Daniel Müller, NTNU)
11:45-12:00	Summary and conclusion (Evi Petavratzi, BGS)
12:00-13:00	Lunch and registration Co workshop
13:00-13:15	Welcome and introduction (Evi Petavratzi, BGS)
13:15-13:40	Introduction to the MinFuture project (Daniel Müller, NTNU)
13:40-14:05	Status of tracking cobalt (Maren Lundhaug, NTNU)
14:05-14:30	Trends, challenges, and opportunities (Evi Petavratzi, BGS)
14:30-14:45	Break
14:45-15:15	Gaps; vision for tracking Co in 10 years (Daniel Müller, NTNU)
15:15-15:45	Addressing the gaps (Daniel Müller, NTNU)
15:45-16:00	Summary and conclusion (Evi Petavratzi, BGS)

4.4 Status, Learning Outcomes, and Challenges

4.4.1 Aluminium

4.4.1.1 Status of Aluminium Cycle

Romain Billy (NTNU) provided a presentation of the status of the aluminium cycle. The presentation gave an overview of the evolution of the aluminium cycle and issues addressed so far (Table 7).

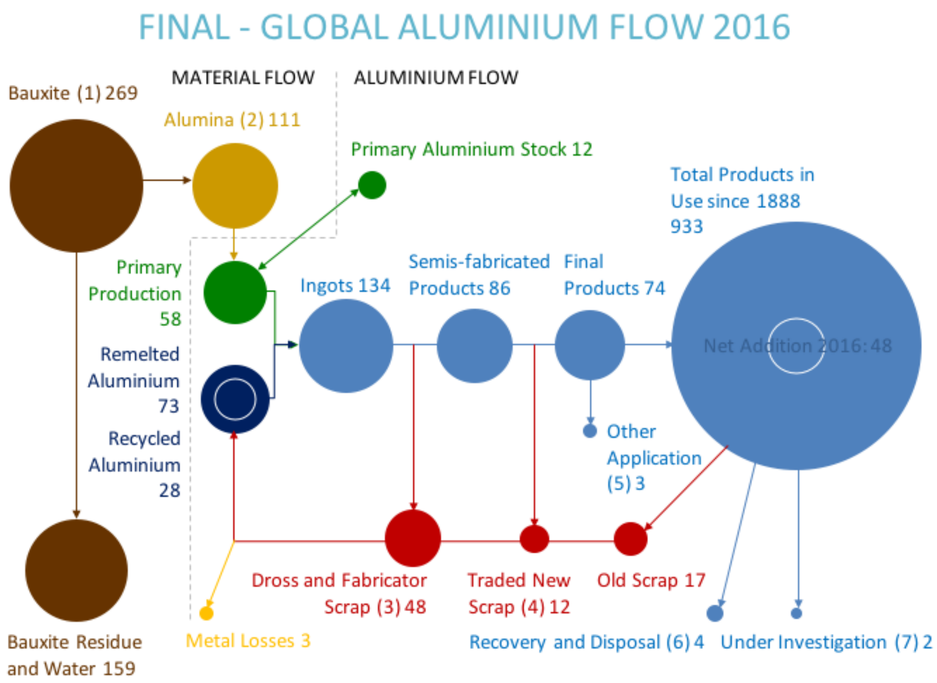
Table 7 Overview of the status of aluminium cycle

	Cases	Dimensions
1	Identifying inefficiencies of global Al cycle	D1 (stages)
2	Forecasting demand-supply	D1 (stages), D4 (time)

3	Energy and GHG scenarios	D1 (stages), D3 (layers), D4 (time)
4	Cascading use / securing scrap usability	D1 (stages), D3 (layers), D4 (time)
5	Trade relationships / spatially explicit demand-supply	D1(stages), D2 (trade), D4 (time)

Most models do not deal with all of the four MinFuture dimensions (Stages, Trade, Linkages, and Time) at the same time. For example, the current global Al cycle mapping only dealt with one dimension—"stages" (Figure 9). Aggregate systems can be useful for providing a crude first overview, but relevant information is lost.

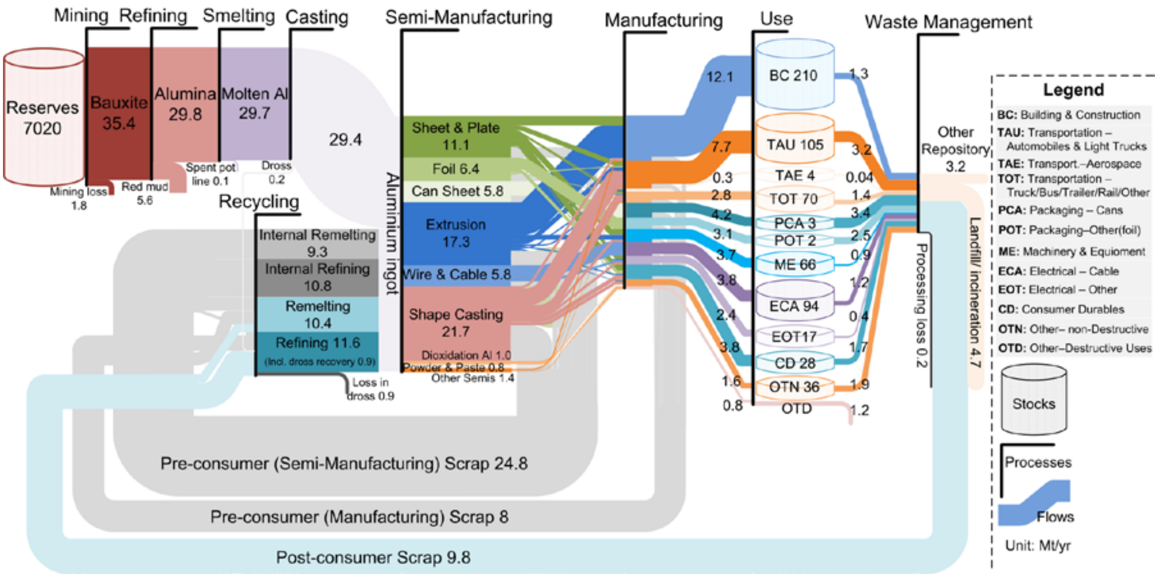
Figure 9: Global aluminium cycle in year 2016



Sources: (IAI, International Aluminium Institute 2017)

A more refined characterization of the contemporary global Al cycle (2009) is demonstrated in Figure 10. The recycled aluminium from scrap already constitutes over half of the global aluminium ingot production in 2009. However, present global aluminium recycling is predominately based on pre-consumer scrap, which can reduce energy demand per unit of production but leads to a higher aluminium demand and an overall increase of emissions due to the inefficiency of forming and fabrication. Only post-consumer scrap recycling has the potential to significantly lower total energy use and emissions. Present post-consumer scrap is available mainly in the form of used beverage cans and end-of-life vehicles, owing to the large consumption of aluminium in these products and their relatively short lifetimes.

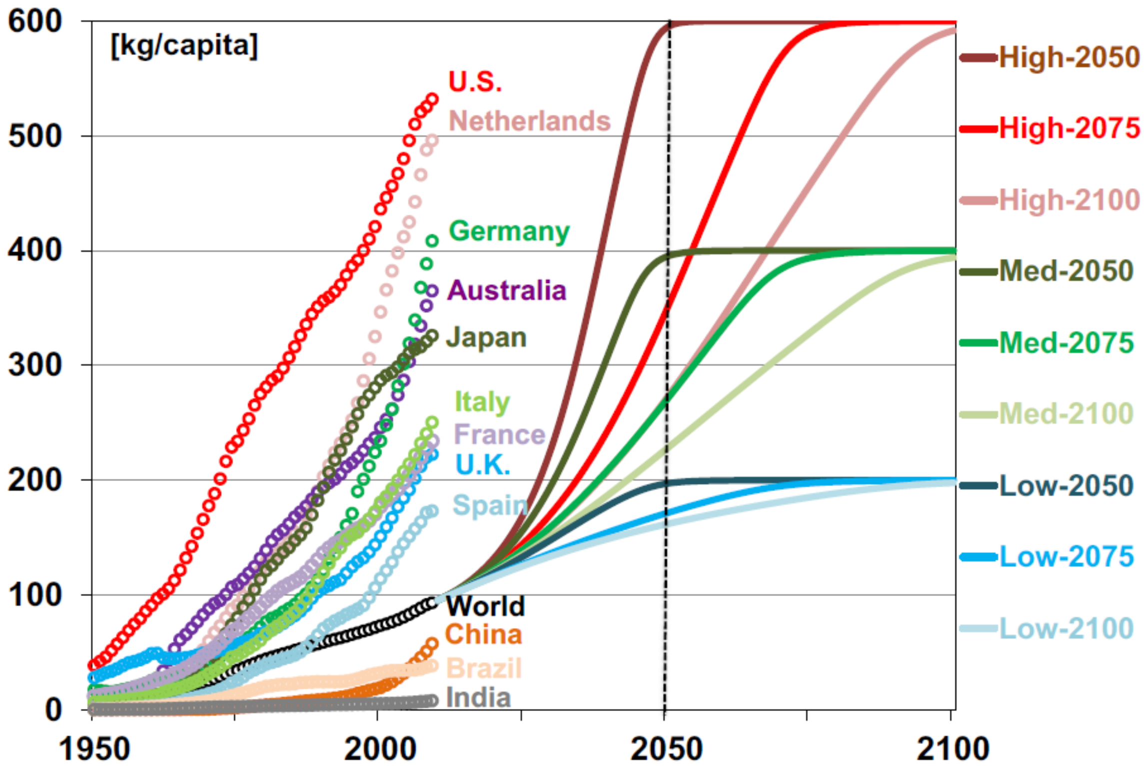
Figure 10: Global aluminium cycle in year 2009



Sources: (Liu, Bangs, and Müller 2012)

A stock-driven approach was used to simulate the future aluminium cycle, assuming that the aluminium in-use stocks eventually saturate. In light of the observed historical patterns in major industrialized countries, nine wide-ranging scenarios that vary in assumed saturation level and time were created (Figure 11).

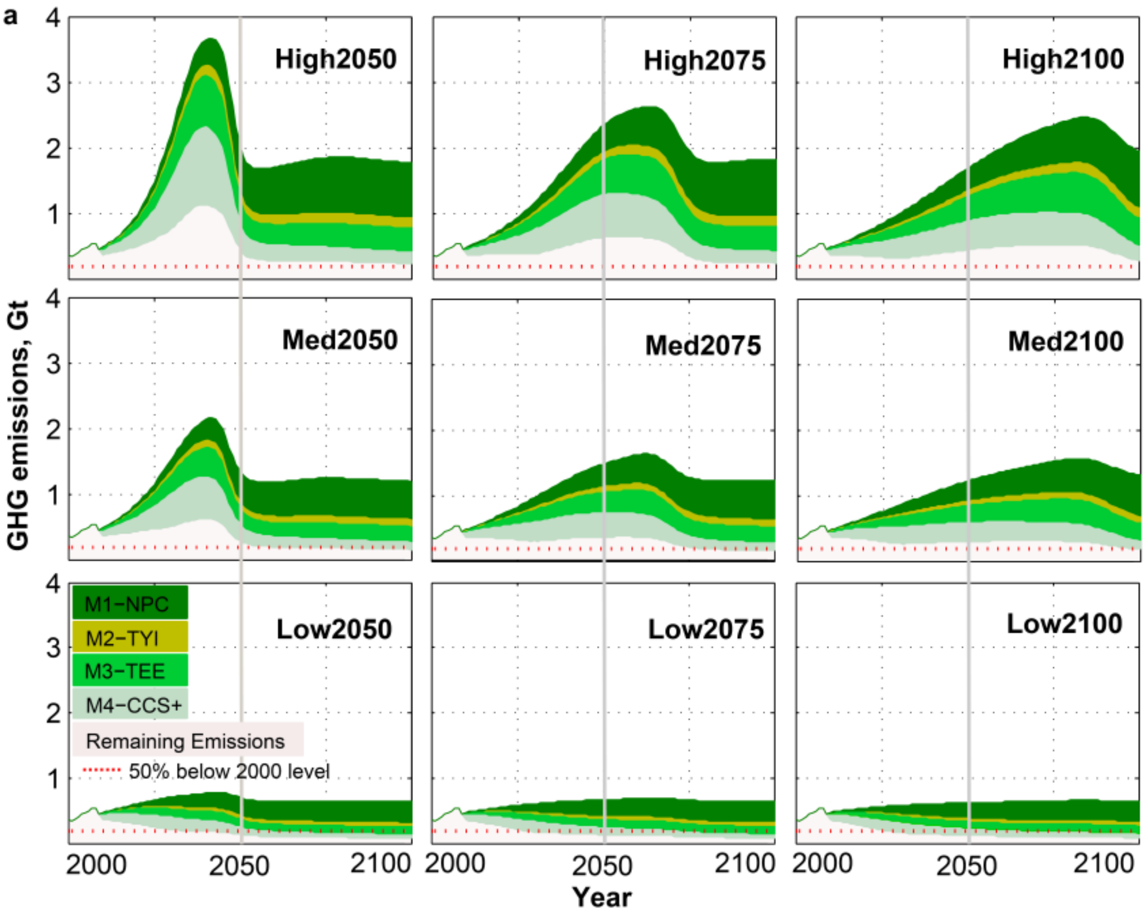
Figure 11: Historical and assumed future Al stock patterns



Sources: (Liu, Bangs, and Müller 2012)

On the top of the material layer, energy and emission layers could be added to explore future emission pathways and mitigation potentials of the global aluminium cycle. Four types of mitigation strategy that have been discussed in the literature are employed to simultaneously (Figure 12).

Figure 12: GHG emission pathways and mitigation wedges for nine dynamic stock scenarios



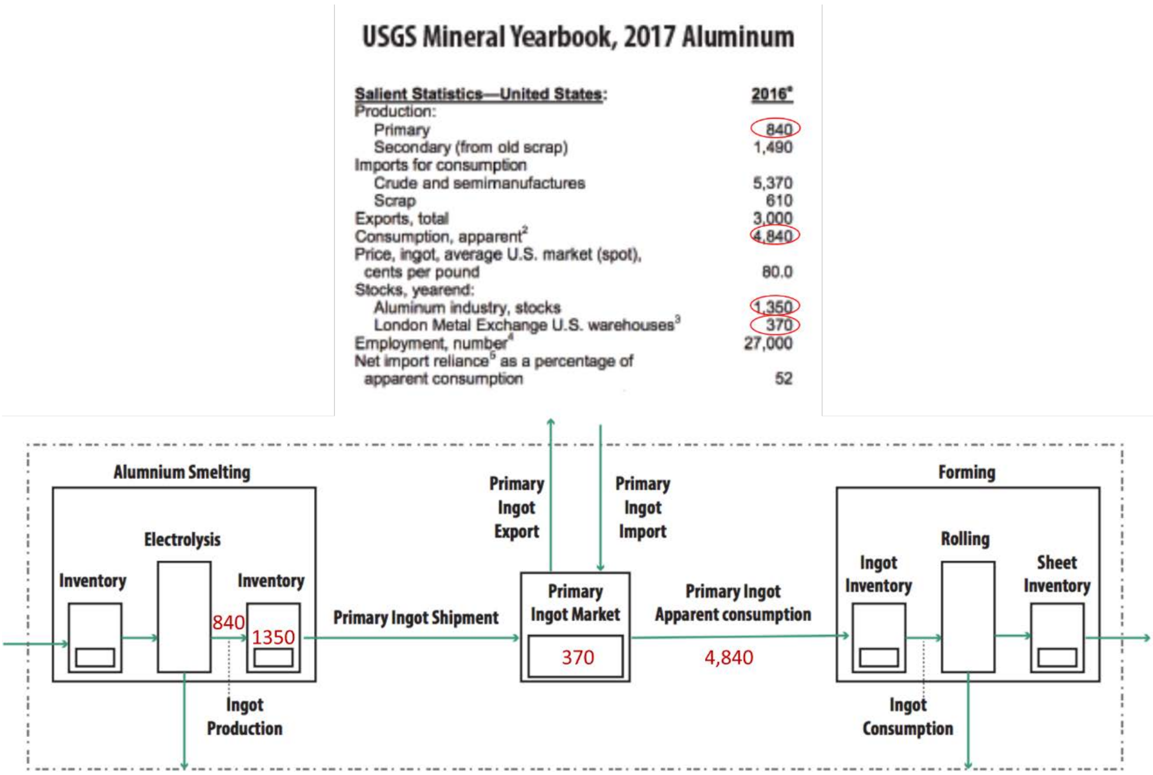
Sources: (Liu, Bangs, and Müller 2012)

Note: M1 - Near perfect collection; M2 - Technologies for yield improvement; M3 - Technologies for energy and emissions efficiency improvement; M4 - CCS and electricity decarbonisation.

4.4.1.2 Learning Outcomes and Challenges

The current system still does not reflect the reality of data measurement. A refined system could reflect the exact location of data measurements (Figure 13). Although a refined system makes the system more complex, the resulting mapping of Al cycle would be more robust.

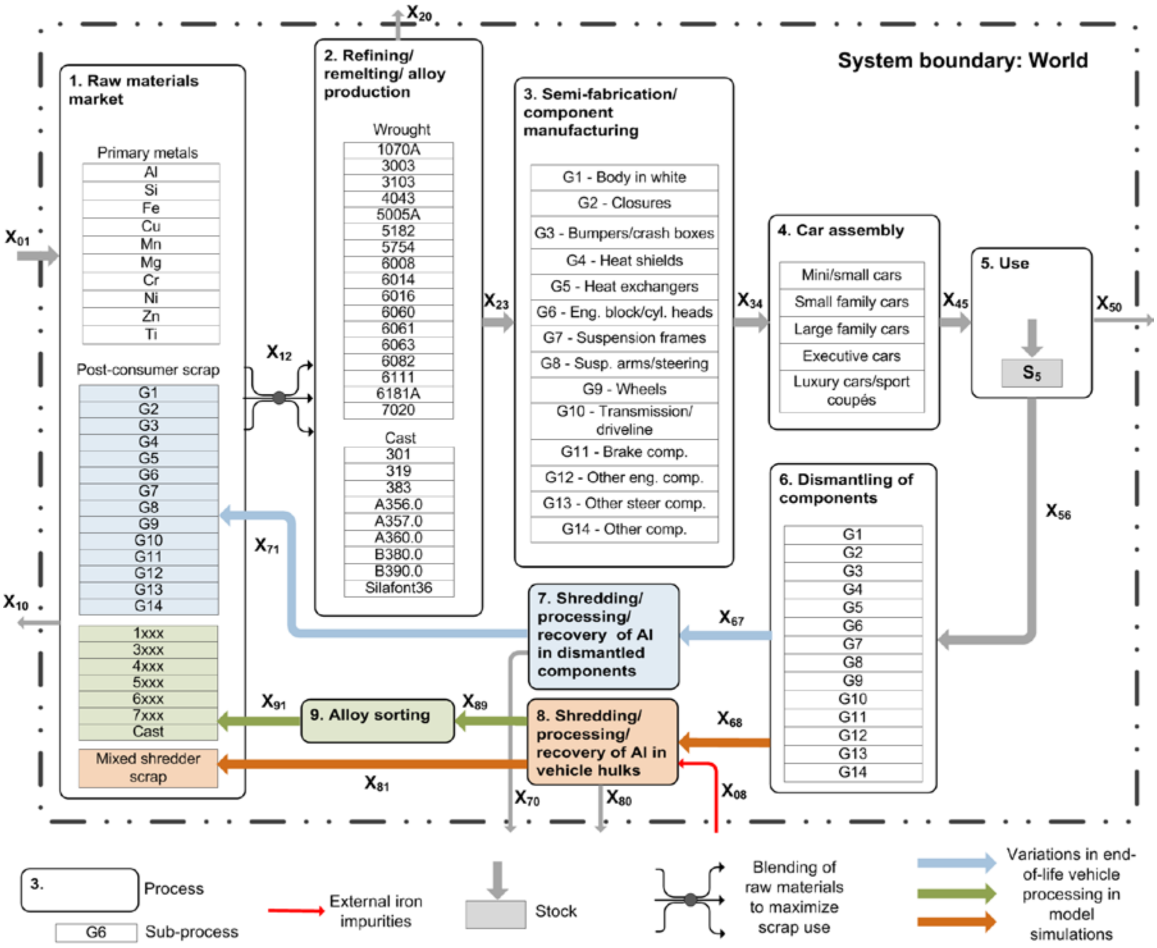
Figure 13: Design principle for system definitions



Sources: developed by Daniel Beat Muller

A multi-layer system with refined resolution enables to analyse linkages between different material cycles and evaluate various recycling strategies. Figure 14 gives a demonstration of the multi-layer system with refined resolution on automobile sector. Implications of various combinations of recycling strategies (e.g., alloy sorting, dismantling, demagging, and scrap used in safety-relevant components) on demands of wrought primary aluminium, wrought secondary aluminium, cast primary aluminium, and cast secondary aluminium (cascading use), as well as surplus scrap aluminium, could be drawn from such a system. The system’s high resolution helps identify the quality of aluminium in different automotive components. The system’s chemical element resolution could also help quantify the capacity of scrap use in other applications than traditional secondary castings.

Figure 14: Multilayer model on Al recycling of automotive industry



Sources: (Løvik, Modaresi, and Müller 2014)

In the interactive session (led by Evi Petavratzi, BGS), workshop participants were asked to brainstorm on major trends and challenges for future Al cycle mapping. Several key aspects were identified.

- System (including scenarios and lifetimes) should be more regional and segment specific, which are needed for industry to predict future Al demands and supplies (primary and secondary), as well as their quality. The future availability and quality of scraps determine the need for sorting and recycling technologies. The emerging new technologies will increase the system's complexity and alter the production and recycling system.
- For the demand forecasting, critical factors were identified, such as automobile light weighting, secondary vehicles management, new technologies development, material substitution, and lifestyle and demographic changes. For the supply forecasting, geopolitics, new resources exploration, industry transfer, and trade of secondary Al-contained products should be taken into consideration.
- For recycling system, regulation changes, such as tariffs and bans, recycling quotas and targets, CO2 emissions reduction target, circular economy target, and sustainable development goals should be taken into consideration.
- For energy and emission layers, tracking the differences between emissions factors for Al production in different regions is of great importance.

In the discussion session (led by Daniel Müller, NTNU), three key challenges were further discussed, especially from industry's perspective.

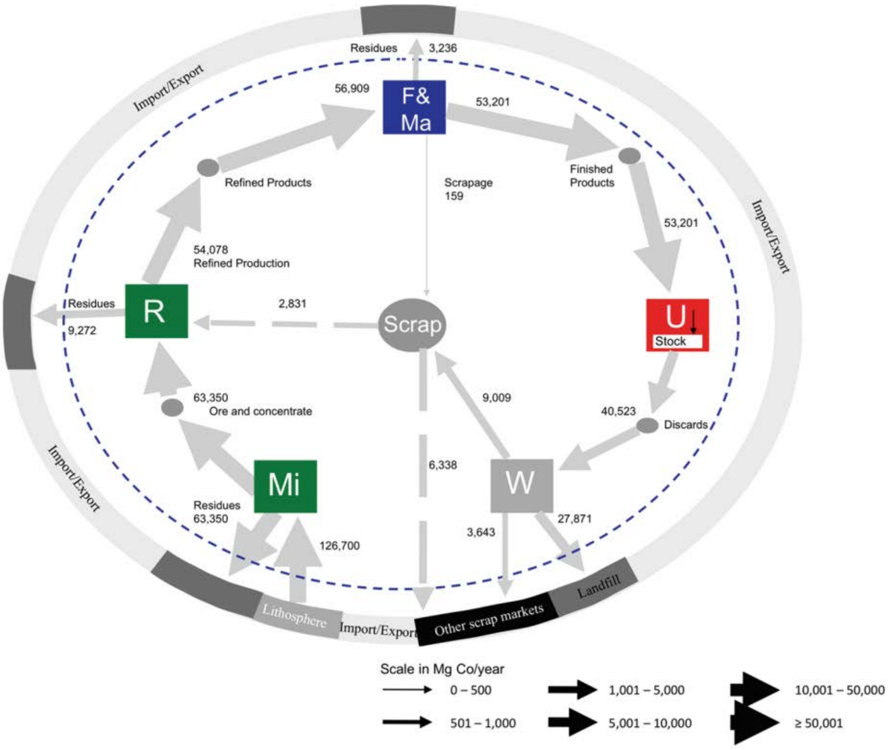
- For the can sector, the most important issue is can recycling. Scrap availability (i.e., maintaining certain recycling levels) is crucial to ensure can recycling profitable. It can be risky having too little or too much scrap available. For example, if there is a surplus of scrap, then the scrap price will go down and scrap collection will not be profitable, which would lead to a decreasing recycled Al in current products. System and data ought to be improved to reflect regional differences in Al content, recycling rate, and so on.
- For the automotive sector, their major concerns are electronic vehicles, exports of secondary cars, and recycling strategies. Electronic vehicles (EVs)' penetration might have impacts on other sectors because of the infrastructure needed (cables, charging stations, changes in grid, etc.) but no numbers are available for this now. The lifetime of EVs are highly different from internal combustion engine vehicles. Exports of secondary cars hinders tracking the Al flows after use stage. Dismantling appears to be superior to shredding, but the relevant polices are still required. Safety regulations could also significantly change the recycling technology choices.
- For the trade flows, the industry is demanding models that well reflect the impacts of market volatility, and protectionism and security of supply. HS codes should be amended based on the understanding of the trade flows and supply chains. New scraps and old scraps in scrap trade flows needs to be differentiated. Metallic and chemical uses of alumina needs to be differentiated. Data providers are reluctant to change the ways data are being collected and reported.

4.4.2 Cobalt

4.4.2.1 Status of Cobalt Cycle

The latest global cobalt cycle was mapped by Yale Industrial Ecology Group in 2011 (Figure 15). The cobalt cycle is on a highly aggregated level with six processes, cycles on such aggregated levels can be used to provide a crude overview of the flow of cobalt. However, a cycle on this levels does not allow for a thorough understanding of what actually occurs within the system. This understanding is essential if we are to better understand for instance the potentials for recycling, and how the overall efficiency of the system can be increased. It also neglects serval aspects such as the production and reefing of cobalt which is primarily mined as a by-product of copper and nickel and has a rather complex production process which is in fact determined by the mineralogy of the ore for instance. Therefore, there is a need to better understand and map the complexities of the cycle which could be done by developing a system with a much higher level of detail.

Figure 15: Global cobalt cycle in year 2005

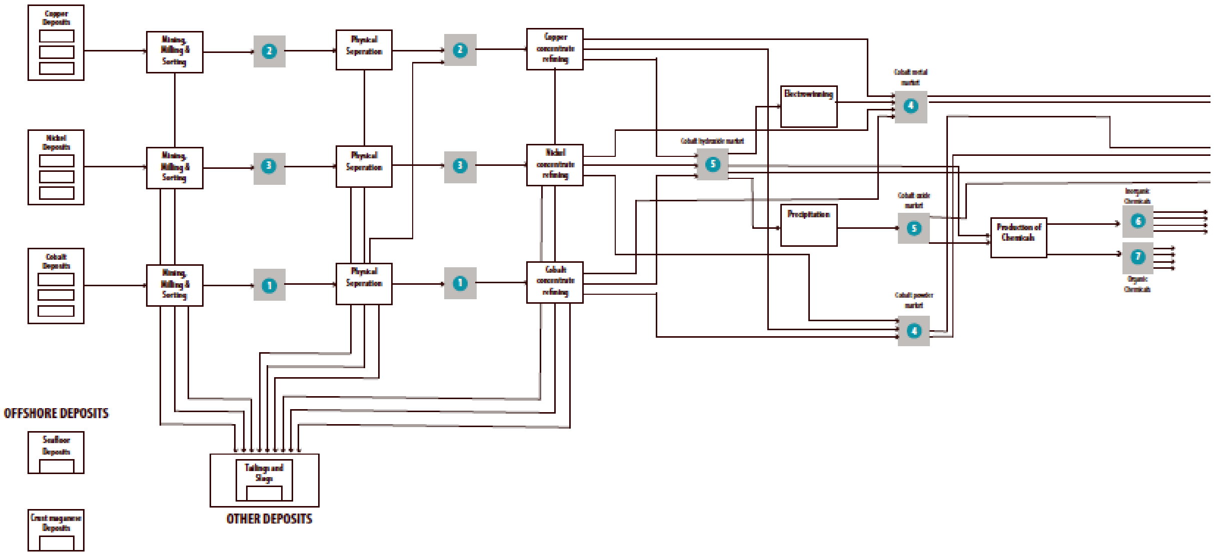


Sources: (Harper, Kavlak, and Graedel 2012)

4.4.2.2 Learning Outcomes and Challenges

In one of the first attempts to establish the global cycle of cobalt, the introduction of markets and trade data was the focus. This was done due to the fact that we have access to large amounts of trade data through UNComtrade, although this data also exists on a highly aggregated level. But this was done to have a starting point for mapping the available data. Nevertheless, overall data availability is a major challenge. After the first attempt of mapping the available trade data, one of the challenges with this is that the trade codes are on such a level that they often reflect different parts in the value chain in one trade code which cannot be further aggregated (Figure 16). An even simpler model might then be needed in order to avoid double counting.

Figure 16 Mining and refining of Cobalt with a focus on trade codes



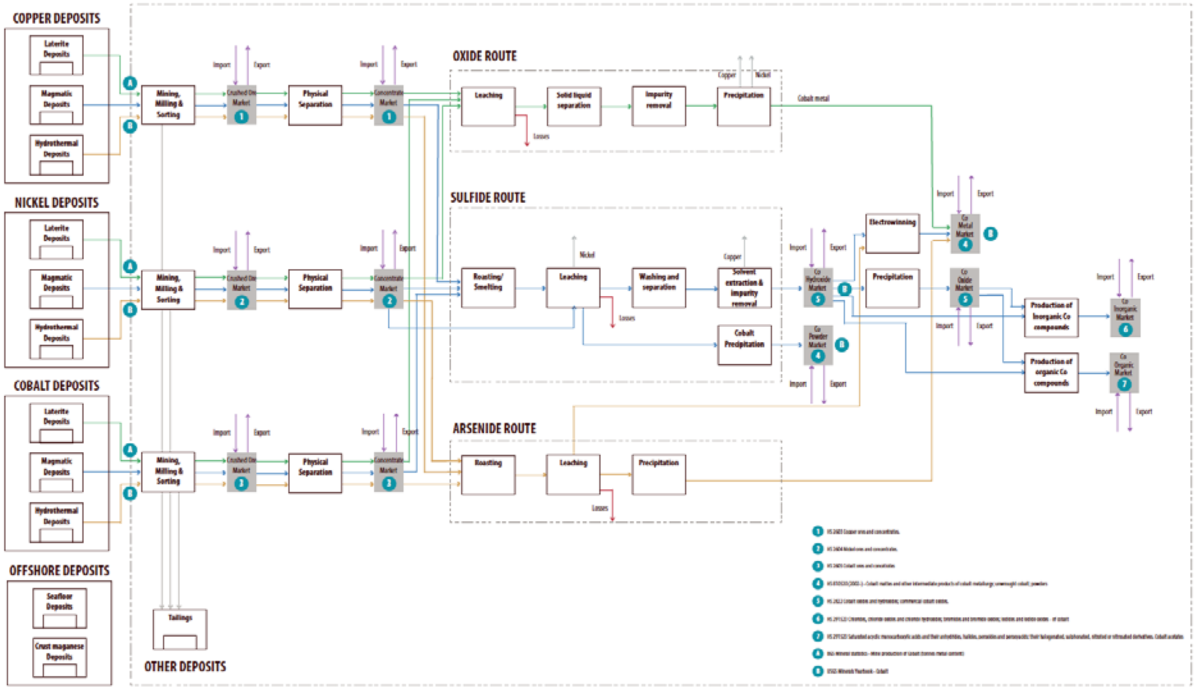
Source: developed by Maren Lundhaug

Cobalt is in high demand, but most of cobalt currently is available as a by-product of Cu or Ni mining. It is unclear whether the cobalt demand will remain high and most importantly, whether the price of cobalt will remain high. Future primary cobalt mining is highly dependent on demand predictions. Even if the demand is highly uncertain, it is believed that the market will experience continuous growth for the next decade.

Cobalt reserves are not always correctly reported because they are mixed with other mineral deposits and not recovered. This might change with the increased prices of cobalt. Information about the intermediate stages taking place prior to the manufacturing of different compounds is not sufficient, which enables the development of a comprehensive system. Some additional data sources should be taken into consideration, such as EU Commission JRC EPTS, market overview information from the cobalt and nickel institutes, LCA studies related to Cu, Co and Ni, and so on and so forth.

To construct a comprehensive cobalt cycle (), some often-neglected flows should be reflected in the system, such as cobalt salts used for animal food and fertilisers due to their irreplaceability, cobalt in artisanal mining due to its significant amounts in global production (supply of cobalt from artisanal mining can be the equivalent of 20% of global production).

Figure 17 Refined mapping of cobalt cycle



Sources: developed by Maren Lundhaug

In order to forecast demand and supply of cobalt, major trends and challenges are identified in the interactive session led by Evi Petavratzi. For future demand, EVs penetration, substitution of cobalt in batteries, and super alloys are the major trends that need to be considered. For future supply, responsible sourcing, increasing investment in exploration projects, extractive metallurgy, agreements between miners and manufacturers to shorten the supply chain, synchronisation of the supply chain, response to supply risk in different regions, transition from by-product to main product, supply diversification, and sector-specific supply chains are identified as the major challenges. For regulation related to cobalt, traceability, trade classification, trade restrictions and taxes, transportation-specific cobalt compounds, circular economy, collection scheme, and inconsistency of compounds registration in the regulation framework are identified as important challenges. For technology, EV battery chemistry and its influence on Co concentration, design for recovery, extraction technology for tailings, deposits in land & seafloor, and massive batteries in heterogeneous products are identified as major trends and challenges.

5 Construction Aggregates Workshop

5.1 Date, Place, and Participants

Table 8 Date, place, and participants of construction aggregates workshop

@ NGU, Trondheim, Norway May 8th 2018	
Name	**Affiliation**
Lisbeth-Ingrid Alnæs	Sintef Byggforsk
Kari Aslaksen Aasly	NGU
Manju Chaudhary	SSB
Ola Kolseth Dahlen	Trøndelag fylkeskommune
Svein Willy Danielsen	Private, Professor emeritus NTNU
Marit Fladvad	NTNU
Tom Heldal	NGU
Jørn Bo Jensen	GEUS
Tine Larsen Angvik	NGU
Lars Libach	DIRMIN
Maren Lundhaug	NTNU
Daniel Beat Müller	NTNU
Vegard Olsen	Franzefoss
Torun Rise	Sintef
Mark Simoni	NGU
Lillian Strand	Trøndelag Fylkeskommune
Maryon Strugstad	Rogaland fylkeskommune
Sytze van Heteren	TNO

5.2 Objectives

The use of natural mineral construction materials such as sand, gravel, stone and crushed hard rock aggregates constitutes the biggest anthropogenic solid material flow. Its importance will continue to grow with regards to urban and land-use planning, materials transport, and circular economy targets. Nevertheless, given the importance of construction aggregates, the associated material flows through the economy are among the least well-constrained and most uncertain. The objective of this workshop is to test our framework for mapping and monitoring the physical economy of construction aggregates, and to develop a roadmap and project collaborations that help secure a long-term sustainable management of construction aggregates for Norway and the EU. In the workshop, we will present our conceptual framework and preliminary results on aggregates material flow and stock modelling, focussing on a system definition that identifies important actors in the different stages of the aggregates life cycle. We brought together stakeholders and researchers involved in aggregates management (production, use and recycling) as well as government administration related to planning, monitoring and data reporting to review, define and advance information on Norwegian aggregates management. Participants were asked to give feedback on i) the methodological framework itself, ii) the current mapping of the aggregates material cycle, and iii) the relevance of this knowledge for business/industry and public planning authorities.

5.3 Contents of Workshop

Table 9 Contents of construction aggregates workshop

Time	Content
10:00-10:15	Registration and welcome coffee
10:15-10:30	Tour de table with introductions
10:30-11:00	Introduction MinFuture (pyramid) & questions
11:00-11:45	Status for tracking aggregates through the physical economy
11:45-12:45	Lunch break
12:45-13:15	Trends, challenges and opportunities
13:15-13:45	Vision and Gaps
13:45-14:00	Coffee break

14:00-14:30	Addressing the gaps (roles, cooperation)
14:30-14:45	Project ideas
14:45-15:00	Summary, conclusion

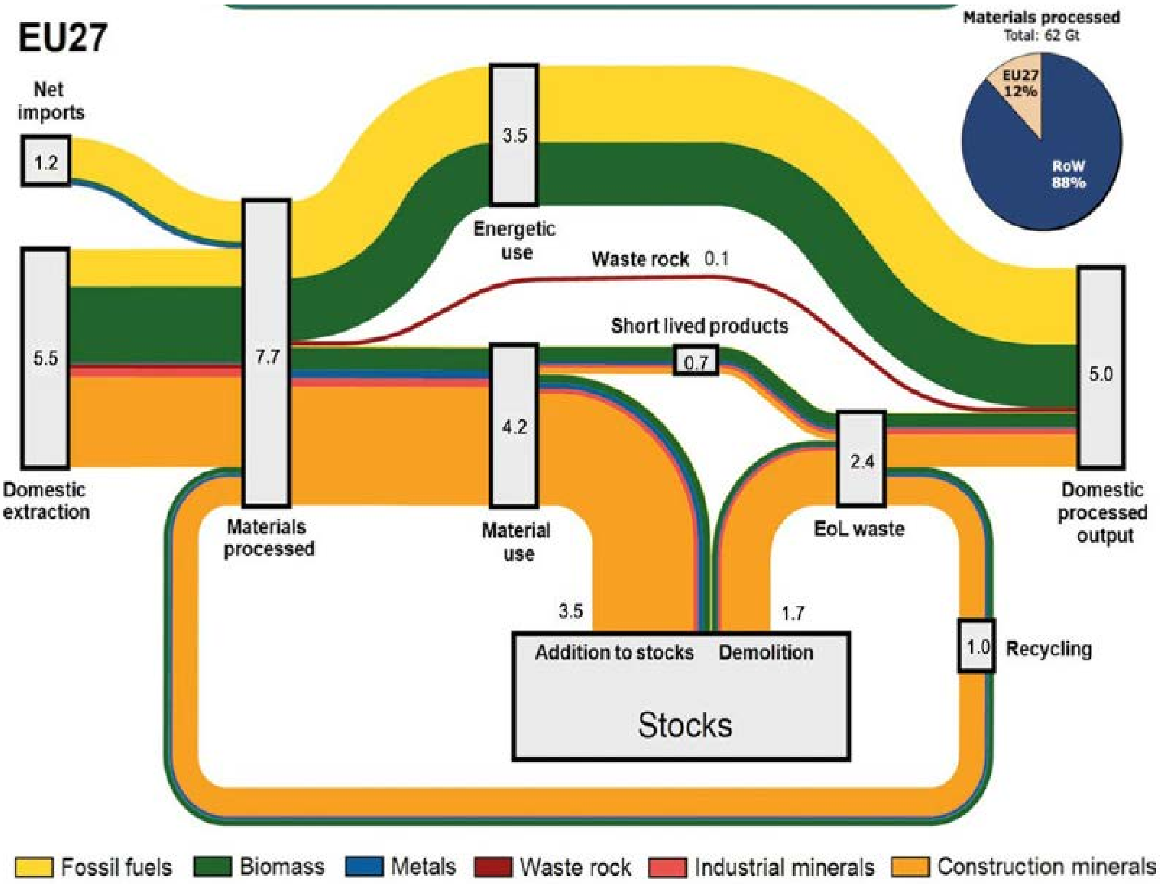
5.4 Status, Learning Outcomes, and Challenges

5.4.1 Status of Construction Aggregates Cycle

National or international statistics generally report only aggregated data for construction aggregates without a system context, because transparency and system understanding is lacking. Legal reporting requirements differ across countries (due to e.g., non-mandatory reporting, data inaccessibility and confidentiality, and data fragmentation across industry stakeholders and public authorities), which leads to data inconsistencies and gaps that are masked by aggregating data to regional or national levels. However, international and national policy targets are based on physical indicators that relate to materials extraction, processing, use, and disposal (e.g., environmental and resource footprints, climate action tracker, and so on). Because of a lack of systems understanding, decisions and policies often fail to address the real problems and their interdependencies on a systems level.

Mineral resource surveys normally only cover the first stages of the supply chain (i.e., extraction and processing) and reported numbers for extraction are often aggregated to a national scale, which makes it, for example, impossible to identify the underlying reasons for regional differences. On an international level, the Minerals4EU database marks a joint effort to compile the production statistics (flows) of European countries, but data are not harmonised across countries due to the different national frameworks. Resources and reserves data (i.e. indications of currently accessible geological stocks) are not reported internationally. Neither for the geological nor for the built environment stocks of construction aggregates is there full information coverage available across all European countries. Only a few selected countries, such as Germany, have estimated the built environment material stocks resolved to different material groups (Felix Müller et al. 2017). However, these studies are usually based on bulk MFAs (top-down) or on upscaling bottom-up case studies for selected areas to a national level (Schiller, Müller, and Ortlepp 2017). Bulk MFA is not of utility for regional resource management due to the missing spatial resolution, but it can still indicate important aspects of the use of raw materials. For example, Figure 18 shows that if the inflow into the built environment stocks is bigger than the outflow this has several implications: i) the built environment stocks are growing; ii) maintenance will gain importance in the mid-term future as there will be a larger stock to maintain; and iii) waste flows are likely to increase in the more distant future when structures reach their end-of-life (EOL).

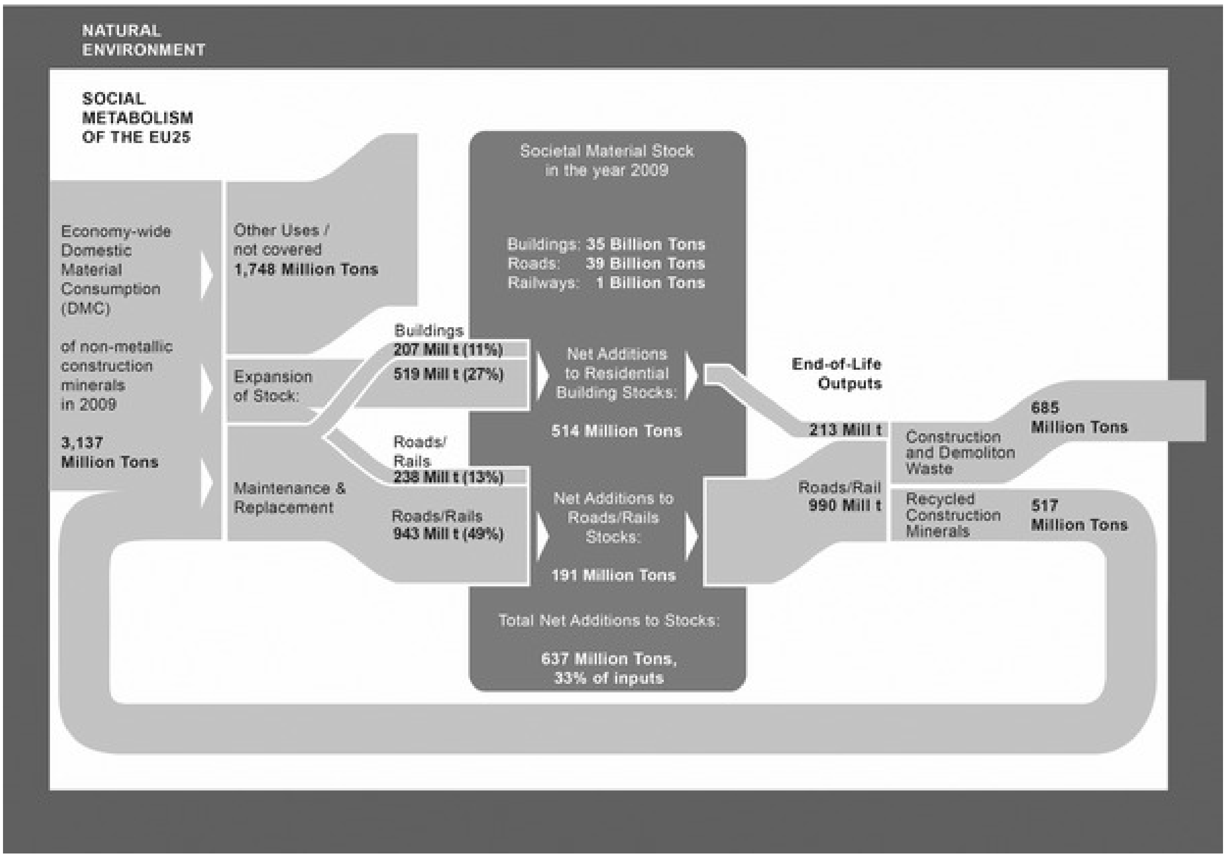
Figure 18: Sankey diagram of material flows through the EU-27 in year 2005



Sources: (Haas et al. 2015)

More detailed knowledge about the different stock categories in the built environment helps understanding the drivers for the flows and their relative contribution to the overall material turnover. For instance, the maintenance and replacement of the road and rail stock consumed a considerable share of the annual non-metallic construction mineral input in the EU in 2009 (Figure 19).

Figure 19 Sankey diagram of the economy-wide consumption of non-metallic minerals in the EU 25 in 2009 with material stocks of residential buildings, roads, and railways



Sources: (Wiedenhofer et al. 2015)

How MFA models of construction aggregates cover the different dimensions of the MinFuture framework varies. The MFA **stages** of the construction aggregates system have, so far, been mainly investigated by academia. Either are they often not disaggregated for the different processing steps, or they cover only sections of the entire material cycle. In addition, MFA models are usually not updated on a regular basis. An excellent example of a recent and updated regional MFA model for construction aggregates can be found in Switzerland: http://www.kar-modell.ch/. As for international **trade,** the import-export statistics of construction aggregates do not add up, which indicates uncertainties and deficiencies in the underlying data and reporting. This discrepancy may, among others, also be influenced by illegal trade. As for the **layers** of construction aggregates mapping, there are no studies with systematic mapping of different properties pertaining to the construction aggregates cycle throughout the entire supply chain. It is, for example, usually not known how the quality (e.g., brittleness) - as one of the key parameters determining possible applications - changes due to blending, manufacturing and other processing steps.. Studies investigating the **time** dimension, which is especially important for scenario analyses of the built environment due to the long life expectancies and long-lasting legacies of built structures, also remain sparse. Nevertheless, circular economy policies, land use planning, and sectoral emission reduction target setting all require temporal resolution for forward-looking scenario analysis.

5.4.2 Learning Outcomes and Challenges

In general, data of construction aggregates are fragmented horizontally across stakeholders along the supply chain, thematically across different layers (e.g., emissions, product sales quantities, tax reports), and vertically over different hierarchical levels of reporting authorities and responsible institutions. Data generally neither covers the entire supply chain, nor does it resolve all the flows for specific processes, such as total material extracted from the lithosphere, waste produced, waste backfilled and product sales. Currently, no country has a complete bottom-up MFA system for construction aggregates that resolves all internal flows in a temporally and spatially explicit manner.

In Norway, some data is reported directly, but most information has to be estimated or calculated from mass balances. Among the challenges are that:

- Geological stocks are based on rough estimates without complete coverage; historical statistics only cover data about goods but not waste;
- Most material flow related data are not reported because processes other than mining or waste disposal (which require permitting) are exempt from mandatory reporting
- In-use stocks are not covered in official statistics
- Data at national level are too aggregated and not sufficient to map the regional aggregates cycle.

In summary, the construction aggregates system definition should be elaborated to allow for bottom-up (local/regional) data and validation with statistics, while the system should still be generic enough to facilitate global application and cross-comparisons. The lifetime of in-use stocks and demographic patterns should be incorporated into the scenarios to add temporal resolution. Supply and demand of concreate aggregates have to be mapped spatially because if they are mismatched this can lead to local 'resource criticality'. Political decisions such as infrastructure spending to stimulate economy, or the taxation of fossil fuels used in transport will be likely to influence both the spatial pattern and the volume of future resource supply and demand. In addition to this, MFA scenario analysis will require the consideration of changing trends of construction materials use (e.g., wood for housing), the availability of recycling materials that can substitute for virgin material (based on analyses of historical data), and the expected spatial patterns of demographical and economic development.

6 Phosphorus Workshop

6.1 Date, Place, and Participants

Table 10 Date, place, and participants of phosphorus workshop

@Oslo, Norway **May 7th 2018**	
Name	**Affiliation**
Lisbeth-Ingrid Alnæs	Sintef
Kari Aslaksen Aasly	NGU
Manju Chaudhary	SSB

Ola Kolseth Dahlen	Trøndelag fylke
Svein Willy Danielsen	Private
Marit Fladvad	NTNU
Tom Heldal	NGU
Jørn Bo Jensen	GEUS
Tine Larsen Angvik	NGU
Lars Libach	DIRMIN
Maren Lundhaug	NTNU
Daniel Beat Müller	NTNU
Vegard Olsen	Franzefoss
Torun Rise	Sintef
Mark Simoni	NGU
Maryon Strugstad	Rogaland fylke
Sytze van Heteren	TNO

6.2 Objectives

Natural resources are under increasing pressure due to population growth, economic development, and climate change. Growing food demands have led to the intensification of agriculture, which has drastically increased the consumption of finite resources as well as environmental pollution. Phosphorus represents one resource that is both critical for food security and a large source of pollution if used unsustainably. Its supply is dependent on finite amounts from reserves concentrated primarily in the Western Sahara and Morocco, which makes other countries particularly vulnerable to supply disruptions. Because of this, in recent years there has been a strong interest from both research and industry to use material flow analysis to understand the metabolism of phosphorus throughout human systems. The work has contributed to increasing the overall understanding of the phosphorus cycle on a variety of scales: from the individual city level to the country level – and even the European Union. The outcomes from these analyses have shown that the metabolism of phosphorus varies greatly between countries, particularly related to the key sectors for phosphorus consumption as well as loss rates.

The main objective of this workshop is to test out the framework we developed in MinFuture towards a roadmap to monitor the physical economy/material stocks and flows using phosphorus as a case. We therefore would like to ask our stakeholders to give feedback on i) the methodological framework itself and ii) the current mapping of the individual physical material cycles. This is with the aim of supporting decision makers through suitable indicators and visualization techniques.

6.3 Contents of Workshop

Table 11 Contents of phosphorus workshop

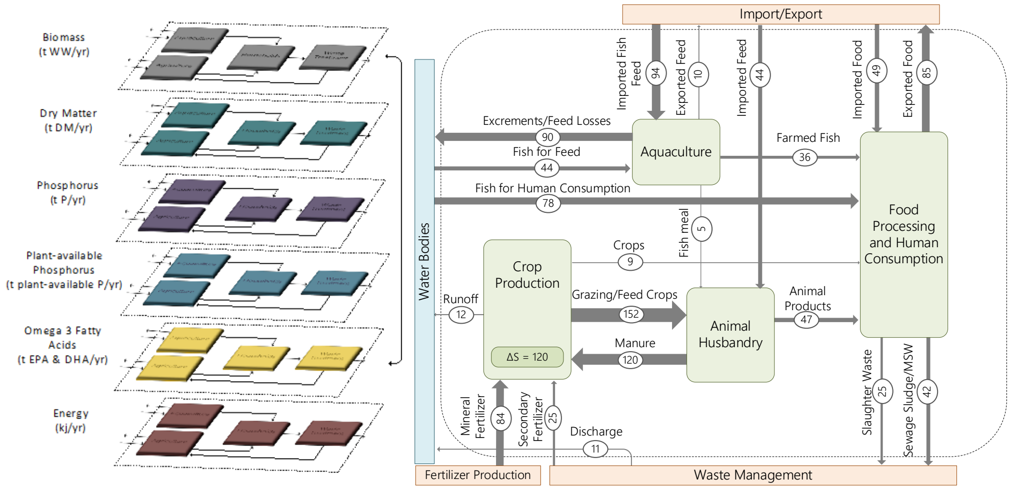
Time	Content
11:30-12:00	Light lunch and registration
12:00-12:15	Introduction round
12:15-12:45	Introduction to MinFuture
12:45-13:45	Status of tracking P through the economy
13:45-14:00	Discussion, synthesis of status
14:00-14:15	Break
14:15-14:45	Trends/Challenges/Opportunities
14:45-15:15	Vision of MFA and gaps for getting there
15:15-15:45	Addressing gaps and future collaboration
15:45-16:00	Conclusions

6.4 Status, Learning Outcomes, and Challenges

6.4.1 Status of Phosphorus Cycle

In Norway, the largest phosphorus flows are aquaculture and agriculture, which are almost equally driving phosphorus consumption (Figure 20). A mass of phosphate ores are imported and processed. A huge accumulation of phosphorus is observed in the soil due to a high input of manure. Aquaculture is primarily dependent on imported feed. Only a small amount of phosphorus actually reaches human consumption due to the losses on the way. A spatially refined model for phosphorus cycle shows that there is a surplus of phosphorus in some areas and a deficit in other areas, because cows and crops are not spatially matched in Norway. The spatial mismatch drives the net accumulation in certain areas. The multilayer model points out that improving one layer can lead to deficits in other layers. Scenarios have been developed to understand how the 5-fold increase in the aquaculture will affect the phosphorus cycle.

Figure 20 A multi-layered approach for phosphorus cycle of food system and its application on Norway's food system



Source: (Helen Ann Hamilton 2017; Helen A. Hamilton et al. 2015)

In Austria, import dependency of phosphorus is quite high, which is exacerbated by losses in the waste sector, unnecessarily high dietary intake, and accumulation of phosphorus in agricultural and urban soils. A refined system covering 9 sectors (each consists of subsystems), 65 processes, 8 stocks, and 122 flows was developed to map the Austrian phosphorus cycle and estimate the Austrian phosphorus budget. Data of mass flows were mainly collected from governmental reports. Data on concentrations or contents were mainly from scientific reports. The ever-changing data collection or reporting methods, data availability of waste treatment paths, less-understood soil-plant interactions, and complex activities in households hinder a reliable mapping of the Austrian phosphorus cycle. For example, a systematic underestimation of soil accumulation is found in time series of phosphorus cycles.

6.4.2 Learning Outcomes and Challenges

Pathways towards independence in Norway are needed and improving manure and fish sludge wastes recycling is of priority. The pathways rely on a better understanding of local secondary P supply potential, plant availability, spatial distribution of P resources, P quality, recycling technology, economic development, and consumer acceptance.

Methodologically, data of phosphate mining, trade, soil stock, and end-of-life are not available or sufficient for mapping the P cycle. For example, trade commodity codes do not necessarily reflect the supply chain due to accumulation of processes and P contents of trade commodities are not available. The quantity and quality of P deposited in soil are not well understood, which requires more expertise from soil chemistry. Data of slaughter waste are not robust.

A correct definition of indicators under system view is crucial for policy formulation. A recycling rate merely looking at the end-of-life stage would make the recycling rate less meaningful. Huge accumulation/losses take place along the supply chain of P cycle. A recycling rate without considering those accumulation/losses would be misleading for policy formulation. For example, micro-improvements can lead to problem shifts between the different sectors. In addition, to improve the P efficiency of an economy, a more meaningful recycling rate should look at the whole system but not only part of it. Indicators that reflect the system status could be import dependency, mineral fertilizer consumption, and emissions to waterbodies.

To reduce the import dependency of phosphorus, three major measures (i.e., increasing recycling, reducing demand, and reducing emissions) are to be taken. To increase recycling of phosphorus, biomass ashes, compost, green waste, meat and bone meal, organic household, and sewage sludge are of priority. To reduce demand of phosphorus, P-N reduced animal feed, P-free detergents, food waste reduction, and healthy diet are highly recommended. To reduce emissions of phosphorus, erosion control, fertilizer efficiency, manure storage, waste water treatment, and plant efficiency are identified as the most effective measures. To assess the significance of individual measures, sensitivity analysis could be a possible solution. A multilayer system could help understand the co-benefits of phosphorus-related measures on nitrogen cycle.

On the demand side, in Norway and globally, the phosphorus cycle is largely driven by dietary intake growth, diet changes (e.g., from fish to plant-based materials), and fish production structure changes. Besides, three other main drivers are increasing electric vehicle ownership and batteries, and increased phosphorus fertilization in forests. A good solution could be reusing ashes from clean bio-waste, although not allowed as of now.

Globally, phosphorus reserves are concentrated in Morocco. To reduce supply risks of phosphorus in Norway, domestic and imported secondary phosphorus would be potential major supply sources. To map the phosphorus cycle and explore pathways towards independence in Norway, models that enables industrial symbiosis (e.g. companies using flows from other sectors) are badly needed. REEs are abundant in phosphate ores (e.g., Yara redeveloped their process to extract REE (0.8%) from Apatite); therefore, a multilayer model could help identify by-products along the phosphorus cycle.

Current extraction focuses on marine sediments, which means other types of deposits (e.g., igneous deposits) should be further explored. However, information on deposits are insufficient or not correctly interpreted. Three challenges (e.g., declining ore grade, poor global inventories, and poor trade data for ore and intermediate products) would hinder a better understanding of phosphorus and pathways towards phosphorus independence in Norway.

In Norway, new suggestions on fertilizer regulations have been delivered to the ministries, aiming at balancing the phosphorus needed by the plant and phosphorus ended up in waters. To do so, the amount of animals on agricultural land should be kept at certain levels, as well as the organic pollutants from wastewater sludge and other waste materials. A spatial refined system is needed to help formulate regulations. Besides, more regulations on circular economy are not in sight, which also needs a clear understanding of secondary fertilizers' effects and phosphorus content. Land is insufficient to receive the pollutions and impacts on fjords are lower. Better definition of primary resources and certification on mining are needed as well.

Wastewater treatment technologies should not just remove phosphorus, but should make it more plant-available, which means the secondary should be in the form of sludge after recovery. Economically competitive technologies on drying manure/fish sludge for transportation are needed.

To go forward, academia and industry should exchange knowledge and propose initiatives (e.g., industrial symbiosis). The economic dimension should be taken into consideration, such as the availability of phosphorus, the quality of phosphorus, export potential, and so on. The transparency and quality of reported data also should be further improved, such as data aggregation to satisfy EU data reporting requirement. Classification on primary and secondary resources should be more explicit. Scenarios should take into account emerging technologies, especially treatment of manure and sewage. Policy makers should collaborate with researchers to look at different scenarios and their consequences of implementing certain regulations.

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