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Towards recycling of scarce metals from complex products

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Abstract

Cars and electronic equipment have come to depend on materially complex designs and are drawing attention to issues around sustainable materials management. The dependence of these products and other applications on metals that can be considered scarce, has been brought into political and scientific focus. This is largely because of potential regional scarce metal supply constraints and the crucial roles the metals may play in current society and in diffusing a variety of ‘green’ technologies. If the societal dependence on scarce metals continues, the demand for these metals may become larger still. It is therefore increasingly relevant to manage scarce metals sustainably. Ultimately, the metals need to be recycled if such sustainable management is to be achieved.

However, recycling industries are not well-adjusted to recovering all scarce metals, and concurrently policy-makers and the research community are only in early stages of finding ways to approach challenges associated with managing scarce metal resources. As a result, instead of being recycled many scarce metals risk being irreversibly lost. Thus, there is need for knowledge in multiple domains if recycling rates of scarce metals are to increase.

This thesis aims to contribute with such knowledge, by studying recycling of scarce metals from end-of-life cars (ELVs) and waste electrical and electronic equipment (WEEE). First, by quantifying scarce metals entering Swedish ELV recycling, tracking the metals through recycling, and identifying where metals end up. Second, by identifying factors that impact on developing industry abilities for recycling scarce metals from ELVs and WEEE. Third, by identifying and discussing research approaches used in waste management (WM), WEE and ELV related research. Fourth, by suggesting measures that may raise recycling rates of scarce metals. Methodologically, the research is based on material flow analysis (MFA), the technological innovation system (TIS) framework and bibliometric analysis.

Results indicate that 2,000-3,000 tonnes of scarce metals annually enter Swedish ELV recycling. Only 8 of 25 studied metals are estimated have any potential for being recycled such that metal properties are reutilised. Salient factors that impact on developing industry recycling abilities include: The material composition of ELVs and WEEE and the current value of contained metals; long-term metal price trends; access by industry actors to metal markets, an experienced work force, waste treatment technology and financial capital;

business models and long-term goals within recycling industries; and EU and Swedish policy. These factors create socio-technical system challenges that need to be addressed by industry actors, policy-makers and researchers if recycling is to develop. Furthermore, some environmental system analysis methods and most socio-technical change approaches have only marginally been adopted in WM, WEEE and ELV related research. Hence, valuable scientific tools are left unutilised. Overall, results highlight that for individual metals to be recycled, there is need for long-term, high impact and metal specific measures that target build-up of entire values chains.

The thesis contributes theoretically to TIS literature by adapting the TIS framework to a new empirical field, and to using it for studying industry developments where multiple and potentially conflicting goals are salient features. Empirically the thesis increases the resolution of knowledge about metal and material flows, and industry conditions, in Swedish ELV and WEEE recycling.

KEYWORDS: Recycling, scarce metal, material flow analysis, technological innovation system, end-of-life vehicle, ELV, waste electrical and electronic equipment, WEEE

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Andersson, M., Ljunggren Söderman, M., Sandén, B.A. Are scarce metals in cars functionally recycled? (2017). Waste Management, 60, pp. 407-416.

II. Andersson, M., Ljunggren Söderman, M., Sandén, B.A. Lessons from a century of innovating car recycling value chains (2017). Environmental Innovation and Societal Transitions, 25, pp. 142-157.

III. Andersson, M., Ljunggren Söderman, M., Sandén, B.A. Challenges of recycling multiple scarce metals: The case of Swedish ELV and WEEE recycling. Submitted to Technological Forecasting and Social Change.

IV. Andersson, M., Ljunggren Söderman, M., Sandén, B.A. Adoption of systemic and socio-technical perspectives in waste management, WEEE and ELV research. Submitted to Resources, Conservation and Recycling.

Regarding paper I, Andersson M. collected data on Swedish ELV recycling, conducted MFA modelling, and co-wrote the initial draft together with Ljunggren Söderman M. The draft was further developed by all authors. Regarding paper II, Andersson M. collected data, made initial theoretical interpretations, and wrote the initial draft, which was further developed by all authors. Papers III-IV were produced in the same way as paper II. All authors took part in discussing, reflecting on, and shaping the empirical contents and theoretical interpretations.

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Table of abbreviations

Chemical elements			Other		
Ag	-	Silver	ECU	-	Electronic control unit
Al	-	Aluminium	ELV	-	End-of-life car/vehicle
Au	-	Gold	EoL	-	End-of-life
Ce	-	Cerium	EPR	-	Extended producer responsibility
Co	-	Cobalt	ESA	-	Environmental system analysis
Cu	-	Copper	IMDS	-	International Material Data System
Dy	-	Dysprosium	MFA	-	Material flow analysis
Er	-	Erbium	MLP	-	Multi-level perspective
Eu	-	Europium	NGO	-	Non-governmental organisation
Fe	-	Iron	PCB	-	Printed circuit board
Ga	-	Gallium	PGM	-	Platinum group metal
Gd	-	Gadolinium	PRO	-	Producer responsibility organisation
In	-	Indium	RDD	-	Research, development and demonstration
La	-	Lanthanum	SFA	-	Substance flow analysis
Li	-	Lithium	SNM	-	Strategic niche management
Mg	-	Magnesium	SPIS	-	Science policy and innovation studies
Mn	-	Manganese	ST	-	Socio-technical
Mo	-	Molybdenum	STS	-	Science and technology studies
Nb	-	Niobium	TIS	-	Technological innovation system
Nd	-	Neodymium	TM	-	Transition management
Pb	-	Lead	WEEE	-	Waste electrical and electronic equipment
Pd	-	Palladium	WM	-	Waste management
Pr	-	Praseodymium			
Pt	-	Platinum			
Rh	-	Rhodium			
Sm	-	Samarium			
Ta	-	Tantalum			
Tb	-	Terbium			
Y	-	Yttrium			
Yb	-	Ytterbium			
Zn	-	Zinc			

1. Introduction

The material complexity of some widely used products in current society has become large, and is drawing attention to new issues of how to manage materials sustainably. Modern cars and electronic products exemplify this development, being highly diffused in society and depending on a large variety of metals and synthetic materials (Holgersson et al., 2018, Huisman et al., 2017, Restrepo et al., 2017). The dependence of these products and other applications expected to be widely used in the future (e.g. renewable energy and electric mobility technologies) on metals that can be considered scarce, has received political and scientific attention in recent years. The attention has largely been motivated by concerns in regions such as the EU, U.S. and Japan over potential disruptions in supply of some scarce metals (the metals are then generally referred to as 'critical'), since many scarce metals mainly are produced outside these regions by countries including China, South Africa, Brazil and Russia (Binnemans et al., 2013, de Koning et al., 2018, European Commission, 2017a, Habib and Wenzel, 2014, Massari and Ruberti, 2013, U.S. Department of Energy, 2011). Such disruptions have occurred in the past, partly set in motion by geopolitical turmoil (Mancheri, 2015, Wübbeke, 2013). Additionally, although there is seemingly no immediate concern for resource depletion in the coming decades, it has since long existed a concern for that unbridled mining eventually could deplete high grade ores of scarce metals (then usually referred to as 'geochemically scarce' metals), leaving only lower concentration ores that would require significantly larger efforts to extract, with detrimental consequences for societal welfare and the environment (de Koning et al., 2018, Skinner, 1979). Hence, if the societal dependence on scarce metals continues, it is increasingly relevant to manage flows of scarce metals sustainably.

A number of strategies could be used to prevent detrimental implications of supply disruptions or shortages, such as making technological advancements in mining of low grade ores (Tilton and Lagos, 2007), or substituting some scarce metals (Arvidsson and Sandén, 2017), but for many metals recycling would ultimately be needed if long-term sustainable management is to be achieved (Graedel, 2018, Graedel et al., 2015). Specifically, the metals would need to be recycled such that the specific properties of each metal can be reutilised, i.e. the metals need to be functionally recycled (Graedel et al., 2011, Guinée et al., 1999). However, current recycling industries are not well-adjusted to recovering all scarce metals, and concurrently, policy-makers and the research community are still only in early stages of finding ways of managing scarce metal resources. As a result, instead of being recycled many scarce metals risk being irreversibly lost (Bigum et al., 2012, Nakamura et al., 2012, Ohno et al., 2014, Restrepo et al., 2017). Thus, there is need for more knowledge in multiple domains if recycling rates of scarce metals are to increase. Such knowledge could be provided by examining recycling of scarce metals from end-of-life cars (ELVs), and waste electrical and electronic equipment (WEEE).

One fundamental issue is the lack of knowledge about flows of scarce metals in general. In fact, many metal flows in society are still uncharted (Chen and Graedel, 2012). It is therefore relevant to uncover how much scarce metals enters recycling via complex end-of-life (EoL) products, what routes metals take within recycling, and where metals ultimately end up. Thus, research studying scarce metal flows from EoL products from a *system* perspective is needed. Such research has only been increasingly undertaken in recent years and there are still large knowledge gaps, particularly around ELVs (Huisman et al., 2017). This lack of knowledge creates difficulties in finding strategies forward, and thus, higher resolution information is needed.

Still, even if high resolution information is acquired, how to develop recycling systems so that individual metals can be functionally recycled would still not be clear-cut. It is known that recycling in general is affected by several intertwined factors related to different dimension. These factors include the design of products, efficient and effective sorting, collection and treatment of waste, public policy, and market demands (Graedel et al., 2011, Reck and Graedel, 2012, UNEP, 2013). It is less clear how such factors in detail affect recycling of individual metals from specific products, and how to manage them so that recycling rates increase. However, there is a strong research tradition in other empirical fields (e.g. renewable energy and mobility) of studying how intertwined factors affect the development of new industry abilities. In these fields, it has been shown that such factors are involved in challenging system problems that require unique theory and analysis of how social and technical change intertwine, i.e. they require ways of understanding and dealing with ‘socio-technical’ change (Markard et al., 2012, Van Den Bergh et al., 2011). Consequently, adopting a socio-technical lens and searching for system factors that specifically impact on recycling of scarce metals from complex EoL products, may clarify how recycling rates can be increased.

Given the issues mentioned above, studying recycling through various research approaches that adopt systemic and socio-technical lenses could provide valuable insight, and enable the WM research community to further contribute to finding ways of developing successful recycling. Various well-known environmental system analysis (ESA) and socio-technical change approaches could be useful in this regard. Thus, it is a relevant issue in itself to examine the extent to which the WM research community has adopted such approaches, and to what extent knowledge generated in the WM field addresses the issues raised above.

1.1. Aim of research

This thesis aims to increase the resolution of knowledge around opportunities for, and challenges of, recycling scarce metals from complex EoL products. Additionally, it aims to identify measures that can raise recycling rates of such scarce metals. This is done by first addressing the three aforementioned issues: (1) the lack of knowledge about flows of scarce metals from EoL products in recycling, particularly from ELVs; (2) the lack of clarity about which factors affect recycling of individual scarce metals from EoL products; and (3) the need for examination of the extent to which ESA and socio-technical change approaches haven been adopted in WM research. Subsequently, obtained insight is used to identify relevant measures.

To this end, four research questions are formulated. Each question is answered using the appended papers according to Table 1. Question one ('How much scarce metals enters recycling via ELVs, what routes do metals take within recycling, where do metals end up and are metals functionally recycled?') is answered by quantifying the contents of scarce metals in Swedish ELVs, by a detailed mapping of material flows in Swedish ELV recycling, and an analysis of where scarce metals end up (paper I). The second question ('Which socio-technical system factors affect recycling of scarce metals from ELVs and WEEE?') is addressed by two case studies, in which a socio-technical lens is adopted and system factors are searched for in Swedish ELV and WEEE recycling (papers II-III). The third question ('To what extent has waste management research adopted environmental systems analysis and socio-technical change approaches?') is answered by quantifying and characterising the research approaches taken in WM, WEEE and ELV literature (paper IV). Methodologically, the conducted research is based on material flow analysis (MFA) (paper I), the technological innovation system (TIS) framework (papers II-III) and bibliometric analysis (paper IV). Question four ('Which measures can be taken to raise recycling rates of scarce metals from ELVs and WEEE?') is answered by compiling findings from papers I-IV.

Table 1. Research questions of this thesis, and the relationship between research questions and appended papers. 'X' indicates that the paper informs the question.

Research question	Paper I	Paper II	Paper III	Paper IV
Q1: How much scarce metals enters recycling via ELVs, what routes do metals take within recycling, where do metals end up and are metals functionally recycled?	X			
Q2: Which socio-technical system factors affect recycling of scarce metals from ELVs and WEEE?		X	X	
Q3: To what extent has waste management research adopted environmental systems analysis and socio-technical change approaches?				X
Q4: Which measures can be taken to raise recycling rates of scarce metals from ELVs and WEEE?	X	X	X	X

1.2. Scope of research

The majority of the conducted research (papers I-III) deals closely with recycling of metals found in ELVs and WEEE generated in Sweden. Of particular interest are metals existing in ELVs or WEEE only in small quantities, that have been highlighted as critical to the EU, U.S. or Japan (European Commission, 2017a, Hatayama and Tahara, 2015, Schulz et al., 2017) or are geochemically scarce (Skinner, 1979). These metals are referred to in this thesis simply as scarce metals (see Section 2.1 for further details). Furthermore, attention is primarily given to the very end stages of products life cycles, i.e. starting from the stage where ELVs and WEEE enter WM industries to the stage where contained metals are refined and sold. Geographically, mainly Swedish conditions are considered both due to practical reasons and because Sweden provides rich empirical material for case studies. The scope is widened to include non-Swedish contexts, and a variety of WM issues, when research approaches in WM research are examined (paper IV). This widening is done to enable a richer discussion on WM research.

1.3. Intended audience

This thesis primarily provides knowledge relevant to the long-term management of scarce metals. Consequently, government authorities, other researchers, as well as actors within industry and the general public concerned with long-term strategic issues are the primary intended audience of the conducted research.

1.4. Outline of thesis

Background information is provided in Chapter 2 on core terminology and issues raised in research related to this thesis, and on current Swedish industry conditions. Subsequently, Chapter 3 provides an overview of starting points for the conducted research, and of utilised theories, concepts and frameworks. Chapter 4 explains the research process, design and methods used, while main results are provided and discussed, and research questions are answered, in Chapter 5. The thesis is concluded in Chapter 6, followed by suggestions for further research in Chapter 7.

2. Background

2.1. Metal terminology

Metals can be grouped and named in many different ways. This thesis makes use of metal terminology that needs some explanation. First, metals and materials that have been associated with concerns over supply disruptions to e.g. the EU, Japan and the U.S. are typically referred to as 'critical', i.e. they are perceived as critical to industrial and overall societal development in these regions (European Commission, 2017a, U.S. Department of Energy, 2011). Second, metals can be referred to as 'geochemically scarce', referring to metals occurring at average concentrations in the earth's crust at <0,01% (Skinner, 1979). Such metals tend to form in unique concentrated ore deposits, which are the focus of current mining operations since mining from other ores would require substantially more energy (ibid.). Hence, metals can independently be labelled as 'critical' or 'geochemically scarce'. However, 'scarcity' is not a terminology tied to simply geology. Rather, scarcity is a wider concept applicable to resources that are perceived as constrained in supply to some extent. Such constraints may be e.g. geological, geopolitical, technical or economic (see Vikström et al. (2017) for a theoretical treatment of the scarcity concept). Hence, both critical and geologically scarce metals can be seen as scarce. In this thesis, metals used in cars and electrical and electronic equipment only in small quantities for their particular metal properties are referred to simply as scarce metals. The rationale is that such metals may constrain the supply of these products if supply disruptions occur. Additionally, the metals referred to here as scarce are either geologically scarce or have been pointed out as critical to the EU, U.S. or Japan (European Commission, 2017a, Hatayama and Tahara, 2015, Schulz et al., 2017). Thus, the usage here of the term scarce takes on multiple meanings.

Furthermore, several other groupings of metals are prominently used in society and in the conducted research. The currently highly valuable metals gold, palladium, platinum, rhodium and silver can be referred to as precious metals (UNEP, 2011). Additionally, a subset of these (palladium, platinum and rhodium) belong to the platinum group metals (PGMs) (Rao and Reddi, 2000). Metals can also be referred to interchangeably as 'base' or 'bulk' metals, referring to metals that are used in significant quantities by society such as aluminium, copper, iron, lead or zinc (UNEP, 2013). Metals produced to a lesser extent may instead be referred to as 'minor' metals (ibid.). Finally, rare earth elements are a collection of 17 chemically similar elements that also commonly have been pointed out as critical (Binnemans et al., 2013, European Commission, 2017a).

2.2. General challenges around recycling scarce metals from complex EoL products

Recycling scarce metals from complex EoL products is affected by aspects that are common to most metal recycling, but also by additional aspects that are more uniquely associated with so-called post-consumer waste, which often is materially complex and difficult to treat (UNEP, 2011, UNEP, 2013). Very materially complex products such as cars and electronics, pose significant recycling challenges in this regard (ibid.). Together, the common and the more unique aspects form some general challenges for recycling scarce metals from complex EoL products.

An important first aspect is described by Müller et al. (2006), who explore the fundamental metal life cycle. Essentially, a metal goes through extraction from primary raw materials (ores), refinement, product manufacturing, product use, and at the product end-of-life various potential waste management operations including collection and recycling. Eventually, this cycle (if losses of metals are avoided) can produce a metal stock large enough to enable circular flows without the need of much additional primary extraction. Naturally, primary production infrastructure thus precedes secondary, may have grown large and may additionally have strong support by multiple actors, as well as having institutional support (see e.g. Johansson et al. (2014)). The fundamental challenge in recycling thus involves shifting metal flows to closed loops, and building infrastructure that can compete with primary production.

Some insight to the scope and scale of this challenge is provided by Graedel et al. (2011), who for 62 metals present compiled knowledge on global average functional recycling rates (i.e. the percentage of a metal in a product that is returned to functional use, as a metal or a useful component in another material). It is estimated that for conditions representative of the period 2000-2005, this rate is above 50% only for 18 metals including base and precious metals, 25-50% for three metals, 10-25% for three others, 1-10% for two, and notably <1%

for the remaining 36 metals. Among the 36 are many non-precious scarce metals dealt with in this thesis. It is also noted that complex consumer products are particularly affected by low recycling rates (in comparison to e.g. industrial manufacturing waste) due to that: Product designs make separation of materials difficult; global mobility of products hampers the possibility to track metals; there is lack of societal awareness about losses of metals; there is lack of financial incentives for recycling metals, present in products at low concentrations; and due to that there is lack of recycling infrastructure compatible with modern products. It is concluded that whether recycling takes place or not ultimately depends on the economic value of metals, technology (of products and recycling systems), and social aspects such as awareness and public policy. It is further suggested by Graedel (2018), that improving EoL recycling rates is one of the grand challenges for managing metal life cycles. Thus, the scale of the challenge of raising low recycling rates is significant, particularly when consumer products are considered.

A number of authors have similarly addressed the scale and scope of the challenge of recycling complex post-consumer goods. It is argued by Izatt et al. (2014) that society at large has not yet appreciated the variety of metals that have become available during the 20th century, and that there is need for significant government and industry action to manage elemental flows. It is argued by Reuter et al. (2006), Van Schaik and Reuter (2004) and van Schaik and Reuter (2010) that the high degree of complexity of products such as cars and electronic equipment requires “product centric” recycling, which in turn requires deep knowledge about product designs, the metal contents of products, the thermodynamic properties of metals in refining, as well as the organisation and optimisation of recycling industries around the best available technologies. Similar issues are touched on in work by Reck and Graedel (2012), who argue that the most important actions for raising recycling rates are to increase collection of EoL products, adapt product designs to recycling, and to deploy modern recycling methods.

Regarding policy, it is widely acknowledged that extended producer responsibility (EPR) regulation plays a significant role in how waste management is performed for those products that are covered by such regulation. Although various EPR implementations generally are considered as favourable to waste management and recycling, such policy has also been criticised for i.a. being toothless against non-compliance, for not sufficiently affecting product designs and for being incapable of affecting highly untreatable materials (for discussions on these aspects, see e.g. Lifset et al. (2013), Gerrard and Kandlikar (2007), Sakai et al. (2014), Sthiannopkao and Wong (2013), or Khetriwal et al. (2009))

In summary, the here covered research indicates that recycling scarce metals from complex EoL products involves economic, social, technical, and political issues, and that raising recycling rates is a challenge of considerable size. There is also evidence for that it is relevant to consider the unique characteristics of individual metals, product groups and recycling industries.

2.3. ELV management in general and recycling of scarce metals specifically

The literature related to ELVs that has received the most attention so far is focused on the following: Assessing technical feasibility of waste management processes and procedures around specific materials; modelling and optimisation of processes and procedures, as well as of waste logistics; and characterising the material composition of various material streams generated in ELV management (see paper IV). In particular, the difficult to treat material stream generated when shredding ELVs, referred to as 'automotive shredder residue', 'shredder light fraction' or simply 'shredder fluff' has drawn much attention (see e.g. Nourreddine (2007), Morselli et al. (2010), de Marco et al. (2007) or Colangelo et al. (2017)). Additionally, focus has also been put on other material or component streams such as tire rubber (see e.g. Rajarao et al. (2015), Fukumori et al. (2002), Ucar et al. (2005), Williams and Taylor (1993) or Williams et al. (1990)), aluminium (see e.g. Modaresi et al. (2014b), Passarini et al. (2014), Modaresi et al. (2014a), Modaresi and Müller (2012), Cui and Roven (2010) or Roth et al. (2001)) and batteries (see e.g. Neto et al. (2016), Hoyer et al. (2015), Gaines (2014), Lux et al. (2010) or Kreusch et al. (2007)).

The number of articles covering recycling of scarce metals from ELVs is low. At the time of writing, only 15 studies can be identified that deals closely with issues around not only precious metals, but multiple non-precious scarce metals. A handful of these have estimated the contents of scarce metals in ELVs. In general results from these studies highlight how scarce metals are used in relatively small quantities compared to other metals and materials, and point to data uncertainty around metals (see Du et al. (2015) for a comparative study, and Restrepo et al. (2017) for a detailed recent study). Scarce metals have also been tracked through ELV shredding processes in Switzerland (Widmer et al., 2015). Although results are somewhat uncertain, they point to that many scarce metals enter shredder fluff and are not recycled.

A number of other studies have covered the potential for recycling alloying elements in steel and aluminium, from ELVs in Japan (Ohno et al., 2017, Ohno et al., 2015, Ohno et al., 2014, Nakajima et al., 2013, Nakamura et al., 2012). In short, these studies highlight how alloying elements are not recovered in current metal refining processes, due to elements ending up in slags (i.e. in by-products from refining processes) or getting enclosed within refined steel or aluminium. Thus, non-recovered elements could, in addition to essentially being lost, also downgrade other materials. Such ‘downcycling’ has also been explored by Ortego et al. (2018).

Recycling of magnets have been studied by Daul et al. (2017) and Jin et al. (2018): Neodymium magnets from ELVs and WEEE that were shredded concurrently with steel were studied by Daul et al. (2017). They confirm that scrap steel refining transfers rare earth elements into slags. Jin et al. (2018) performed an LCA on theoretical recycling of neodymium-iron-boron magnets from electric vehicles, and found that a recycled magnet would have significantly less environmental burden than one produced using virgin raw materials.

Furthermore, various implications for supply and demand of certain scarce metals due to potential introduction of new vehicle technologies have been studied. The effect on supply and demand in the U.S. of rare earth elements, under the scenario that aluminium-cerium-magnesium alloys are extensively used in emerging vehicles, has been studied by Fishman et al. (2018). It is suggested that the U.S. production capacity from mining would be exceeded in such a scenario, pointing to that improved ELV recycling would be relevant to meet supply. Yano et al. (2016) and Xu et al. (2016) examined the potential for recycling some rare earth elements from the transmission system, magnets, and the battery unit in future Japanese hybrid electric and conventional vehicles (time period 2010-2030). Results suggest that studied components will contain enough metals to cover significant amounts of the demand from new vehicles in 2030, if metals could be recycled (i.e. make the production-recycling system closer to being self-sustained). Bulach et al. (2018) assessed the financial potential and environmental implications of recycling gold, palladium, silver, tantalum and some base metals from power electronic modules in future electric vehicles in Germany. The assessment focuses on the use of current ELV treatment technology, accompanied with a proposed chemical disassembly step for printed circuit boards. Results point to that the recovery of precious metals could be financially and environmentally beneficial, but that recovery of tantalum would be environmentally and financially problematic.

In summary, ELV research in general is technically oriented, and the research that takes multiple scarce metals into account is still in its infancy. However, the existing research on scarce metals points to that recycling of most scarce metals is lacking, but it also strongly indicates that more research is needed.

2.4. WEEE management in general and recycling of scarce metals specifically

Two bodies of literature have drawn significant attention in the WEEE related research domain (see paper IV). The first is concerned with various assessments of hazardous conditions in WEEE treatment, particularly in countries or regions with underdeveloped WM. Major attention has been given to some Chinese regions, highlighted as being of major concern for the global management of WEEE since they have been recipients of large international WEEE flows and lack modern recycling methods (see e.g. Lin et al. (2017), Zhang et al. (2016), Tan et al. (2016), Luo et al. (2011), Chi et al. (2011) or Fu et al. (2008)). The second body is primarily centred on technology assessments of various automated waste treatment or metal refining processes (see e.g. Beiyuan et al. (2017), Petersen (2016), Akcil et al. (2015), Tuncuk et al. (2012), Zhou and Qiu (2010), Park and Fray (2009) or Li et al. (2007)).

Although there is a large number of articles dealing with precious metals (close to 500 can be identified at the time of writing), fewer also deal with non-precious scarce metals. However, since 2010 there has been a growing number of articles published dealing with non-precious scarce metals such as rare earth elements, or other metals considered by the EU, U.S. or Japan as critical. At the time of writing, ca 140 such articles can be identified. Similar to the field at large, most are dedicated to assessing various technical processes for recovering metals. Some relate more to the here conducted research.

Exports of discarded electronics and electrical equipment from Japan are quantified by Fuse et al. (2011), showing that of domestically discarded products, half of the contained indium, 20-30% of the contained antimony, barium, gold, lead, silver, strontium, tin and zirconium are exported mainly to other Asian countries where recycling is unlikely. On a related note, Nakamura (2014) instead discusses Japanese domestic scarce metal recycling technologies, suggesting that significant advancements are needed.

Regarding European conditions, neodymium and dysprosium from mostly WEEE products but also ELVs are tracked through Danish recycling by Habib et al. (2014). It is concluded that recovery is challenging due to that scarce metals exist in small quantities relative to other materials in waste flows, and due to the diverse nature of product types and configurations. Additionally, Habib et al. (2015) track neodymium-iron-boron magnets from hard drives through conventional Danish WEEE treatment to final treatment of materials, showing that steel and aluminium can be recycled but that rare earth elements are fully lost as dust when components are shredded, or in later refining processes. The recycling of multiple metals from mobile phones by two different industry value chains, including metal refining, representing Belgian and other European conditions is modelled by Valero Navazo et al. (2014). It is estimated that antimony, copper, gold, lead, nickel, palladium, silver and tin can be recycled at between 80-99%, while other scarce metals are not recycled. Flows of gallium through German chip and LED production and through WEEE treatment and refining was modelled by Ueberschaar et al. (2017b), showing major losses through the entire industry value chain. Most gallium is lost before entering WEEE treatment, and post entry complete loss of all remaining gallium is expected. It is further noted that the only industrial scale process for gallium recovery exists in Belgium, but that this process only recovers the metal from some varieties of solar modules. Finally, flows of bulk and precious metals as well as some rare earth elements (Ce, Eu, La, Nd, Y) through Italian WEEE processing are studied by Marra et al. (2018), who conclude that 80% of the rare earth elements likely are lost as dust particles in the processing, while the remains are intermixed with other materials streams produced.

Related to global and future prospects for recycling it is suggested by Nassar (2017) that, after studying world tantalum supply and demand in the period 1970-2015, at least 75% of all tantalum produced since 1970 now has been lost due to lack of recycling, including tantalum in electronics. Future potentials and barriers for recovering tantalum from WEEE are studied by Ueberschaar et al. (2017a). Results indicate that there is technical potential in recycling tantalum, but that costs of recovery, and use of energy and chemicals, along with uncertainty around the continued use of tantalum in future products and the tantalum price, form barriers to deployment of recycling technology.

In summary, WEEE research has covered scarce metals to some extent. The research reviewed here indicates that at least European and Asian WEEE treatment and metal refining infrastructure is not well suited to recover non-precious scarce metals. Additionally, most studies that quantify metal flows point to large data uncertainties and express the need for higher quality data. Several studies identify domains of interventions needed to increase recycling rates, such as technology, policy, or public awareness but tend not to study these simultaneously. It can be noted that such interventions are more clearly discussed by studies focused on severely underdeveloped WEEE treatment in some countries (mostly China). Although such studies cover important humanitarian and/or environmental issues, they typically do not relate to recycling of scarce metals.

2.5. Current Swedish ELV and WEEE management and metal refining capabilities

The issues covered in Sections 2.2-2.4 are relevant also to Swedish conditions. Swedish treatment of ELVs and WEEE is conducted in two separate industries. Metal-rich raw materials produced by these industries may be utilised by Swedish metal refining industries, which hold capacity to refine a multitude of metals.

Swedish ELV treatment is essentially made up of two activities: Manual dismantling and automated treatment (see paper I, Section 2.2 for a detailed description). There currently exist roughly 300 dismantling firms. These receive ELVs from private individuals or insurance companies. In the dismantling process, dismantlers typically remove spare parts, steel or aluminium-rich components, along with components (e.g. oils, catalytic converters, main batteries, window shields) that are required to be removed according to EU and Swedish ELV legislation. Subsequently, dismantled ELVs are sold to companies that rely on large-scale shredding facilities (i.e. automated treatment) to grind down ELVs and produce a diversity of raw materials. Primarily three companies currently perform automated treatment. These companies can produce a variety of raw material streams rich in iron (from steel or cast-iron components), aluminium, and to some extent copper that can be sold to metal refining industries. Other produced material streams can be used as construction materials, are incinerated or landfilled. Adherence of industry activities to ELV regulation is managed by one producer responsibility organisation (PRO), which is owned by the Swedish Car Recyclers Association (SBR, representing car dismantling firms) and the largest automated treatment company. Within the PRO, there are internal agreements around how to organise ELV management. Hence, ELV regulation significantly affect work procedures and relationships.

Similar to ELV treatment, WEEE treatment involves manual dismantling and automated treatment, but companies involved in WEEE treatment perform both activities (see paper III for additional descriptions). Due to different legislative requirements and physical characteristics of different WEEE, all WEEE is not treated the same. In practice, light sources, large domestic appliances (e.g. washing machines and cooking stoves), fridges and freezers, and various electronic devices (e.g. mobile phones, computers and vacuum cleaners) are treated separately. During dismantling, parts covered by EU and Swedish WEEE legislation are removed manually. Some additional items rich in metals may be removed if deemed economically viable by the person performing the dismantling. The remains are shipped to automated treatment, i.e. shredding followed by automated sorting processes. The produced metal-rich raw materials are sold to metal refineries. Legal requirements are managed by two PROs, of which one (owned by industry associations tied to production of electrical and electronic equipment) organises the vast majority of all WEEE flows, by procuring waste treatment services from WEEE treatment actors.

Regarding metal refining, Sweden holds (beyond secondary steel and aluminium production) one facility, which is one of the largest consumers worldwide of raw materials from electronic scrap. It currently produces copper, gold, lead, platinum group metals, silver and zinc, and primarily sells these to manufacturing industries in northern Europe (see paper I and papers I-II regarding details on production of secondary Al and secondary steel respectively, and paper III regarding production of Ag, Au, Cu, Pb, PGMs and Zn).

2.6. Summary

The research covered in Sections 2.2-2.4 suggests that recycling scarce metals from complex products involves both large-scale challenges that are associated with metal recycling in general, and unique challenges that apply to specific metals, waste groups, and recycling industries. Additionally, it is frequently expressed in the literature covered that there is need for a shift in the production of metals or materials in society towards closed loops, but it is more seldomly expressed in detail what such a shift would entail. Moreover, the multitude of challenges highlighted in the literature, are thus relevant to consider when studying the Swedish treatment and refining industries that were introduced in Section 2.5.

3. Theoretical foundations

3.1. Implications of some initial starting points

The conducted research is influenced by ideas expressed in systems science literature, in that the research gravitates towards taking holistic perspectives. More specifically, the conducted research adheres to the central idea in systems oriented research, that when a complex phenomenon is studied involving several components, it is relevant to study sets of components and their relations rather than studying each component in isolation (Laszlo, 1972). Additionally, the research is aimed not only at *describing* complex phenomena through system perspectives, but at using system perspectives as an *approach* for suggesting solutions to systemic problems (Churchman, 1968). Moreover, the research is somewhat influenced by the idea of soft systems, in terms of that a system can be thought of as "an abstract organising structure rather than an entity in the real world" (Flood and Carson, 1993), and that several representations of a real world phenomenon are valuable.

Furthermore, at the core of the thesis lies the motive of addressing societal challenges around scarce metals. To this end, much of the conducted research focus on understanding physical flows of metals and materials, and explaining such flows by studying aspects such as the use of technology, industry activities, policy and development of these over time. Less attention is given to explaining such flows through pure social lenses and taking into account aspects such as beliefs, values or norms existing in society or held by individuals. Although the present focus is informed by the aspects discussed in literature, it is likely also influenced by the natural science and engineering background of the author.

3.2. Modelling physical flows in systems

For studying flows of products, materials or substances through systems, material flow analysis (MFA) is commonly employed (see Ayres and Ayres (2002) for a comprehensive overview). Studies that specifically analyse substances are sometimes treated as a subfield of MFA studies, and the approach may then instead be referred to as substance flow analysis (SFA) (Van Der Voet, 2002). Regardless, the approach taken is similar, and essentially involves making an account of physical flows entering, being manipulated within, and exiting a studied system comprised of various processes. MFA has seen extensive use and development within the field of Industrial ecology since the mid-90s (Bringezu and Moriguchi, 2002). There, the approach has been used for studying physical flows through firms, industrial sectors, regions and at the global level (ibid.)

The approach involves making use of quantitative data about physical flows, modelling of processes (e.g. manual operations, machinery, turnover of materials in industries or by nations) and using the principle of mass balance to accurately quantify physical flows. In essence, each process needs to be represented by so-called transfer coefficients, which allocate process inputs to process outputs. Doing this for an entire system reveals how physical flows propagate through the system. The aims of such studies can be many, e.g. finding salient physical flows or accumulated stocks, or highlighting certain characteristics such as if materials are dissipated or concentrated by a system. Results from MFA studies are commonly visualised through so-called 'Sankey diagrams' or 'Sankey charts', in which the size and direction of physical flows are represented by arrows of varying thickness, and processes are represented by boxes.

The MFA approach is typically credited with being able to elucidate physical flows that otherwise are not intuitively comprehended, thus enabling creation of unique knowledge and decision support that in turn may assist intervention for or against certain flows, e.g. intervening against flows of hazardous substances (Bringezu and Moriguchi, 2002).

3.3. Understanding socio-technical change and innovation systems

Literature concerned with large-scale socio-technical change in different ways highlights the idea that technical and social change is intertwined, and thus that the technical dimension cannot be separated from the social. Some of the literature today provides concepts and analytical tools that can be used for describing and addressing 'green' industry development challenges. This literature can thus provide an additional lens to MFA modelling (Section 3.2), in terms of giving insight into what 'drives' materials flows. Naturally, because socio-technical change is a broad topic, it is not covered by one unified body of work alone. Rather there are multiple salient bodies of work, often of a multidisciplinary type, with ties to several intellectual roots. Consequently, the literature is not easily delineated, and is much too large to cover in full. Nevertheless, before introducing current key literature, a brief introduction to some intellectual roots is needed.

A starting point is given by Martin (2012), who suggest that 'Science policy and innovation studies' (SPIS) can be outlined as an established scientific field since the late 1950s. Among concepts dealt with in the field are 'systems of innovation', first introduced by Freeman (1987) to explain development of technologically advanced industries in Japan (with the ultimate goal of better explaining economic growth). The concept was further developed in parallel by Freeman (1988), Lundvall (1988) and Nelson (1988) who referred to 'national systems of innovation' (Markard et al., 2012, Martin, 2012). Essentially, the concept stresses that industrial change has a system property. It is suggested that R&D activity in a nation, public policy, and activities and relationships between multiple types of actors (e.g. universities, research institutes, and government agencies) can be understood as a system that influences industrial development (and economic growth) (Carlsson et al., 2002). According to Carlsson (2016) the national innovation system concept subsequently served as inspiration for other system innovation perspectives. For instance, that of 'technological systems' (Carlsson and Stankiewicz, 1991), developed to more specifically account for the role of technological development in economic growth models. It can be noted that the innovation system idea can be seen as an opposing view to the 'linear model of innovation', which suggests that technological innovation and economic growth can be understood as a sequential process initiated by basic research, followed by R&D, production and diffusion (Godin, 2006). Furthermore, Nelson and Winter (1977) are credited with providing the initial version of the widely used concept of a technological 'regime', which in its current version can be interpreted as an established and socially entrenched use of a technological infrastructure (e.g. the fossil fuel, car and road system).

Another body of influential literature is 'Science and technology studies' (STS), which according to Martin et al. (2012) has been a distinct although fragmented field since the 1960s. In the field, there is influential work that emphasize the social dimension of technological development. For instance, in the work by Pinch and Bijker (1987) the ideas of sociology of technology is exemplified. It is highlighted how the development of the bicycle was driven by multiple social groups assigning different meanings to the bicycle. Furthermore, the development of large technical systems, such as electric grids has been described by Hughes (1987). He illustrates that multiple components such as technical artefacts, actors (individuals, organisations etc.) and policy are interdependent and jointly involved in messy and complex development processes.

The aforementioned literature has, as described by Markard et al. (2012), been influential to the field of 'Sustainability transitions', which is suggested to be an emerging field of its own involved with taking "*systemic views of far-reaching transformation processes of socio-technical systems*". In particular, transition management (TM), strategic niche management (SNM), the multi-level perspective (MLP) on socio-technical transitions, and the technological innovation systems (TIS) framework, are pointed out as current key bodies of literature. These approaches are multidisciplinary, and typically involve collecting and analysing multiple types of data, often including data from interviews or observations made in case studies.

SNM put emphasis on nurturing the development of immature technologies in protected spaces, so-called 'niches', through e.g. R&D and demonstration projects or artificially created markets, so that the technologies may mature and eventually compete with and replace regimes, thereby inducing socio-technical transitions (Schot et al., 1994, Kemp et al., 1998, Schot and Geels, 2008). It is emphasised in SNM that the deliberate (i.e. strategic) set up of such niches, where users can experiment with technology and develop practices, is key for enabling technical and social co-development. The approach thus draws on both the SPIS literature around regimes and STS literature.

Similar ideas around actor involvement and experimentation is also present in TM, a framework aimed at formalising an approach to governance of socio-technical transitions (Loorbach, 2010, Loorbach and Rotmans, 2010). It has formally been part of Dutch national environmental policy, and is based on purposely establishing coalitions of actors (e.g. government agencies, NGOs, firms, private individuals) that have potential to create influential societal movements by co-creating and experimenting with strategies for change.

The ideas associated with SNM are further enriched by the MLP, which provides a conceptualisation of large-scale and broad socio-technical transitions from one socio-technical configuration to another. For instance, in the highly cited paper by Geels (2002), the transition from the prevalent use of sailing ships to the use of steamships during 1780-

1900 is used as a case study. Other examples include studies of the Dutch electricity system (Verbong and Geels, 2007), and the shift from horse-drawn carriages to cars (Geels, 2005). The MLP has since been further developed in a number of papers (see e.g. Geels (2011) for a retrospective view). In summary, technological transitions and its dynamics are conceptualised by the MLP as interplay between three socio-technical 'levels': Regimes, niches, and broader cultural movements occurring at the 'socio-technical landscape' level. Transitions are conceptualised as occurring in different ways. For instance, they may take place through changes occurring at the landscape level that result in weakened support of a regime, thereby making room for alternative technologies and enabling niche technologies to challenge and ultimately replace the regime.

The TIS framework has instead typically been used to in detail study the emergence and diffusion of specific technologies, interpreted as products (goods/services), processes or technical knowledge (Bergek et al., 2008a). The aim has been to in a structured way find means of intervention (typically through policy) by identifying mechanisms that both support and block development. The TIS concept is usually traced back to the aforementioned 'technological systems' concept, but it has since drawn inspiration also from the STS literature at large, SNM and the MLP (Bergek et al., 2008a, Hekkert et al., 2007). Additionally, the framework has been developed to include descriptions of different types of socio-technical change process, so-called 'functions', with the motivation to describe, explain and address development dynamics in more detail.

There is thus a rich literature available that can describe and address complex multidimensional industry development challenges. Although there is significant cross-fertilisation between the key literature described, it is the view of the author that TM, SNM and the MLP emphasise social construction and historically have been rooted in description to larger degree than the TIS framework. In contrast, TIS has more strongly emphasised a system perspective with the aim of intervention and problem solving. The conducted research makes use of the TIS framework due to its tradition in detailed studies of specific technologies/industries, and in finding means of intervention.

4. Research process, design and methods used

Before describing used methods in detail, some comments on the overall research process and design can be made. It can be noted that papers I-IV were produced more or less in sequence, i.e. paper I was followed by paper II etc. However, some overlap existed. The overall research process can be likened to the process described by Marshall and Rossman (2011). Although their description aims to capture more qualitative case work, the general principle applies. The process can be described as cyclical, starting with research design (choice of case, framework etc.), followed by data collection, analysis, production of the outcome (i.e. research papers etc.) and taking the research experience (i.e. empirical knowledge, theoretical considerations and methodological know-how) into the next cycle of research. In the conducted research, the starting point was the attempt to quantitatively describe physical flows of scarce metals through ELV waste management (paper I). From paper I, appreciation (i.e. experience) was gained for the multiple issues involved in raising recycling rates of scarce metals. Hence, theory, frameworks and cases were sought for that could aid in capturing, and making sense of, these issues (e.g. how recycling rates are affected by materially complex waste streams, by the use of technology in industry, policy, metal markets etc.). This led to the production of papers II-III. Paper II attempts to gain insight from historic events, while paper III attempts to apply that insight and develop new, case-specific insight, from current conditions. An increased understanding of relevant issues, theory and frameworks, subsequently led to examination of current waste management research itself (paper IV). Papers I-III rely on case studies to produce rich and realistic descriptions and explanations, while paper IV uses bibliometric analysis to provide a broad knowledge overview. The methods used in papers I-IV are summarised in Sections 4.1-4.3.

4.1. Method of paper I

To track scarce metals through ELV recycling, paper I relies on a three-step procedure. First, annual input of some scarce metals to Swedish ELV recycling is estimated using product data on three diesel-powered Volvo cars, representative for the Swedish market. The data predominantly originates from the International Material Data System (IMDS) (Cullbrand and Magnusson, 2012), but is supplemented with some other sources (see supplementary material to paper I). The analysis covers 25 metals (Ag, Au, Ce, Co, Dy, Er, Ga, Gd, In, La, Li, Mg, Mn, Mo, Nb, Nd, Pd, Pr, Pt, Rh, Sm, Ta, Tb, Y, Yb). Each metal is allocated to 'main application categories', i.e. categories of car components that are reported in the IMDS data, or are estimated by the authors, as holding a predominant share of the scare metals reported in the IMDS data. Four categories are metal alloys where the base is either steel, aluminium, magnesium or nickel. The remaining three categories are lubricants, catalytic components (the catalytic converter system) and electric, electronic and magnetic components. The three car models are separately used to calculate annual input of scarce metals to recycling, resulting in input intervals (Figure 1). Intervals are assumed as fairly representative for conditions in the late 2020s or early 2030s, since the car models were produced around 2010 and the life-span of cars in Sweden is roughly 18 years.

Second, pathways taken by application categories through ELV recycling are estimated using a MFA model of Swedish ELV recycling. The model is based on officially reported ELV statistics, and on data on key system processes. Process data is sourced from WM literature, relevant technical reports and from qualified experts through interviews or e-mail. Data from 16 open-ended interviews and five e-mail correspondences were used for modelling (see the Appendix, Table A2, for the used the interview guide). Interview data was cross-checked by querying multiple experts, or comparing statements to literature.

Third, based on the identification of pathways taken by component categories, the final fate of each contained scarce metal is estimated. Fates are categorised as either (i) functional recycling, (ii) non-functional recycling in a carrier metal, (iii) non-functional recycling in other materials, (iv) no recycling or (v) unknown. Landfilling of metals is categorised as no recycling (iv), and dispersion of metals in construction materials as non-functional recycling in other materials (iii). A metal refined such that the metal itself is the dominant constituent of the refined output, is considered functionally recycled (i). A scarce metal instead contained inside a refined metal alloy, is categorised as functionally recycled (i) if the alloy makes use of the elemental properties of the scarce metal, otherwise the fate is categorised as non-functional recycling in a carrier metal (ii). The allocation of scarce metals to outputs from metal refining is based on work by Lagneborg and Waltersson (2004), Nakajima et al. (2011), Nakajima et al. (2010) and Steinlechner and Antrekowitsch (2015). When such allocation cannot be defined, the categorisation unknown (v) is applied.

4.2. Methods of papers II-III

Papers II and III essentially rely on similar approaches. Paper II makes use of the TIS framework to explain historic events that formed two segments of the industry value chain that currently recycles iron from ELVs. Hence, paper II exemplifies how functional recycling of a metal (Fe) can be developed. Paper III instead uses the framework to explain current challenges, in segments associated with recycling multiple scarce metals (Ag, Au, Ga, Pd, Ta) from ELVs or WEEE. The TIS framework is described in general below, before the specific methods of papers II and III are described in Sections 4.2.1-4.2.2.

A TIS study requires a delineation of a socio-technical system, composed of more or less networked actors, physical artefacts and various relevant institutions (e.g. regulation, norms, values). The system is primarily interpreted as an analytical construct, and thus the system may not be observable in real life (Bergek et al., 2008a). Furthermore, the system enables *"the development, diffusion and use of a particular technology"* where 'technology' refers to products (goods/services) or technical knowledge (ibid.). It should be noted that there is no one single way to delineate a system under study, or to define a technology, instead this is up to the analyst and depends on the problem under study (ibid.). Often, a 'technology' in TIS studies (as in everyday life) is thought of as a physical artefact, such as car or a windmill. In such a case, the TIS would be the networked actors, physical artefacts (which may or may not include the car or the windmill depending on the studied problem) and various institutions that enable the development, spread (diffusion) and use of the car or the windmill. This view of a TIS and a technology is sufficient for many studies, however in the research conducted here it is of interest to elucidate the relationship between flows of scarce metals through many stages of recycling systems, and industry development. It can therefore be highlighted that, for a physical artefact such as a car to actually be developed, spread and used, an industry value chain (including car manufacturing, suppliers and sourced raw materials etc.) would concurrently need to be developed. Hence, the development of a physical artefact cannot be separated from the development of an industry value chain, which itself can be seen a socio-technical system. It follows, although somewhat unwieldly to think about, that the TIS enables the development, diffusion and use of a particular socio-technical system. It can thus be methodologically useful to first delineate socio-technical components that are perceived as being part of the value chains (the 'technology') studied, and then interpret the TIS as the socio-technical components that enables these value chains to develop. The conducted research utilises these ideas.

However, the TIS concept is also a description and an explanation of change. It conceptually links the development of the socio-technical system under study to a set of factors that support or block development. A variety of factors has been identified in TIS literature. Additionally, such factors have been referred to differently by different authors depending on the application of the TIS concept. Factors have generally been captured as either ‘structural components’, referring to socio-technical components of the studied system (i.e. more or less networked actors, physical artefacts, or institutions) or as innovation system ‘functions’, referring to socio-technical change processes such as the development of new knowledge or markets (Bergek et al., 2008a, Hekkert et al., 2007). The general idea is that configurations of socio-technical components can take part in functions and thereby develop a technology. Some configurations may instead block development, thus factors can both support and block development. Moreover, the influence of changing socio-technical components on these type of developments has been referred to as ‘forces’ (Hillman and Sandén, 2008). Several sets of functions have been proposed, this thesis makes use of those suggested by Bergek et al. (2008a), see Section 4.2.1.

The development of a technology, i.e. the socio-technical system under development, is further conceptualised by distinguishing between factors that are external and those that are internal to the system (Hillman and Sandén, 2008, Bergek et al., 2008b). In early stages of a development the system lacks many abilities, and external factors determine the strength of functions. However, as the system matures the strength of functions is increasingly determined by internal factors. This can create circular causality, leading to both self-propelled growth and lock-in to certain development trajectories (Bergek et al., 2008b, Arthur, 1988). This type of snow-balling effect and directionality of developments have been widely observed in SPIS and STS literature (see e.g. Nelson and Winter (1977) or Hughes (1987)).

4.2.1. Specifics regarding the method of paper II

The technology in focus of paper II is described as the capability of transforming ELVs to iron (‘iron’ should in the context of this thesis be interpreted as iron-rich raw materials). Hence, the socio-technical components that represent current Swedish ELV dismantling and automated treatment are delineated and seen as the 'technology'. Subsequently the build-up of this value chain is traced through history. The temporal scope of the study is 1910-2010, chosen in order to capture salient events. The spatial system boundary is Sweden. Car manufacturers and users are viewed as suppliers outside the system, since they operated largely independently of the system in the studied period. Similarly, steel manufacturing and other downstream industries are treated as external.

Procedurally, time periods of significant events are first identified and described. Then, the TIS functions by Bergek et al. (2008a) are used to suggest an explanation for observed events (see Paper II, Chapter 2). The observed events and theoretical explanations are subsequently organised into 'sequences' of events, to explain observed developments in a condensed way. For each sequence, exogenous and endogenous forces are noted (see Paper II, Table 2). Finally, using these sequences as base, it is discussed to what extent interventions (referred to in Paper II as initiatives) can be formed.

For data input the paper relies on numerous literature sources, longitudinal statistics and interviews with qualified experts. Sources of literature used, beyond research articles, include reports or books published by relevant firms, trade associations, research organisations, government agencies, local history societies and governmental bills and official inquiries by the Swedish government. Some longitudinal statistics are used to track the number of sold and scrapped cars, active dismantling actors, and the production of Swedish steel. Certain statements on past events were collected through six open-ended interviews with key qualified experts, who were involved in the development (see the Appendix, Table A2, for the used the interview guide). Interview data was cross-checked with one or multiple sources, either printed material or statements from interviews.

4.2.2. Specifics regarding the method of paper III

In paper III, value chains associated with Swedish ELV and WEEE treatment and metal refining are studied. Specifically, the potential is examined for recycling metals from printed circuit boards (PCBs), present in ELVs and WEEE. Among metals studied are gold, silver and palladium, treated as one group and referred to as 'precious metals'. Additionally, gallium and tantalum are studied, referred to as 'minor metals'. The selection of waste streams, value chains and metals is made to illustrate opportunities and challenges of recycling multiple scarce metals from complex EoL products.

To this end, a number of socio-technical focal systems (i.e. focal ‘technologies’) are analytically delineated. Studying multiple systems at a time is still rare in research related to socio-technical change, but examples exist (see e.g. Magnusson and Berggren (2018) or Sandén and Hillman (2011)). The delineation is done by specifying the transformation that each system performs, in terms of turning waste inputs into outputs of refined metals (see T_{F1-4}, Table 2). Each focal system is assigned the analytical goal of outputting the entire amount of the metal that is contained in the PCBs of the system input, i.e. achieving a recycling rate of 100%. Importantly, some segments of the real-world value chains that the focal systems represent, are the same (Figure 4). The systems are still treated as separate technologies, since they may perform differently according to their analytical goals. Additionally, in a similar way a number of other identifiable socio-technical systems are specified, referred to as contextual (see T_{C1-8}, Table 2). Sweden is set as the spatial boundary for all systems, to support data collection and because Sweden provides an illustrative case of the challenges involved in recycling individual scarce metals. Temporally, paper III uses data representing ca 2017, in order to examine current conditions, and to analyse the potential for future developments of the delineated systems.

Table 2. Delineations of focal and contextual technologies studied in paper III. Systems in focus of the study are denoted by index F (T_F). Other identifiable systems are denoted by index C (T_C). The socio-technical boundaries are defined by inputs and outputs. Spatial and temporal boundaries are Sweden and current conditions respectively. T_{F1}-T_{F4} are assigned the goals of fully recovering the metals described by system outputs.

	OUTPUT						
INPUT	Refined precious metals from PCBs (Au, Ag, Pd)	Refined minor metals from PCBs (Ga, Ta)	Other refined precious metals (Au, Ag, Pd)	Other refined minor metals (Ga, Ta)	Refined copper (Cu)	Other refined metals (Pb, Zn)	Raw materials treated outside studied value chains (Cu, Fe, Al, Other)
WEEE	T_{F1}	T_{F2}	-	-	T_{C1}	-	T_{C2}
ELV	T_{F3}	T_{F4}	-	-	T_{C3}	-	T_{C4}
Other (e.g. primary raw materials)	-	-	T_{C5}	T_{C6}	T_{C7}	T_{C8}	-

To explain the challenges involved in developing recycling, paper III is focused on identifying and subsequently assessing the impact of a set of external and internal factors that support and block recycling. The following external factors are studied: The magnitude, composition and economic value of waste streams, as well as industry access to markets and guidance from policy-making on scarce metals. Regarding internal factors, the following are studied: EPR regulation; internal value chain relations and business models; the historical heritage of physical infrastructure, knowledge, and actor networks; and the industry’s revealed goals and associated investment in new capability. The selection of factors is partly based on paper II, and the empirical findings of paper III. The point of distinguishing between internal and external factors in paper III, is mainly to expose the possibility for studied actors to influence developments: Internal factors are more open to influence by actors in or at the fringe of the studied systems, while external factors may be out of reach. For further theoretical considerations, see paper III, Chapter 2.

Data sources used include publicly available information by companies, industry associations, research organisations, government agencies, public and governmental bills and official inquiries. Some data was also collected through seven open-ended interviews covering industry specifics (see the Appendix, Table A2, for the used the interview guide).

4.3. Method of paper IV

Paper IV relies on bibliometric analysis to study the research approaches taken in WM, WEEE and ELV related research. Particular attention is given to WEEE and ELV research. Specifically, it is examined to what extent ESA and approaches associated with studying socio-technical (ST) change are adopted. The following three principal steps are conducted:

1. Identification of relevant search terms, that can be associated with ESA and ST research approaches and the three empirical fields (i.e. WM, WEEE, ELVs).
2. Quantification of articles that use the identified terms associated with ESA or ST research approaches and empirical fields.
3. Quantification and characterisation of articles in the WEEE and ELV fields that do not use any of the identified terms associated with ESA or ST approaches.

The research approaches selected for examination are displayed in Table 3. Approaches that take a multidimensional and/or a system perspective, and have been pointed out by Allesch and Brunner (2014), Finnveden et al. (2007) and Zurbrügg et al. (2014) as being highly relevant to WM research, were categorised as ESA approaches. Approaches instead mentioned by Markard et al. (2012), Sovacool (2014), Sovacool and Hess (2017) and Van Den Bergh et al. (2011) as commonly used for studying socio-technical change, were categorised as ST approaches. Among the selected ESA approaches, five broad categories can be distinguished: (1) Quantitative methods that focus on an energy dimension (emergy, energy, entropy, exergy analysis); (2) methods focused on physical flows (material flow accounting/analysis and substance flow analysis); (3) approaches aimed at assessing environmental impacts (ecological footprint, environmental impact assessment, life cycle assessment, life cycle inventory, strategic environmental assessment); (4) approaches emphasizing an economic dimension (cost-benefit analysis; eco-efficiency analysis; input-output analysis; life cycle costing; systems of environmental and economic accounting); and (5) other approaches, including multi criteria decision making (used to rank and prioritize in decision making processes), risk assessment (used to evaluate e.g. implications of hazardous substances) and stakeholder analysis (used to e.g. assess the impact of a decision on different actors). Within the ST category, two categories are distinguished in paper IV: (1) Approaches with an emphasis on describing, explaining or addressing socio-technical change through system perspectives; and (2) approaches that emphasize actor involvement, social construction and social change in such change processes.

For these approaches, and for the empirical fields under study, a number or search terms were generated that form the basis for the bibliometric analysis undertaken (step 1) (see paper IV, Section 2.1 for details).

Table 3. ESA and ST approaches selected for examination in paper IV.

Research approaches	
Environmental system analysis (ESA) approaches	Approaches associated with socio-technical (ST) change
Approaches focused on an energy dimension:	**Approaches emphasising a system perspective on socio-technical change:**
Emergy analysis	Large technical systems (LTS)
Energy analysis	the Multi-level perspective (MLP) on socio-technical transitions
Entropy analysis	National innovation systems (NIS)
Exergy analysis	Regional innovation systems (RIS)
	Sectoral systems of innovation and production (SIS)
Approaches focused on physical flows:	Strategic niche management (SNM)
Material flow accounting/analysis (MFA)	Technological innovation systems (TIS)
Substance flow analysis (SFA)	
Approaches focused on environmental assessment:	**Approaches emphasising actor involvement, social construction and social change:**
Ecological footprint	Actor-network theory (ANT)
Environmental impact assessment (EIA)	Discourse theory
Life cycle assessment (LCA)	Social construction of technology
Life cycle inventory (LCI)	Social practice theory (SPT)
Strategic environmental assessment (SEA)	Transition management (TM)
Approaches emphasizing an economic dimension:	
Cost-benefit analysis (CBA)	
Eco-efficiency analysis	
Input-output analysis	
Life cycle costing (LCC)	
Systems of environmental and economic accounting	
Other:	
Multi criteria decision making (MCD)	
Risk assessment (RA)	
Stakeholder analysis	

Paper IV examines the adoption of these approaches in current WM, WEEE and ELV research (step 2) by setting a temporal boundary to 2008-2017. Additionally, trends in use of the approaches are examined. Then the 30-year period 1988-2017 is instead considered. The characterisation of articles that do not mention the selected research approaches (step 3), is applied to articles in current WEEE and ELV research, i.e. research published in the time period 2008-2017. The characterisation is done manually by reading of article titles, abstracts and keywords. If characterisation cannot be made, the main text is read. Additionally, only the largest groups of articles citing each other are selected for characterisation. Moreover, if these groups are too large for manual examination, only the most well-cited articles within the groups are characterised. The rationale is that such groups represent important subsets of literature, and thus help to signify the types of approaches typically utilised in a field (see paper IV, Chapter 2.3). Following the three principal steps, the types of knowledge being created within the empirical fields are discussed.

4.4. Some notes on reliability, validity and generalisability

Due to the methods taken in the conducted research, some salient limitations are imposed on results in terms of reliability, validity and generalisability. Regarding reliability, specifically in terms of data reproducibility, the aim in general of the conducted research was to cross-check the multiple data sourced used. Additionally, beyond cross-checking, results were repeatedly presented to researchers and industry actors with domain competence, who took part in the research projects that the conducted research was part of (Chalmers University of Technology, 2012, Swedish Foundation for Strategic Environmental Research Mistra, 2018a). This resulted in feedback on the extent to which the collected data was reliable. Moreover, regarding interview data, according to Alvesson and Sköldberg (2009), interview situations in particular must be seen as social interactions where data is co-created by the interviewer and the interviewee rather than being collected. Interview data was thus cross-checked with other more tangible sources where possible. Regarding more specific data issues, it can be noted that much like other studies concerned with scarce metals, the conducted research suffers from data uncertainty. Hence, it should be noted that results regarding the quantity of scarce metals in ELVs, WEEE and waste flows should be interpreted as indications. On a related note, IMDS data on metal contents of cars (used in paper I) has been compared to multiple other data sources by Du et al. (2015), indicating that IMDS data is comparable to these other sources.

Regarding validity, in terms of the validity of conceptualisations, frameworks, and methods to represent a phenomenon, the aim of the research has been to draw on both empirical observations and on related scientific literature and widely acknowledged theory to form valid representations. The use of the TIS framework (papers II-III) to identify and assess factors affecting recycling of scarce metals, involves interpretations by the authors of papers II-III. The approach in the interpretative work was to let the empirical material be guiding, and to compare this material to core issues and theory expressed in literature (i.e. abductive reasoning). Specifically, taking into account key dimensions expressed in recycling related research (Sections 2.2-2.4) was important. Additionally, as many similar dimensions are discussed also in literature on socio-technical change (Section 3.3), frameworks developed within that literature were deemed useful as tools for representations, in particular the TIS framework (see Section 3.3). It should be noted that although it is the belief of the author that salient factors have been captured through the lens of the TIS framework, it is not precluded that there may be other useful lenses and factors of importance.

Regarding generalisability, the methods of papers I-III are designed to cover Swedish conditions. Although geographical differences exist, the core issues covered likely also apply to other European countries, specifically EU members (due to EU directives) with WM similar to Swedish conditions. Resource supply issues around scarce metals have been discussed intensely in at least the U.S. and Japan. Hence, insight provided by the conducted research may be relevant to those regions, depending on the characteristics of the WM industries in those regions. However, countries producing the scarce metals discussed in this thesis, countries with vastly different policy setups or those with very immature waste management systems would likely require dedicated research.

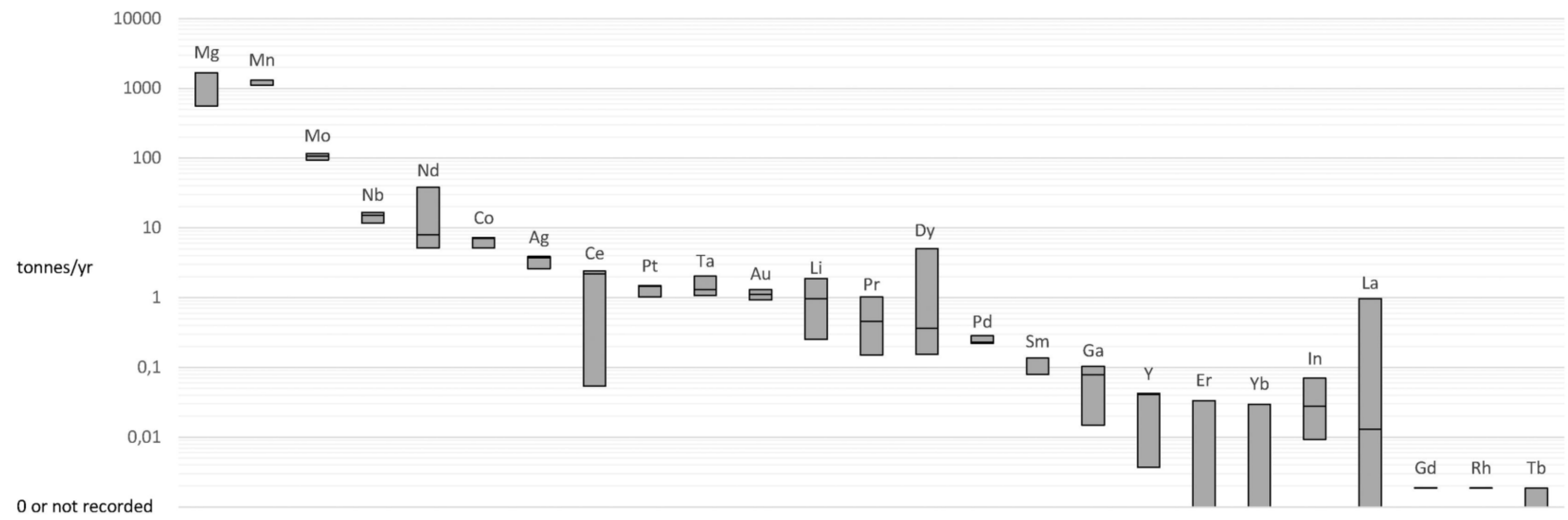
5. Main results and discussion

5.1. Flows of scarce metals in Swedish ELV recycling (paper I)

The amount of scarce metals estimated in paper I to enter Swedish ELV recycling is summarised by Figure 1. The figure displays the estimated entered amount for each of the 25 studied metals, and how the metals are applied in ELVs.

The annual input of the 25 metals is estimated at 2,000-3,000 tonnes/year, corresponding to ca 1% of the total annual ELV mass flow. It is notable that the magnitude of the input differs substantially for individual metals, from a few kilograms to thousands of tonnes. Additionally, the range of the input varies significantly for some metals, despite that the cars used for modelling are produced in the same time period and are of the same brand, indicating that car designs influence input. The bulk of the total input is made up of magnesium and manganese, which are input at around 1,000 tonnes/year each. The remaining mass is made up of multiple metals.

Furthermore, it is evident that the use of metals varies considerably among different application categories. Electric, electronic and magnetic components are identified as significant applications for 20 metals (Ag, Au, Co, Dy, Er, Ga, Gd, In, La, Li, Mn, Nd, Pd, Pr, Rh, Sm, Ta, Tb, Y, Yb). Of these metals, six (Co, Gd, La, Li, Pd, Y) are found in one additional category. Three metals (Mg, Mo, Nb) can be allocated to metal alloys only, while two (Ce, Pt) is only identified in catalytic components. Manganese is the only metal allocated to three categories. The number of reported applications per metal ranges from ca 1-1,000 (Supplementary material to paper I). Thus, while some metals are concentrated to one application (e.g. Er is identified only in LCDs), others are dispersed throughout the car (e.g. Li is identified in around 1,000 applications). Consequently, the magnitudes of input and how metals are applied, will significantly impact on the potential for recovery of scarce metals.



Steel alloys		Mn	Mo	Nb		Co																			
Aluminium alloys	Mg	Mn																					Gd		
Magnesium alloys	Mg																								
Nickel alloys				Nb														Y							
Lubricants												Li													
Catalytic components								Ce	Pt						Pd							La			
Electric, electronic & magnetic components		Mn			Nd	Co	Ag			Ta	Au	Li	Pr	Dy	Pd	Sm	Ga	Y	Er	Yb	In	La	Gd	Rh	Tb

Figure 1. Estimated annual input to Swedish ELV recycling in the late 2020s to early 2030s, of 25 scarce metals, and the main application categories of these metals. The displayed upper, in-between and lower values correspond to quantities reported for three cars models representative for Swedish conditions (see paper I and its supplementary material for details).

The scarce metals enter Swedish ELV recycling where numerous material flows and processes exist, as shown by the Sankey diagram displayed in Figure 2. The subsystems of Figure 2 are: (A) Dismantling; (B) processing of dismantled components and materials; (C) shredding operations; (D) post-shredding operations; (E) energy recovery and slag treatment; and finally, (F) metal refining.

Roughly 230,000 tonnes annually enter the system. Of this mass, 25% is recovered in dismantling (A) in the form of materials and components sent to dedicated processing (B) or as spare parts. The remaining 75% constitutes the car body, which is sent to shredding (C). The largest outputs from shredding are ferrous streams (iron or steel), used domestically or abroad in steel production. Numerous other smaller streams are also generated in shredding and subsequent processes.

These many flows serve as potential routes for scarce metals within the recycling system. Some flows end up within Sweden, others outside. The possibility for a scarce metal to be functionally recycled thus depends on which route is taken and where material flows ultimately end up (paper I, Sections 3.2-3.3). Functional recycling of Pt in catalytic components is well-established. There is also potential for functional recycling of Ag, Au, Co, Mn, Mo, Pd, and Rh, but this will depend on in which component or material the metals are applied in, what routes are taken and how the metals are used at the final destination (paper I, Table 1). Some are likely non-functionally recycled or not recycled at all. For the remaining metals under study, no functional recycling can be identified. Thus, only for 8 of the 25 studied scarce metals is there any identified potential for functional recycling in the current system.

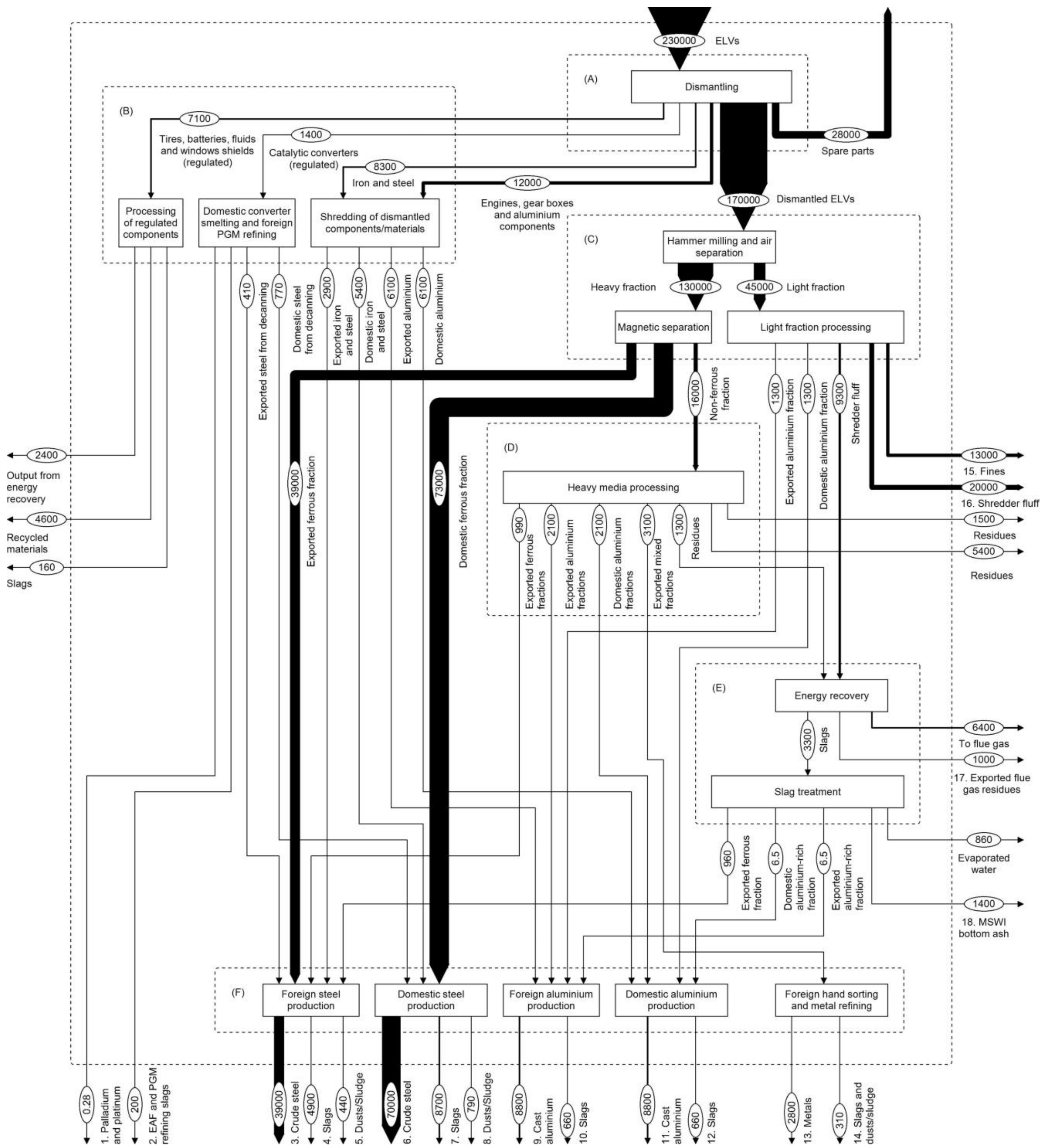


Figure 2. Processes and material flows (in tonnes/year) in Swedish ELV recycling, modelled according to conditions around 2014. Flows 1-18 are identified as potentially carrying materials or components that contain one or several of the studied scarce metals.

It is discussed in paper I, that industrial scale technologies capable of functionally recycling the metals under study are lacking. Consequently, it is suggested that one strategy for raising recycling rates would be dismantling components rich in those metals (e.g. Ag, Au and PGMs), for which there are already well-established value chains. For instance, dismantling electronic control units (ECUs), PCBs connected to GPS, audio or user interface equipment. Another strategy would be to shred cars in batches and implement unique quality specifications for shredded steel and aluminium from ELVs. Today, such specifications do not exist, but could enable steel and aluminium recyclers to better identify and utilise scarce metals applied as steel or aluminium alloying agents (Co, Gd, Mg, Mn, Mo, Nb). Other strategies identified in paper I include altering car designs, modifying EPR policy to target scarce metals, and supporting technical development of sorting and refining processes.

5.2. Lessons from the past on recycling iron from ELVs (paper II)

Results of paper II show how during the first half of the 20th century several factors or 'forces', acted on the Swedish steel industry and on small-scale actors (individuals or small firms) involved in trading and treating a variety of goods and recovering and trading materials such as scrap metal. These factors strengthened early stages of a development that took several decades: Many of the current capabilities for recycling iron from Swedish ELV were not in place until around the year 2000. Along the way, numerous factors contributed to the development. These factors originated from both broad societal developments, as well as from individual actions taken by numerous actors in or outside steel industry value chains. Both industry and government actors played significant parts in the overall development. The salient observation is that although secondary iron raw materials were sought after by the steel industry early on, it took a multitude of factors gradually coming together and collectively supporting the development before a well-working value chain had been established.

The development is explained using development sequences occurring over five time periods (see paper II, Section 5.1). In summary, significant structural build-up within the steel industry occurred during 1910-1950, leading to a strengthened market for scrap metal, i.e. a stronger raw materials market ('1st period', Figure 3). Subsequently, a growing number of ELVs during the 1950s, motivated actors already involved in dealing with scrap to specialise in car dismantling. In 1961 these actors establish a formal network (a trade association), to better organise scrap metal trade and as a response to political discussions about more stringent waste management legislation (‘2nd period’, Figure 3). The first Swedish shredding facility was put in place in the early 1970s, after a large-scale firm active in the waste management industry invested in already existing technology from abroad, with investment support from the Swedish government (‘3rd period’, Figure 3). In subsequent years the shredding infrastructure grew as more actors became convinced of its usefulness, and because the first environmental regulation aimed at ELVs demanded mechanical treatment of ELV scrap (‘4th period’, Figure 3). The industry value chain became further refined during the 1990s, when EU directives started to place stricter requirement on actors operating in the system (‘5th period’, Figure 3).

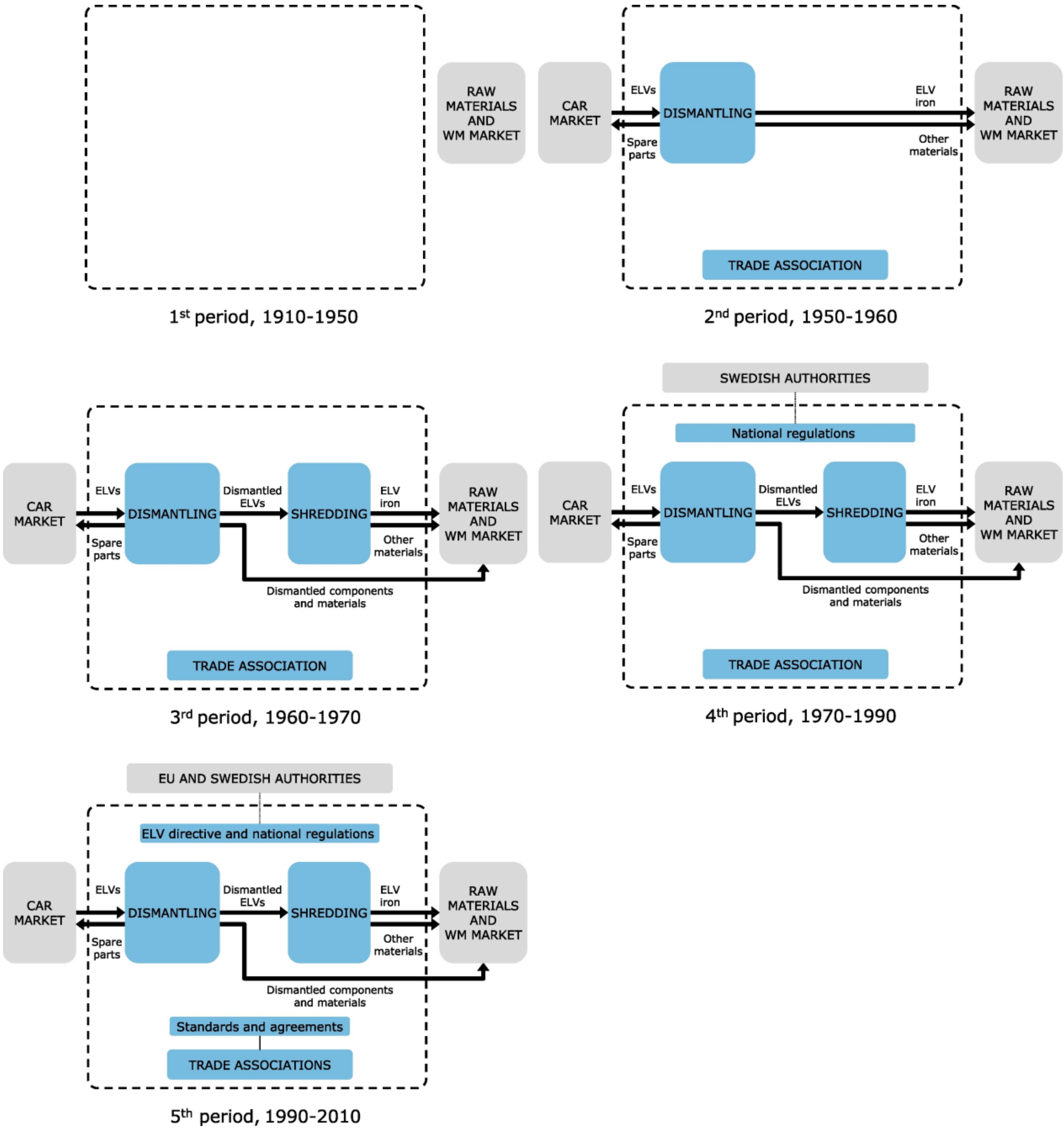


Figure 3. Graphic representation of how, during 1910-2010, the ELV iron recycling value chain gradually formed. Each smaller figure represents the state of the value chain at the end of each period.

Based on this historic case, several strategies are suggested in paper II that may improve recycling of metals and materials from complex products. The build-up of raw material markets could be incentivised by forming procurement organisations, where prices and quality of raw materials are negotiated, set and formally communicated. An additional strategy could be forming policy that support trade of secondary raw materials (e.g. support for efficient raw material logistics), or policy that influence demand through raw material specific quotas or feed-in tariffs placed on steel refineries. To instead affect the material streams *entering* recycling, improving waste collection (e.g. coordinating the collection of waste groups containing high concentrations of specific metals), altering product designs, and forming product policy such as taxes, subsidies or labelling to directing consumption towards such products are pointed out. Changes to EPR regulation and industry certification schemes are suggested to promote development of work procedures in dismantling (e.g. dismantling of components rich in scarce metals). Furthermore, to promote development of automated treatment (such as shredding), venture capital and funding for research, development and demonstration (RDD) are suggested. To promote diffusion of work procedures and automated treatment processes, directly setting up networks or promoting the formation of networks through policy requirements are suggested.

5.3. Factors affecting current recycling of scarce metals from ELVs and WEEE (paper III)

It is identified in paper III that, out of the focal value chains studied, the most developed are in descending order: WEEE to precious metals from PCBs (T_{F1}, Figure 4); ELVs to precious metals from PCBs (T_{F3}, Figure 4); WEEE to minor metals from PCBs (T_{F2}, Figure 4); and ELVs to minor metals from PCBs (T_{F4}, Figure 4).

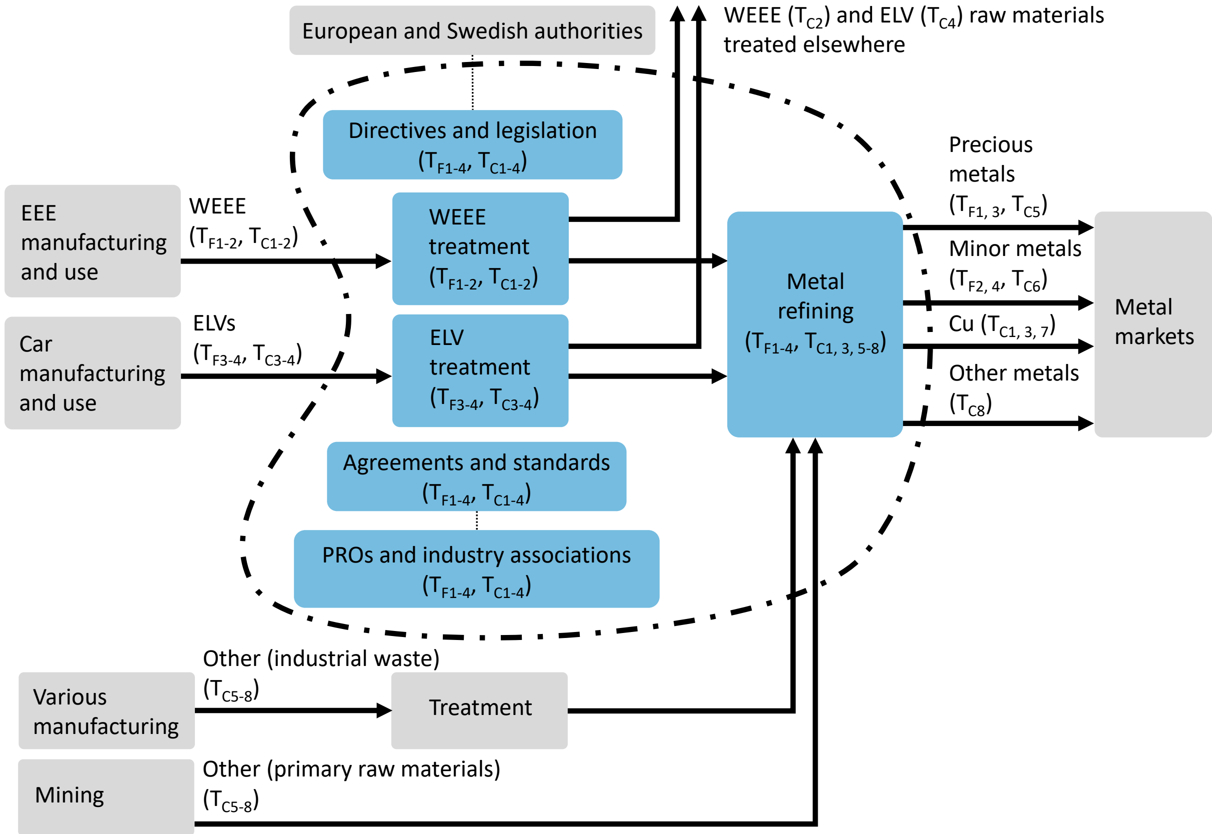


Figure 4. Representation of current and potential Swedish value chains related to WEEE and ELV treatment, and refinement of PCB metals. The delineated components represent focal and contextual technologies studied in paper III.

Furthermore, nine factors are identified as impacting on recycling and as relevant to explain the difference in maturity of the value chains (Table 4): (1) The metal contents and composition of WEEE and ELVs; (2) the historically accumulated industry capabilities for recycling specific metals; (3) the economic potential of each metal in WEEE and ELVs, i.e. the value of each metal if sold at a world metal price level; (4) long-term industry goals; (5) political visions and policy-making for the future of scare metals recycling; (6) long-term metal price trends; (7) the characteristics of metal markets (i.e. metal market design); (8) how procedural requirements are formulated for WEEE and ELV treatment in current EPR legislation; and (9) the extent to which business models support recycling under certain conditions. Five of these factors are defined as external, four as internal. One external factor is seen as blocking the development of recycling for all the metals under study, while the others both support and block recycling depending on which metal is considered (Table 4). Details on each factor is provided in Paper III, Chapters 4-5. A key observation is that the most developed systems are supported by several factors, while the least developed systems are instead blocked by these same factors. If recycling is to increase, the blocking factors would need to be addressed so that a more balanced support system is created.

Table 4. Impact of investigated factors on the development of the four focal technologies T_{F1-F4}. A supporting factor is represented by '+', and a blocking factor not contributing to development or counteracting it by '-'.

Factor	Internal or external	T_{F1} Precious metals from PCBs in WEEE	T_{F3} Precious metals from PCBs in ELVs	T_{F2} Minor metals from PCBs in WEEE	T_{F4} Minor metals from PCBs in ELVs
Metal contents and composition of WEEE and ELV flows	*External*	-	-	-	-
Accumulated industry capabilities	*Internal*	+	-	-	-
Economic potential of system inputs	*External*	+	+	-	-
Long-term industry goals	*Internal*	+	+	-	-
Political visions and policy-making for the future of scare metals recycling	*External*	+	+	-	-
Long-term metal price trends	*External*	+	+	-	-
Metal market design	*External*	+	+	-	-
Current EPR requirements	*Internal*	+	-	+	-
Business models	*Internal*	+	-	+	-

Regarding the internal factors in Table 4, three strategies are suggested in paper III for building new industry capabilities (i.e. to change ‘accumulated industry capabilities’): (1) Funding of RDD projects to build practical and formal knowledge; (2) enabling access to financial capital at favourable conditions (e.g. through green investment funds) to promote industry investments in physical capital; and (3) incentivising new actors with specialised capabilities to enter industry value chains (e.g. by in different ways qualifying RDD projects and access to investment funds). Regarding the third strategy, it is noted in paper III that there are already refining companies in existence that are more specialised towards scare metals in the EU, and within Sweden there is capacity for refining metals from catalytic car converters, i.e. recovering specific metals from specific components. These actors could thus possibly add capability for highly targeted metal refining. To affect ‘long-term industry goals’, it is suggested that political bodies need to set stronger and more precise goals of moving towards circular flows of scarce elements, and be given the mandate to do so. This could affect general expectations in society and also goal setting in industry. It is highlighted that ‘current EPR requirements’ would need to be more metal specific to affect recycling of scarce metals. Additionally, ‘business models’ may need to change in ELV recycling to spread the risk and rewards of treating ELVs also among car producers, especially if more stringent EPR requirements are to be implemented.

The identified external factors in Table 4, may be out of reach for most studied actors and difficult to alter. The factor ‘metal contents and composition of WEEE and ELV flows’ blocks all focal systems, while the remaining external factors block minor metals recycling only. A significant observation is that the economic value of minor metals in ELVs and WEEE if sold, is low compared to other metals (i.e. the ‘economic potential of system inputs’ is small, Table 4). Additionally, the prices of minor metals have been relatively low for decades with the exception of occasional price spikes in tantalum (i.e. ‘long-term metal price trends’ are unfavourable, Table 4). Also, in comparison to base metals, gold, silver and PGMs, the European market is not as well developed (weak ‘metal market design’, Table 4). These three blocking factors severely diminish incentives for the industry actors studied in paper III to engage in recycling, and may call for significant policy intervention if recycling is to be achieved (i.e. altered ‘political visions and policy-making for the future of scare metals recycling’, Table 4). For instance: intervention leading to changed product designs (affecting ‘metal contents and composition of WEEE and ELV flows’, Table 4); the formation of new markets, or building links to existing regional or farther away located markets through e.g. trade agreements (affecting ‘metal market design’, Table 4); and artificially created prices (affecting ‘economic potential of system inputs’ and ‘long-term metal price trends’, Table 4).

In summary, paper III highlights that if scarce metals are to be recycled there is need for long-term, high-impact and metal-specific strategies that target build-up of entire values chains. This likely requires political intervention, which in turn would require dedicated political bodies aimed at managing metal resources.

5.4. The approaches used in waste management related research (paper IV)

The number of papers mentioning one or several ESA or ST approaches in current WM, WEEE or ELV research (the time period 2008-2017) are few, relative to the total number of papers published in these fields, as indicated by paper IV: In each empirical field, the share of articles *not* mentioning any of the approaches ranges between 88-94% (paper IV, Tables 4-6). Among the articles that *do* mention any of the selected research approaches (of ESA or ST type), ESA approaches are the most mentioned. In contrast, articles referring to ST approaches hardly exist in any of the fields.

In the WM field, of the total number of ESA and ST articles identified, life cycle assessment (LCA) and risk assessment (RA) are mentioned the most, at 39% and 18% respectively. It should be noted that, in the WM field, the number of articles referring to some ESA approaches actually make up a considerable share of all identifiable published articles using those approaches: LCA/LCI, MFA, SFA and emergy analysis stand out in this regard (paper IV, Table 4). Thus, these ESA approaches can be considered as well-adopted in the WM management field, despite the apparent overall lack of them.

In the WEEE and ELV fields, of the total number of ESA and ST articles identified, ESA approaches dominate as well. In the WEEE field, RA, LCA, and MFA make up 36%, 26%, 12% respectively of these articles. In the ELV field, LCA, MFA, and cost-benefit analysis (CBA) make up 38%, 21%, and 10% respectively.

When looking at trends, there is evidence for that the use of some approaches is growing in the WM and WEEE fields. In the WM field, the share of articles using ESA terms have grown from ca 1% to 6% (from 20 to 540 articles/year) during the 30 years spanning 1988-2017 (Figure 5). Most of the increase is due to LCA/LCI terms being mentioned by a larger number of articles. This corresponds well with the wide use of LCA as an environmental assessment tool in general, and with that LCA has been a core tool used in WM specifically to analyse environmental implications of different WM solutions (Baumann and Tillman, 2004). There is also an increasing number of ST approaches being mentioned in the WM field, which potentially indicates an adoption trend of these approaches. However, since the number of articles is low, it is difficult to reliably conclude that there is such a trend (Figure 6).

In the WEEE field, while LCA/LCI, RA and MFA/SFA terms are increasingly being used post ca 2007 (Figure 7), there is no identifiable trend in the use of ST terms (Figure 8). The jump in the share of WEEE articles using ESA terms in year 2000, and the increasing number of published WEEE articles and use of ESA approaches shortly after, coincide well with the introduction of the first EU WEEE directive (Directive 2002/96/EC) and the directive restricting use of hazardous substances in electrical and electronic equipment (RoHS Directive 2002/95/EC), which came into force in early 2003.

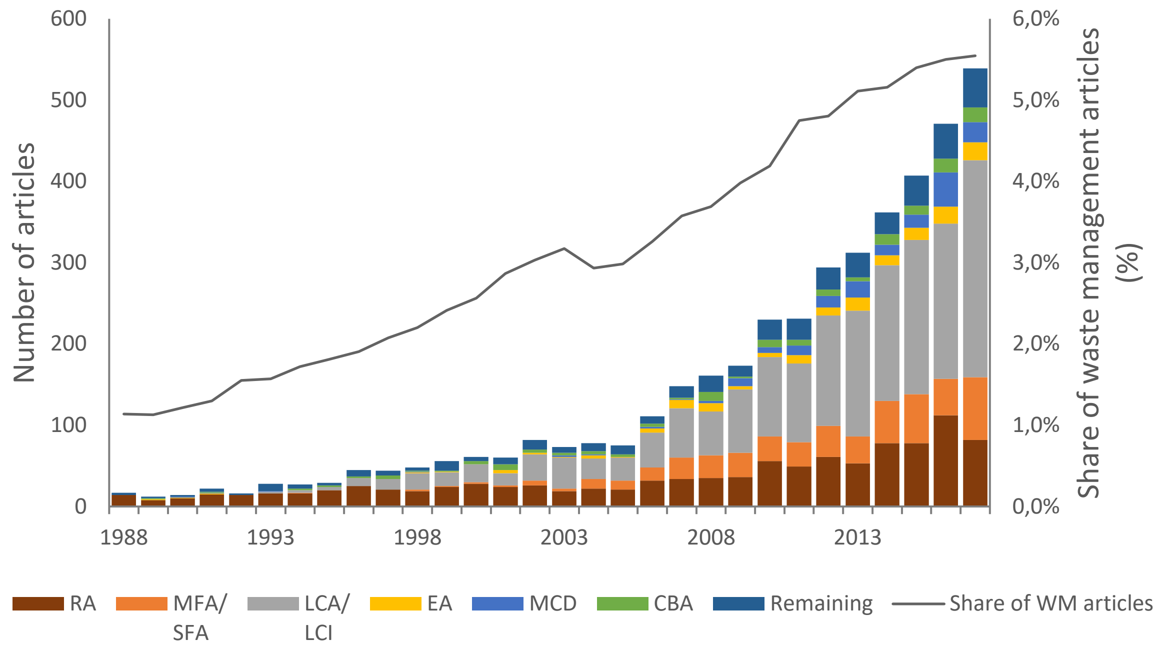


Figure 5. Number of articles, and the share of all WM articles, published in 1988-2017 mentioning an ESA approach (see Table 3 for an explanation of abbreviations). For readability, data on energy, entropy, emergy and exergy analysis have been compiled into "EA". MFA and SFA have been compiled into "MFA/SFA". Data on LCA and LCI into "LCA/LCI".

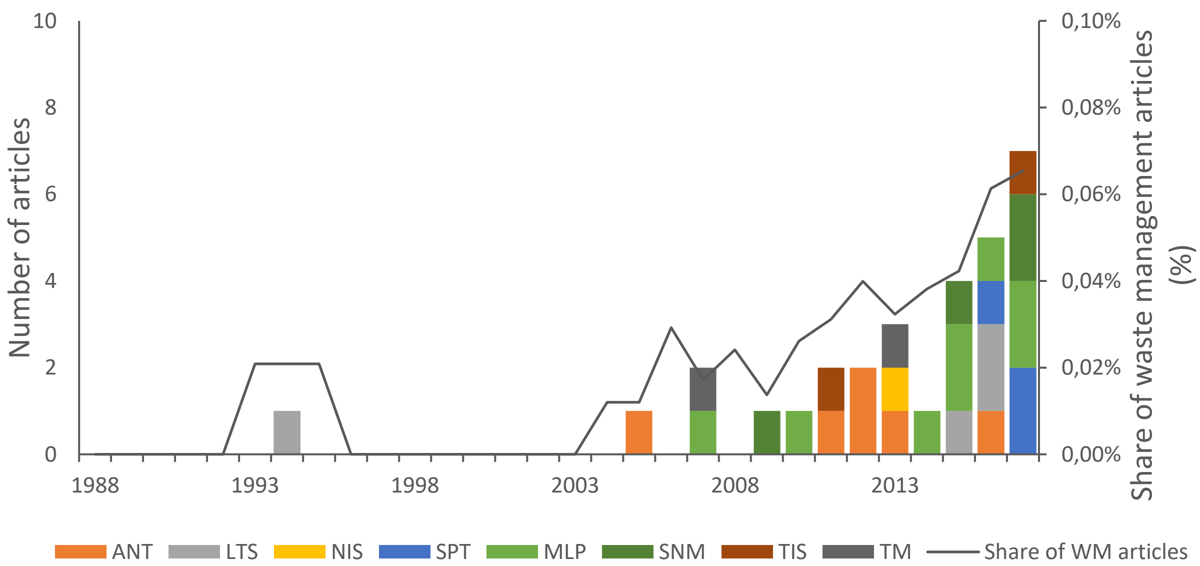


Figure 6. Number of articles, and the share of all WM articles, published in 1988-2017 mentioning a ST approach (see Table 3 for an explanation of abbreviations).

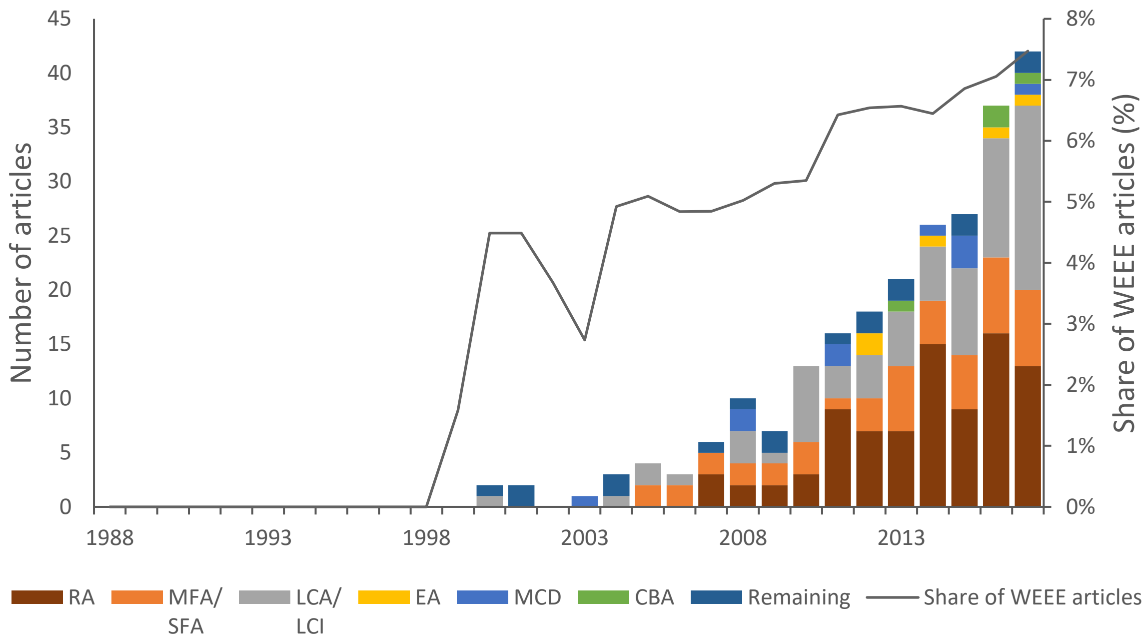


Figure 7. Number of articles, and the share of all WEEE articles, published in 1988-2017 mentioning an ESA approach (see Table 3 for an explanation of abbreviations). For readability, data on energy, entropy, emergy and exergy analysis have been compiled into "EA". MFA and SFA have been compiled into "MFA/SFA". Data on LCA and LCI into "LCA/LCI".

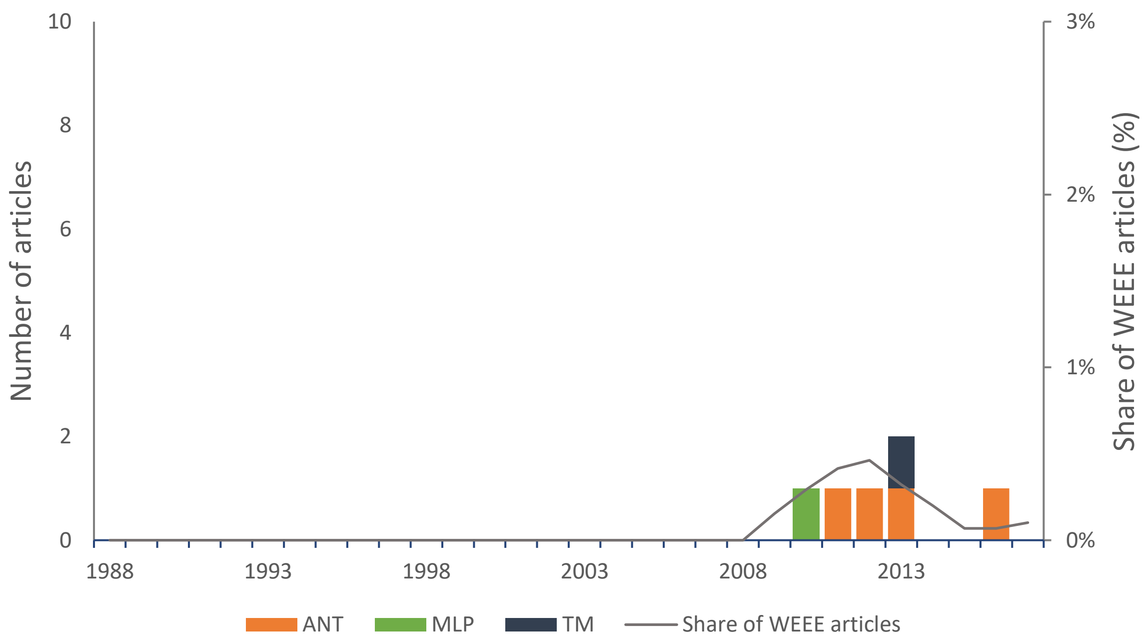


Figure 8. Number of articles, and the share of all WEEE articles, published in 1988-2017 mentioning a ST approach (see Table 3 for an explanation of abbreviations).

In the ELV field there is potentially an ongoing adoption trend of LCA/LCI and MFA/SFA approaches, but the usage of terms related to these approaches is too low and irregular to strongly support this observation (Figure 9). Regarding ST approaches, only one ELV related article has been found to use ST terms. Consequently, there is no evidence pointing to an adoption trend of ST approaches.

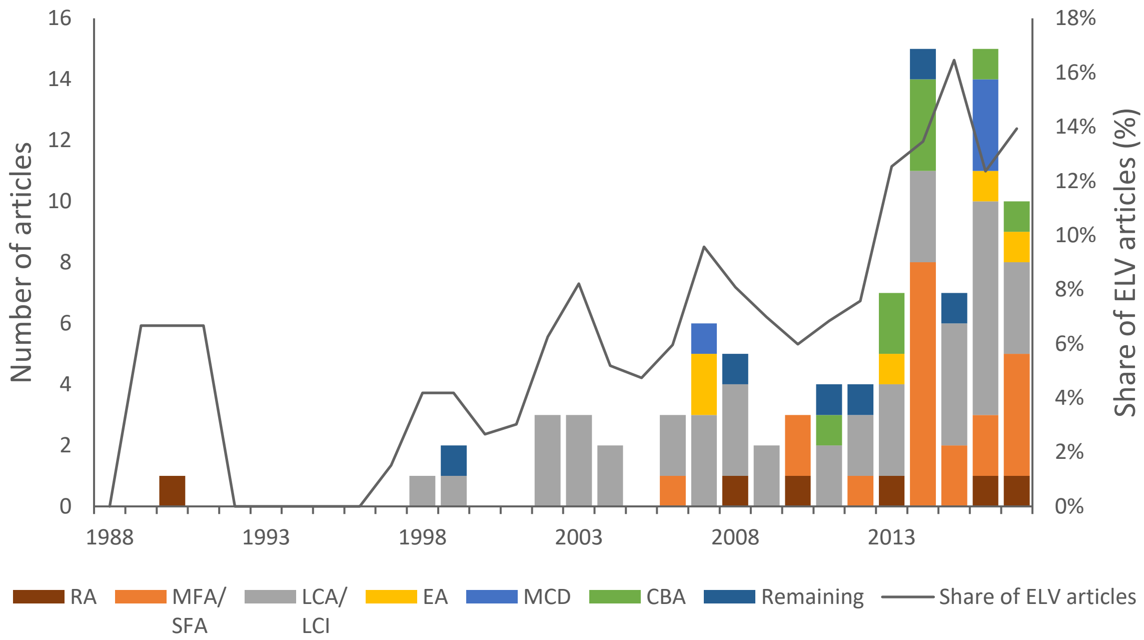


Figure 9. Number of articles, and the share of all ELV articles, published in 1988-2017 mentioning an ESA approach (see Table 3 for an explanation of abbreviations). For readability, data on energy, entropy, emergy and exergy analysis have been compiled into "EA". MFA and SFA have been compiled into "MFA/SFA". Data on LCA and LCI into "LCA/LCI".

When examining the articles in the WEEE and ELV fields that *do not* mention any of the approaches, paper IV indicates that there are some differences in the type of utilised approaches. In the WEEE field, paper IV indicates that among the 200 most cited and interlinked articles, the largest number of studies do the following: Analyse impacts on local environments or on human health by toxic or in other ways hazardous substances present in WEEE; or assess existing or experimental manual procedures, automated waste treatment or metal recovery processes. The articles performing toxicity/hazard analysis primarily focus on the local environment in a specific region or in smaller areas around WEEE treatment operations. Alternatively, the focus is put on health implications for specific populations that have been exposed to hazardous conditions. Assessment studies instead focus on the technical or manually feasibility of performing certain waste treatment or metal recovery procedures. Additionally, 10 other types of approaches can be identified (Table 5).

In the ELV field, the dominant type of approach is instead assessment of existing or experimental waste treatment procedures (similar to those in the WEEE field). Also common is mathematical modelling and optimisation of technical processes, manual procedures or waste logistics. Such studies are less common among the characterised WEEE articles. Characterisation, or chemical or toxicity analyses, of ELV waste streams are also frequently made. Additionally, nine other types of approaches can be identified (Table 6).

Table 5. Types of approaches used (according to the characterisation made in paper IV) by the 200 highest cited articles, in the largest identifiable group of WEEE articles that cite each other and do not mention ESA or ST approaches. Period 2008-2017.

Type of study	Number	Share (%)
Toxicity/Hazard analysis, of impact of various WEEE materials/treatment procedures on local environment/population	83	42%
Technical assessment/experiment, of technical processes or manual procedures	43	22%
Policy analysis	9	5%
Characterisation/Chemical analysis, of various WEEE products/materials	8	4%
Framework development, for technical/economic/environmental assessment of processes or manual procedures	8	4%
General, country specific, overview of WEEE management	8	4%
Modelling and optimisation, of technical processes, manual procedures or logistics	8	4%
Survey, on attitudes/behaviours regarding WEEE collection/treatment	7	4%
Comparison of recycling industries in multiple countries	6	3%
Other	6	3%
Technology review	5	3%
Waste generation estimation	5	3%
Technical assessment/experiment, of processes for generating new composite materials from waste	4	2%
SUM	200	100%

Table 6. Types of approaches used (according to the characterisation made in paper IV) among the largest identifiable group of ELV articles that cite each other and do not mention ESA or ST approaches. Period 2008-2017.

Type of study	Number	Share (%)
Technical assessment/experiment, of technical processes or manual procedures	53	30%
Modelling and optimisation, of technical processes, manual procedures or logistics	46	26%
Characterisation/Chemical analysis, of various materials	18	10%
Policy analysis	11	6%
General, country specific, overview of recycling industries	8	5%
Other	8	5%
Survey, on ELV industry conditions or public perception of ELV management	6	3%
Technology review	6	3%
Economic assessment, of technical processes or manual procedures	5	3%
Toxicity analysis, of various materials	5	3%
Design for recycling	3	2%
Waste generation estimation	3	2%
SWOT analysis	2	1%
SUM	174	100%

Although the characterised articles in WEEE and ELV related research as a whole, cover a multitude of aspects, each individual article tends to target specific aspects. This facilitates the creation of important deep knowledge, but to gain transdisciplinary insight other types of studies may be required. The articles that cover multiple aspects tend to be of review type and tend not to incorporate these aspects into a formal framework. The take-away message is that the lack of some ESA terms and most ST terms in WM, WEEE, and ELV research indicates that there is a risk that in these fields, relevant insight into how multiple systemic and socio-technical aspects can simultaneously affect developments of WM systems may be overlooked.

5.5. Compilation of measures for raising recycling rates of scarce metals

The observations made in paper I highlight how losses of scarce metals depend on a mismatch between what enters the ELV recycling system and what can be produced by it. This is evident, e.g. in that many of the system outputs are produced in thousands of tonnes, i.e. quantities much larger than the mass of most scarce metals. The resulting effect is that losses of scarce metals could occur in several segments of the industry value chains contained in the system studied in paper I (Figure 2). Although not studied in detail here, similar observations have been made about WEEE recycling (Section 2.4). Consequently, several segments in ELV and WEEE recycling may need change if scarce metals currently not recovered are to be recycled.

Paper II makes it clear that even developing two segments (dismantling and automated treatment) of an industry value chain may require significant resources, time, and intervention by several different types of actors with different means at their disposal (particularly actors capable of dismantling EoL products; actors with access to financial capital and automated treatment processes; and actors with mandate to form policy). Although paper II does not cover the development of other value chains existing in ELV and WEEE recycling, it is conceivable that the development of these other value chains also required similar types efforts. Hence, developing recycling of scarce metals from complex EoL products likely means developing multiple industry value chains dedicated to specific metals and materials, and this may require significant resources, time, and intervention.

The challenges involved in developing multiple industry value chains are illustrated by paper III, where a salient observation is that value chains for individual metals or materials may exist at different stages of development: While some value chains have reached a more or less mature stage (e.g. Al, Cu, Fe from WEEE and ELVs) others have developed much less. Less developed value chains may require a scale and variety of efforts similar to those that developed the ELV iron value chain. Paper III also indicates that there is inherent 'competition' between different value chains. Already developed value chains are at an advantage as they require less 'new' means and incentives to develop further. Additionally, their development may occur at the expense of less developed value chains. Moreover, when an industry value chain has been established it may be difficult to change, as is evident by the current challenges of recovering some scarce metals. Thus, the conducted research highlights that recycling multiple metals involves manging this competition, by balancing the advantages and disadvantages that each individual value chain is affected by.

Another important observation regarding the challenges involved, made primarily in papers II-III, is that recycling industry value chains are not only affected by the type of waste entering them (as is evident by paper I), but also by policy-making and what industries are accessible 'downstream' (i.e. by markets). There is thus a socio-technical environment around each value chain that needs to be developed enough to support recycling.

Consequently, developing recycling systems seemingly involves creating *potential* for recycling in terms of influencing the generated amount and composition of waste (i.e. the supply of materials), and in terms of building markets (i.e. demand) for contained metals and materials. Additionally, to realize such a potential, segments of value chains with unique capabilities are needed.

The aspects of recycling discussed above point to the value of adopting system perspectives and conceptualisations of how recycling systems develop. Given this, it is notable that in WM related research, only a few ESA tools have been adopted at any scale, and that approaches aimed at capturing socio-technical change have essentially not been used at all (paper IV). More research taking ESA perspectives and/or socio-technical change perspectives could further elucidate metal flows in society, and show how to develop recycling value chains.

Following this discussion, it is possible to compile groups of measures that could raise functional recycling rates of scarce metals from complex EoL products arising in Sweden. It is indicated throughout papers I-III that each segment of a value chain would need different types of development, and thus unique measures, if a metal is to pass through an entire value chain and not only certain segments. Metals for which some well-developed value chain segments exist (currently this applies to Ag, Au, PGMs and to a lesser extent Co, Gd, Mg, Mn, Mo, and Nb used as alloying agents in steel or aluminium) could be recycled better by utilising current segments in new ways, Table 7. Other scarce metals would likely need additional groups of measures, of which some include large-scale intervention, Table 8.

Table 7. Suggested measures for raising recycling rates of scarce metals from ELVs and WEEE. Applicable to metals for which well-developed value chain segments exist (currently applies to Ag, Au, PGMs and to a lesser extent Co, Gd, Mg, Mn, Mo, and Nb used as alloying agents in steel or aluminium).

Group of measures (no.)	Type of development targeted	Type of measure(s)	Metals targeted	Actors with ability to act
1	Enhancing capabilities to dismantle components rich in scarce metals	i) Dismantle components similar to ECUs or PCBs connected to GPS, audio or user interface equipment in ELVs (paper I) ii) Incorporate procedural requirements in industry certification schemes (paper II) iii) Make EPR legislation more metal specific (papers I and III) iv) Initiate RDD projects (paper III)	Scarce metals concentrated to specific components	Industry actors (i-ii, iv), policy-makers (iii-iv)
2	Improving automated treatment	i) Increase batch-wise automated treatment (paper I) ii) Extend quality specifications of raw materials generated by automated treatment (paper I) iii) Invest in automated sorting techniques of aluminium (paper I) iv) Give firms aiming to adopt automated treatment access to financial capital at favourable conditions (via venture capital or green investment funds) (papers II-III) v) Initiate RDD projects (if automated treatment processes are not readily available) (papers II-III) vi) Make EPR legislation more metal specific (papers I and III)	Scarce metals used as alloying agents in e.g. steel and aluminium	Industry actors (i-iii, v), policy-makers (iv-vi)
3	Diffusing knowledge about dismantling procedures, and the use of automated treatment	i) Directly set up new network organisations (e.g. industry organisations) (paper II) ii) Promote formation of new network organisations in industry, or strengthen already existing ones, through stringent EPR requirements (paper II)	The metals targeted by groups 1 and 2	Industry actors (i), policy-makers (i-ii)

Table 7 (continued). Suggested measures for raising recycling rates of scarce metals from ELVs and WEEE. Applicable to metals for which well-developed value chain segments exist (currently applies to Ag, Au, PGMs and to a lesser extent Co, Gd, Mg, Mn, Mo, and Nb used as alloying agents in steel or aluminium).

Group of measures (no.)	**Type of development targeted**	**Type of measure(s)**	**Metals targeted**	**Actors with ability to act**
4	Improving the capability of business models to distribute high financial risks and rewards	i) Develop financial compensation schemes around EPR requirements between product producers and actors operating in recycling value chains (paper III)	The metals targeted by groups 1 and 2	Industry actors
5	Strengthening secondary raw material markets	i) Set up procurement organisations, where prices and quality specifications of secondary raw materials are negotiated, set and communicated (paper II) ii) Form policy support for trade of secondary raw materials (e.g. support logistic efficiency) (paper II) iii) Influence raw material demand through raw material specific quotas or 'feed-in' tariffs placed on metal refineries (paper II)	The metals targeted by groups 1 and 2	Industry actors (i), policy-makers (i-iii)

Table 8. Suggested measures for raising recycling rates of scarce metals from ELVs and WEEE. Applicable to metals for which value chains are immature. These measures need to be complemented with those specified in Table 7.

Group of measures (no.)	Type of development targeted	Type of measure(s)	Metals targeted	Actors with ability to act
6	Altering long-term industry goals	i) Set stronger and more precise goals of moving towards circular flows of scarce elements (paper III) ii) Give relevant political bodies mandate to set goals (paper III)	Scarce metals not currently recovered	Industry actors (i), policy-makers (i-ii)
7	Advancing WM related research	i) Use a variety of ESA and ST approaches in WM, WEEE and ELV related research (paper IV)	Scarce metals not currently recovered	WM research community
8	Altering material compositions of waste flows	i) Promote design for recycling (papers I-III) ii) Form policy (e.g. taxes, subsidies, labelling) for directing consumption towards products adapted to recycling (paper II) iii) Continuously improve/promote collection of waste into homogenous streams (paper II)	Scarce metals not currently recovered	Industry actors (i, iii), policy-makers (i-iii)
9	Advancing metal refining capabilities	i) Initiate RDD projects (paper III) ii) Enable access to financial capital at favourable conditions (via green investment funds) (paper III) iii) Incentivise development of refining capabilities through metal specific quotas or 'feed-in' tariffs placed on metal refineries (paper III) iv) Incentivise new actors to enter value chains (through e.g. qualifying RDD projects and access to financial capital) (paper III)	Scarce metals not currently recovered	Industry actors (i), policy-makers (i-iv)
10	Influencing metal markets and prices	i) Form international trade agreements (paper III) ii) Compensate for differences in price between metals at a general level (through e.g. metal specific tariffs at national or regional levels) (paper III)	Scarce metals not currently recovered	Policy-makers
11	Improving the governance structure aimed at managing scarce metal resources	i) Create political bodies or collaborations (e.g. new agencies or network organisations between existing agencies) at national and EU levels, dedicated to forming policy on scarce metals (papers I and III)	Scarce metals not currently recovered	Policy-makers

It should be noted that, since metals in complex EoL products are highly intermixed, some segment will need to take part in multiple value chains if recycling is to occur. Since the means and incentives for recycling different metals vary, some metals will likely never be economically attractive to recover. For these, policy intervention along with actions taken by the research community and ultimately by industry actors would likely be needed if recycling is desired. Notably, regarding policy, the measures suggested here are in line with the idea of nurturing industry development (Section 3.3) until value chains become competitive. Most such measures are not covered by current EPR legislation. Additionally, since the use of materials shifts in society, societal material flows need to be monitored, and interventions would continuously need to be designed to orchestrate development of key recycling value chains. In summary, results point to the need for long-term, high-impact and metal specific measures that target build-up of entire value chains if a larger set of scarce metals are to be recycled.

5.6. Empirical and theoretical contributions

Empirically the conducted research adds to the limited current literature dealing with recycling of scarce metal from ELVs, by significantly increasing the resolution of general material flows in ELV recycling via MFA of Swedish recycling. Significant details are also provided about the contents of scarce metals in ELVs, how these metals propagate through recycling, and where metals end up. It also adds empirical material at a detailed level about industry conditions around e.g. business activities, use of technology, implications of policy and markets in entire industry value chains associated with ELVs and WEEE. Additionally, new quantitative data is provided on the use of methods in WM related research, in particular on the use of approaches aimed at studying socio-technical change.

Theoretically, the conducted research adds to MFA related research, by exemplifying how flows of metals may be studied despite substantial lack of data about material compositions and system transfer coefficients at a substance level. It also adds to WM research, by integrating several interrelated problem dimensions related to recycling of complex EoL products into a formal analytical framework (TIS), and more clearly framing the issue of raising recycling rates of scarce metals as an industry development issue. Finally, it also adds to TIS literature by: Adapting the TIS framework to a new empirical field; exposing the underlying industry value chains of a ‘technology’, to enable more targeted analysis and intervention; and enabling the framework to be used for studying multiple intertwined industry value chains existing at different degrees of development, and for cases where multiple and potentially conflicting goals are salient features.

6. Conclusions

This thesis is concerned with increasing the resolution of knowledge around opportunities for, and challenges of, recycling scarce metals from complex EoL products. Additionally, it aims to identify measures that can raise recycling rates of such metals. It does this by addressing four research questions.

Question one is ‘How much scarce metals enters recycling via ELVs, what routes do metals take within recycling, where do metals end up and are metals functionally recycled?’. Results in this thesis show that the input to Swedish recycling via ELVs of metals that are considered as scarce in the conducted research, amounts to 2,000-3,000 tonnes/year. The ELV recycling system contains a vast abundance of material flows, of which several reach outside Sweden. These flows serve as routes for scarce metals. Of the 25 metals studied only 8 have potential to end up in applications that can be considered as functional recycling, i.e. end up in applications where metal properties are reutilised.

The second question, ‘Which socio-technical system factors affect recycling of scarce metals from ELVs and WEEE?’, is answered using two papers. Results indicate that there are numerous socio-technical system factors. Paper II shows how a multitude of factors gradually came together and collectively formed strong support for the development of functional recycling of a specific metal (iron). Salient supporting factors were: A well-established market; easy access to the metal in waste flows; access to an experienced work force (coming from the metal scrap trade); access to financial capital and waste treatment technology; and environmental regulations acting on the development over the long-term. Paper III indicates that in current recycling the following factors can both support and block development, depending on which metal is considered: The material composition of WEEE and ELVs and the value of metals contained; long-term metal price trends; the availability of regional metal markets; accumulated recycling capabilities, business models and long-term goals in recycling industries; policy-making related to recycling within the EU and Sweden, and the specifications of EPR requirements. Such factors create socio-technical system challenges that need to be addressed by industry actors, policy-makers and researchers if recycling is to develop.

Consequently, related to question three (‘To what extent has waste management research adopted environmental systems analysis and socio-technical change approaches?’) both environmental system analysis and socio-technical perspectives seem highly valuable to WM research. Results presented in this thesis show that environmental systems analysis tools such as life cycle assessment, risk assessment and material flow analysis, are being used by the community to a significant extent. In contrast, research approaches aimed at capturing socio-technical change is a lens rarely used in WM research. Hence, potentially valuable scientific tools are left largely unutilised. This is notable, since low recycling rates of scarce metals can be seen as corresponding to underdeveloped industry value chains.

The final question is ‘Which measures can be taken to raise recycling rates of scarce metals from ELVs and WEEE?’. In short, the conducted research highlights that for individual metals to be recycled, there is need for long-term, high impact and metal specific measures that target build-up of entire value chains. The multiplicity of factors taking part in creating socio-technical system challenges would need to be considered by industry actors, policy-makers and waste management researchers.

7. Suggestions for further research

This thesis provides data on the contents of scarce metals in end-of-life vehicles (ELVs), and on how these metals propagate through recycling industries. It also describes industry conditions at a detailed level in ELV, and waste electrical and electronic equipment (WEEE) recycling. Furthermore, it provides data on the use of methods in waste management (WM) research. Regarding theoretical contributions, it exemplifies how material flow analysis (MFA) can be used despite substantial lack of data. It also integrates several interrelated problem dimensions related to WM into the technological innovation system (TIS) framework, and shows how raising recycling rates of scarce metals can be seen as an industry development issue. In doing so, the TIS framework is adapted to a new field and it is illustrated that it is valuable to treat a 'technology' as an industry value chain, since this enables more targeted analysis and intervention.

However, more research is needed on the contents of scarce metals in products, since data availability is still limited. Additionally, a variety of studies are needed that uncover the fate of scarce metals from different products in WM systems in different regions. Only a small number of such studies still exist.

Furthermore, more research is also needed that uncovers the industry development aspects of WM. A variety of lenses are needed, the socio-technical change literature can provide some. Particularly, industry development dynamics between primary and secondary metal refining (along with associated value chains) needs to be better understood. To this end, multiple systems can be studied using TIS concepts as is done in this thesis, using the multi-level perspective (MLP) framework (Geels, 2002) or other frameworks that support multi-system analysis such as the one developed by (Sandén and Hillman, 2011). National, regional and even global levels of observation are likely needed. Additionally, social dimensions related to WM need to be understood better. The lack of public awareness about losses of metals is expressed throughout WM research. Little is said about the underlying reasons for this. Potential avenues of research include studying consumer knowledge and attitudes towards recycling, how educational programmes cover WM issues, or utilising concepts from sociology of technology (Pinch and Bijker, 1987), to explore how different social groups assign meaning and act in favour of or against closed material loops. On a related note, studies on how various advocacy coalitions promote and form policy on WM issues, could be valuable to better understand how to implement a governance system for scarce metal flows. The transition management framework (Loorbach, 2010) could possibly be used for this.

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Appendix

The total number of personal communications that have been made during the making of papers I-III are shown in Table A1. The types of communication used were face-to-face or phone interviews, and e-mail communication. These communications contributed to the overall understanding of the issues covered in this thesis. Ultimately, however, many were not relevant enough to be cited in papers I-III, or the equivalent information could be found in printed material. Hence, only a limited number were cited (as specified in Chapter 4).

Table A1. The total number of personal communications made during the making of papers I-III.

	Type of communication		
Description	**Face-to-face**	**Phone**	**E-mail**
Long interview, 60-90 min	14	12	-
Short interview, 30-60 min	1	31	-
E-mail communication	-	-	7
SUM	15	43	7

Interviews were open-ended and utilised interview guides. Examples of questions asked are displayed in Table A2. Interviews underpinning paper I focused on current conditions, while interviews underpinning papers II-III also focused on past and future conditions (Table A2).

Table A2. Examples of interview questions used to underpin papers I-III. Interviews underpinning paper I focused on current conditions, while interviews underpinning papers II-III also focused on past and future conditions. Interviews were open-ended, questions were asked where applicable.

Area of inquiry	**Question**
Past developments (papers II-III)	-How would you describe the historic development of your organisation? -Are there any salient milestones that were important to the development? -What type of factors impacted greatly on the development?
Introduction to the organisation (papers I-III)	-How would you describe your organisation to someone who does not know it? -How would you describe the business model of your organisation? -How is the organisation structured? -What is your current role at your organisation? What responsibilities do you have? -What type of work duties take place within the different parts of the organisation?
Internal conditions (papers I-III)	-Can you describe the dismantling/automated treatment/refining processes taking place in your organisation? -What type of raw materials are utilised by your organisation? From where are raw materials sourced? -What type of products and waste streams are produced by your organisation? Where do products and waste streams go? -What determines what components/materials/metals are produced? -What are the most important factors for the work duties/processes in your organisation to run well? -Is there anything in current work duties/processes that you would like to change? -How does your organisation engage with development work (e.g. R&D)?
External conditions (papers I-III)	-Who are your suppliers, customers and competitors? -Is your organisation connected to other types of organisations (e.g. industry associations, network organisations)? -Is your organisation affected by policy? If so, in what way?
Future developments (papers II-III)	-How do you envision the future of your organisation? -How do you envision the future of the industry that your organisation is involved in? -What opportunities and/or obstacles do you see regarding the future development of your organisation?
Other (papers I-III)	-Are there any relevant topics that we have not discussed? -Is there anyone that you would recommend for a future interview?