

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Innovating Recycling of End-of-Life Cars

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ABSTRACT

There are currently a billion cars in use worldwide, and car design trends point at increasing variety in material utilisation. Cars today contain several types of steel and aluminium, an assortment of textiles and padding materials, and an increasing amount of polymers and scarce metals. Since recycling may have environmental, economic, and in the case of scarce metals, resource security benefits, the scale of car usage strongly motivates efficient and effective recycling of discarded cars, also referred to as end-of-life vehicles (ELVs).

However, current ELV recycling systems are typically aimed at isolating hazardous content, selling spare parts, recovering and recycling some regulated parts and recycling metals existing in sizable quantities. Small material constituents, e.g. scarce metals, and materials of currently low market value, e.g. plastics, risk being lost, used as construction materials, incinerated or landfilled. Thus, system capabilities currently exist for recycling some materials at high recycling rates, while such capabilities are lacking or are non-existent for other materials. Consequently, there is need for developing recycling systems that are more in tune to the material complexity of present and future ELVs.

The aim of this thesis is to increase the knowledge base related to the state of ELV recycling and to means of improvement. Particular attention is given to what extent ELV recycling is a source of scarce metals, to what extent these metals are recycled so that their metal properties are utilised (i.e. are functionally recycled), and what insights can be obtained from examining the historic development of ELV iron recycling, which is well-established today. The thesis is concerned with the following questions: (1) What is the magnitude of scarce metals in discarded cars? (2) What are the fates of these metals in current ELV recycling? (3) Which fates constitute functional recycling and which risk leading to irreversible losses? (4) Which were the key system-building processes that led to current capabilities for ELV iron recycling?

Using material flow analysis, it is indicated that only 8 out of 25 studied ELV scarce metals have potential to be functionally recycled. Consequently, it is stressed that metal specific strategies are needed. Additionally, using the technological innovation systems framework, it is indicated that current capabilities for ELV iron recycling resulted from evolution of the ELV recycling system with the system demand side, supply side and policy. Consequently, it is argued that strengthening capabilities for recycling ELV materials such as scarce metals and plastics, may depend on initiatives that promote similar evolution. Furthermore, given that material configurations of ELVs may change continuously over time, uncertain recycling market conditions may be the normal case rather than an exception. Thus, long-term policy is argued for that promotes the orchestration of continuous and adapting evolution.

KEYWORDS

Recycling, Technological Innovation System, Material Flow Analysis, End-of-Life, Car, Vehicle, Scarce metal, Critical material

APPENDED MATERIALS

PAPER I

Andersson, Magnus; Ljunggren Söderman, Maria; A. Sandén, Björn (2016). Are Scarce Metals in Cars Functionally Recycled?

Submitted to *Waste Management*.

SUPPLEMENTARY MATERIAL TO PAPER I

Andersson, Magnus; Ljunggren Söderman, Maria; A. Sandén, Björn (2016). Supplementary material to: Are Scarce Metals in Cars Functionally Recycled?

Submitted to *Waste Management*.

PAPER II (MANUSCRIPT)

Andersson, Magnus; A. Sandén, Björn; Ljunggren Söderman, Maria (2016). System Innovation in Swedish Car Recycling, 1910-2010.

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1. INTRODUCTION

The scale of societal car use is large, and the material complexity of cars is increasing. With that, the issue of how to manage recycling of car materials becomes increasingly relevant. Today, there are a billion cars in use worldwide (Sakai et al., 2014), and design trends for current cars point at increasing utilisation of a wealth of materials in order for car manufacturers to meet extensive market and policy requirements on e.g. safety, performance, environmental pollution, comfort and infotainment (Edwards, 2004, Ghassemieh, 2011, Ljunggren Söderman et al., 2014). Among materials contained in current cars are several types of steel and aluminium, an assortment of textiles and padding materials, and an increasing amount of polymers and scarce metals (Alonso et al., 2012, Ljunggren Söderman et al., 2014, Ljunggren Söderman and Ingemarsdotter, 2014). Metal scarcity may arise because of increasing global demand and limited availability due to geological rarity, geopolitical issues and technical or economic constraints on extraction (European Commission, 2010, Skinner, 1979, U.S. Department of Energy, 2010). Thus, cars represent an increasing stock of a multitude of materials. Recycling of such materials may have environmental, economic, and in the case of scarce metals, resource security benefits (Graedel et al., 2011, Thompson et al., 2009, UNEP, 2013). Considering the scale of car usage, efficient recycling and high recycling rates of materials from discarded cars, also referred to as end-of-life vehicles (ELVs), may thus be vital not only for reaping aforementioned benefits, but for avoiding detrimental effects.

However, current ELV recycling systems are typically aimed at isolating hazardous content, selling spare parts, recovering and recycling some regulated parts and recycling metals existing in sizable quantities such as steel and aluminium (Andersson et al., 2016). Small material constituents, e.g. scarce metals, and materials of currently low market value, e.g. plastics, risk being lost as tramp elements in metals, used as construction materials, or incinerated or landfilled (Nakamura et al., 2012, Ohno et al., 2014, Andersson et al., 2016, Vermeulen et al., 2011). Thus, system capabilities currently exist for recycling some materials at high recycling rates, while such capabilities are lacking or are non-existent for other materials. Consequently, there is need for developing recycling systems that are more in tune to the material complexity of present and future ELVs.

Current ELV related research gives limited insight into how to achieve such development. Attention has been given to, e.g. assessing the potential for various treatment processes to accommodate more ELV materials (Vermeulen et al., 2011, Morselli et al., 2010, Santini et al., 2011), assessing implications of policy setups of different countries (Gerrard and Kandlikar, 2007, Smink, 2007, Smith and Crotty, 2008, Xiang and Ming, 2011), and optimising end-of-life procedures such as logistics, dismantling and shredding (Cruz-Rivera and Ertel, 2009, Go et al., 2011, Krikke et al., 2008, Mansour and Zarei, 2008, Simic and Dimitrijevic, 2012). Rarely is it explicitly revealed how successful recycling systems may form and develop. Regarding ELV scarce metals specifically, knowledge is lacking to a great extent in relation to both car metal contents and fates of individual metals in recycling systems, which makes attempting to improve ELV scarce metal recycling challenging.

1.1. AIM AND SCOPE OF RESEARCH

The aim of this thesis is to increase the knowledge base related to the state of ELV recycling and to means of improvement. Particular attention is given to what extent ELV recycling may be a source of scarce metals. To this end, increased knowledge is needed of the contents of scarce metals in discarded cars, how these metals distribute in ELV recycling systems, and to what extent these metals are recycled to material streams where their metal properties are utilised, i.e. are functionally recycled. Additionally, greater insight is needed into how an ELV recycling system may form, develop and be changed to accommodate recycling of individual elements better. Potential for such insight lies in the historic development of ELV iron recycling, which is currently at a mature stage. Consequently, the thesis is concerned with the following research questions: (1) What is the magnitude of scarce metals in discarded cars? (2) What are the fates of these metals in current ELV recycling? (3) Which fates constitute functional recycling and which risk leading to irreversible losses? (4) Which were the key system-building processes that led to current capabilities for ELV iron recycling?

Questions 1-3 are answered by paper one, while question four is answered by paper two. Additionally, the following is discussed in paper two; can key system-building processes be imitated to form initiatives that strengthen capabilities for recycling ELV materials other than iron? In summary, questions and the discussion point provide grounds for a synthesised view on the state of ELV recycling and to means of improvement. The unified spatial scope of research in appended papers, and thus in this thesis, is Sweden. With regards to elements, the work covers 25 scarce metals and iron.

1.2. THESIS OUTLINE

The reader is provided an introduction to theoretical and methodological starting points of this thesis in Chapter two. Chapter three introduces the empirical field of the thesis, and describes employed methods of paper one and two. Chapter four provides summarised results and discussions from both papers, as well as a synthesised perspective on these two papers. The research is concluded in Chapter five. Contributions by this thesis to current research, and suggestions for further research is given in Chapter six.

2. THEORETICAL AND METHODOLOGICAL FOUNDATIONS

2.1. MATERIAL FLOWS IN SYSTEMS

Commonly employed methods for analysing material flows in systems differ slightly in nature depending on the level of detail that is desired. Typically, methods are divided into substance flow analysis (SFA) (van der Voet, 2002), and material flow analysis (MFA) (Brunner and Rechberger, 2004). Both methods employ mass balancing of input and output flows of a system, and modelling of processes, such as production machinery, that interact with flows in the system. This is done in order to calculate how flows distribute in the system and for analysing various related topics, e.g. finding salient system flows, material stocks or specific patterns of material flows. Processes are modelled, so that so-called transfer coefficients may be established for each process. This enables allocation of input flows to output flows of individual processes in the system, and ultimately reveals how inputs to the entire system propagate and are output from the system, or accumulated within it. SFA is concerned with flows of substances, such as individual elements or chemicals, while MFA studies flows at a more aggregated level, e.g. flows of products or material flows containing several substances. Results from these methods, may be visualised by a so-called Sankey chart, where the direction and size of flows correspond to arrows of various thickness.

2.2. INNOVATION SYSTEMS

How to identify and describe key mechanisms behind sustainability related system innovation, transformation, and transitions are matters which have gained increasing attention within several literature bodies in recent time (van den Bergh et al., 2011). Among the wealth of research strands, various innovation system approaches have gained traction. The technological innovation systems (TIS) approach, has made advancement in the last decade towards creating a dynamic framework that captures innovation and diffusion of emerging technologies (Hekkert et al., 2007, Bergek et al., 2008a). In the TIS approach, technical change is framed as a collective process, involving interdependent agency of many types of individuals and organisations, and as a sociotechnical process, involving coevolution of actors, technology and institutions.

In TIS studies a 'technology' is in focus, identified with a product or knowledge field (Carlsson et al., 2002). More generally, a technology can be defined as 'a means to an end' (Arthur, 2009), i.e. a capability of transforming immaterial and material resources into something useful, which in the economy can be interpreted as a bundle of complementary and alternative value chains (Kushnir and Sandén, 2012). Any given 'technology' is defined and delineated by a set of supply chains and end uses. The choice of delineation depends on the goal and scope of the study and can be wider or narrower in both ends of the bundle. For example, studies of biofuels can focus on transportation fuels made from any type of biomass, or only on ethanol made from corn, but including not only transportation as end use but also chemical feedstock.

Furthermore, the 'technology' is viewed as a sociotechnical system, comprised of heterogeneous structural elements, including artefacts and knowledge, actors and networks, and cognitive, normative and regulative institutions (Bergek et al., 2008a). The TIS is the systemic description of how such systems emerge, develop and expand.

The TIS is conceptualised with the help of a number of key processes, so-called functions, which work to build and sustain sociotechnical structures. The strength of functions depend on both endogenous and exogenous forces (Hillman and Sandén, 2008), i.e. both influence stemming from already existing 'technology-specific' system components and forces imposed by the sociotechnical environment,

Figure 1. While several sets of functions have been proposed paper two makes use of the list provided by Bergek et al. (2008a), Table 1. As the internal structure becomes more developed, the strength of the functions are mainly determined by endogenous forces (positive feedback) and the system becomes more resilient to exogenous forces, i.e. it gains momentum (Hughes, 1987) and to some extent becomes locked-in on a certain development trajectory (Arthur, 1988). This process includes the development of positive externalities in the system, that is, newcomers may benefit from earlier investments in infrastructure, knowledge, markets, legitimacy etc. 'free of charge' (Bergek et al., 2008a), and a tendency towards specialisation (Bergek et al., 2008b), i.e. division of labour (Smith, 1776), which enable more refined and targeted development.

A TIS study requires analytical temporal, spatial and sociotechnical system boundaries, which may to smaller or larger extent mimic real world differences, e.g. in terms of type and intensity of interaction (Markard and Truffer, 2008). A natural system boundary separates elements that affect and are affected by the technology specific development (system components) from those that only affect it (system environment) (Bergek et al., 2008b). In the sociotechnical dimension, that means that one makes a cut-off in the bundle of value chains where actors, technical infrastructure, knowledge etc. are only marginally affected by the existence of the technology. What is affected, may of course change over time spans longer than the temporal boundary set in the study. While technological innovation systems framed in this way can cross all kinds of spatial boundaries (Binz et al., 2014, Carlsson and Stankiewicz, 1991), national boundaries are often imposed, for practical reasons or because the study intends to inform national policy making (Bergek et al., 2008b).

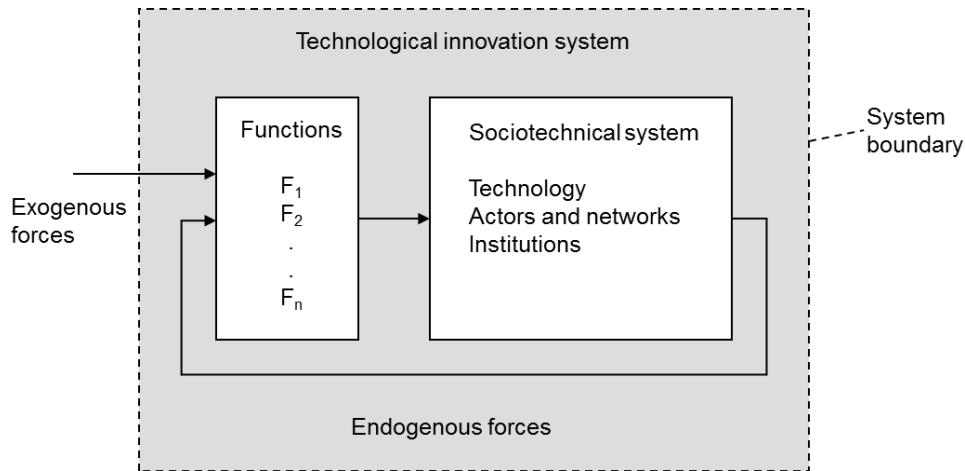


Figure 1. Schematic representation of the technological innovation system that drives the evolution of a sociotechnical system, i.e. ‘a technology’, through internal feedback and external influence, based on Hillman and Sandén (2008a).

Table 1. Functions of a technological innovation system, based on Bergek et al. (2008a).

FUNCTION	DESCRIPTION
Knowledge development and diffusion	The development and diffusion of explicit technology specific knowledge.
Entrepreneurial experimentation	The emergence of new opportunities and know-how through testing of new technologies, applications and markets.
Influence on the direction of search	The creation of incentives for individuals and organisations to enter the system stemming from expectations, changing norms, regulation, articulated demand, crises in current business, etc.
Resource mobilisation	The mobilisation of human and financial capital and complementary assets, such as network infrastructure, for system development.
Market formation	The formation of demand due to changed preferences, cost, performance or regulation.
Legitimation	The emergence of social acceptance and alignment with relevant institutions.
Development of positive externalities	The development of free utilities in the system, i.e. how investments by one firm may benefit other firms ‘free of charge’.

3. MATERIALS AND METHODS

3.1. CURRENT SWEDISH ELV RECYCLING

The current value chain of Swedish ELV recycling is made up of two main activities; dismantling and shredding (see paper one, Section 2.2). ELVs are supplied to dismantlers by private individuals or insurance companies. Dismantlers typically remove spare parts and some aluminium that may be sold, remove liquids and some components due to EU and Swedish ELV regulation, and sell dismantled ELVs to shredding companies. These utilise large-scale shredding facilities to grind the ELVs and isolate materials. Typically, iron, aluminium and other ELV metals existing in sizable quantities, can be isolated and sold, while other materials are used as construction materials, are incinerated or landfilled (within the waste management (WM) industry) at a cost (Jensen et al., 2012). Two trade associations work to promote and organise ELV recycling: the Swedish Car Recyclers Association (SBR, in Swedish) and the association responsible for adherence to ELV regulation (BilRetur). SBR promotes good practice by e.g. certifying new members (standards). Within BilRetur, there are internal agreements on ELV management. ELV regulation, i.e. technology specific regulation, put in place by the EU and Swedish authorities, heavily influences work procedures and relationships. See paper one for details, and Figure 2 for a simplified graphical representation of Swedish conditions that is used in paper two.

3.2. METHOD OF PAPER I

Paper one employs a three-step procedure. First, annual input of scarce metals to the ELV recycling system is estimated by combining the number of discarded vehicles with product data on three recently produced diesel-powered Volvo cars, manufactured for the Swedish market. Data originates from the International Material Data System (IMDS) (Cullbrand and Magnusson, 2012), but is complemented with some other sources (Geological Survey of Sweden, 2014, Ljunggren Söderman and Ingemarsdotter, 2014, Widmer et al., 2015). The data-set includes 19 scarce metals at component level and six at vehicle level. Each scarce metal is allocated to one, two or three *main application categories*. Four of the categories are alloys of major metals; steel, aluminium, magnesium and nickel. The remaining three are lubricants, catalytic components (interior of catalytic converter unit) and electric, electronic and magnetic components. The three models are separately used to calculate annual metal input, resulting in input intervals (Figure 3). Intervals are assumed as fairly representative of ELVs around 2030.

Second, to identify potential pathways of application categories in ELV recycling, a MFA model of the Swedish ELV recycling system is constructed. The model is based on official ELV waste streams statistics, complemented with data on key system processes. Data was sourced from official statistics, reports, waste management literature and qualified experts. Industry association directors or specialists were regarded as experts on activities representative for their industries, i.e. as industry experts. Technical specialists at companies treating large ELV waste shares, were regarded as technical experts. Industry experts provided descriptions, statistics or estimates related to companies or processes of their industries, or identified technical experts. Technical experts provided descriptions or estimates on process details. Five industry and 13 technical experts from five associations and 10 companies were sourced. Open-ended interviews were conducted by phone on 13 occasions, face-to-face on three. E-mail data acquisition occurred five times. Individual statements were cross-checked by querying multiple experts or comparing statements to literature if available.

Third, based on identified pathways of categories, potential fates of each scarce metal are established. Fates are assessed in terms of what type of recycling they correspond to. Fates are identified at the

modelled system border and corresponding recycling types categorised as a) functional recycling, b) non-functional recycling in carrier metal, c) non-functional recycling in other materials, d) no recycling or e) unknown. Landfilling of metals is categorised as no recycling, while metals dispersed in construction materials are viewed as non-functional recycling in other materials. Scarce metals contained in metal outputs exiting metal refining are regarded as functionally recycled if outputs make use of individual scarce metal properties, otherwise as non-functionally recycled in carrier metal. Allocation of metals to outputs of metal refining processes is based on literature on distribution tendencies of elements among gas, slag, and metal phases in commercial refineries (Lagneborg and Waltersson, 2004, Nakajima et al., 2011, Nakajima et al., 2010, Steinlechner and Antrekowitsch, 2015). When distribution tendencies cannot be defined, the recycling type is categorised as unknown. See paper one and its supplementary material for details.

3.3. METHOD OF PAPER II

Paper two utilises a model representing current Swedish ELV recycling conditions (Section 3.1). The model includes a TIS, being governed by European and Swedish authorities and situated in a supply chain. The entirety is embedded in the larger sociotechnical environment, see Figure 2.

The technology in focus is the capability of transforming ELVs to valuable products and raw materials containing iron, i.e. ELV iron recycling. The temporal scope covers a century from 1910 to 2010. The spatial system boundary is Sweden, which over the selected time span, appears to be a reasonable choice, despite a great deal of (mainly unidirectional) foreign influence. Car manufacturers and users are viewed as suppliers outside the system boundary, since car manufacturing and use operated rather independently of the recycling system in much of the studied time period. For a similar reason, raw materials producers, such as the steel industry, are also considered to be external, but on the demand side. The study thus tries to describe and explain the historical development of Swedish ELV iron recycling and the emergence of the particular value chain that presently represents this capability.

For many technologies it is possible to capture and present overall system development with a diffusion curve, e.g. depicting MWs of installed wind power capacity. Due to data insufficiency, there is no reliable quantitative approach for tracing how the ELV recycling system has 'improved', e.g. in terms of recycling rates. Instead, in paper two, it is observed that ELV recycling did not exist before there were cars to recycle and it is further postulated that ELV iron recycling has improved notably since the mid-1960s, when ELVs were in plentiful supply, but to a greater extent than today were left by the road-side, dumped in the wild or mismanaged at dismantling sites. Furthermore, it is presumed, that the TIS framework holds explanatory power in understanding this system improvement.

Procedurally, time periods of significant structural change are first identified. Subsequently, the course of events that coincide with the structural change are examined, and the functions are used to propose a theoretical explanation for the observed system development. In doing so, the key system-building processes that led to current capabilities for ELV iron recycling become apparent. These processes are analysed and discussed, by dividing them into sequences. For each sequence, the observed exogenous and endogenous forces are summarised, and the strengthened functions and built system components are noted (paper two, Table 2). Finally, using these sequences as base, it is discussed to what extent they can be imitated, to form initiatives that may strengthen capabilities for recycling other ELV materials besides iron.

The types of data used for identifying structural changes and courses of events are numerous grey literature sources, political documents, official statistics, and interviews with qualified experts. Utilised grey literature types include reports and books published by companies, trade associations, research

organisations, government agencies and local history societies. Political documents include governmental bills and official inquiries of the Swedish government. Relevant official statistics include the number of annual ELVs and authorised dismantling actors. Some statements regarding past events were collected by interviewing six key qualified experts, positioned in different parts of the system, including former or current directors and specialists that hold key historic insights. Interviews were open-ended and conducted face-to-face two times, and by phone the remaining four. Face-to-face interviews were recorded, while phone interviews were documented in notes. Collected data was cross-checked with one or multiple sources, either printed or statements from interviews. Additionally, collected material was presented on six occasions to researchers and industry representatives with domain competence, and at one conference.

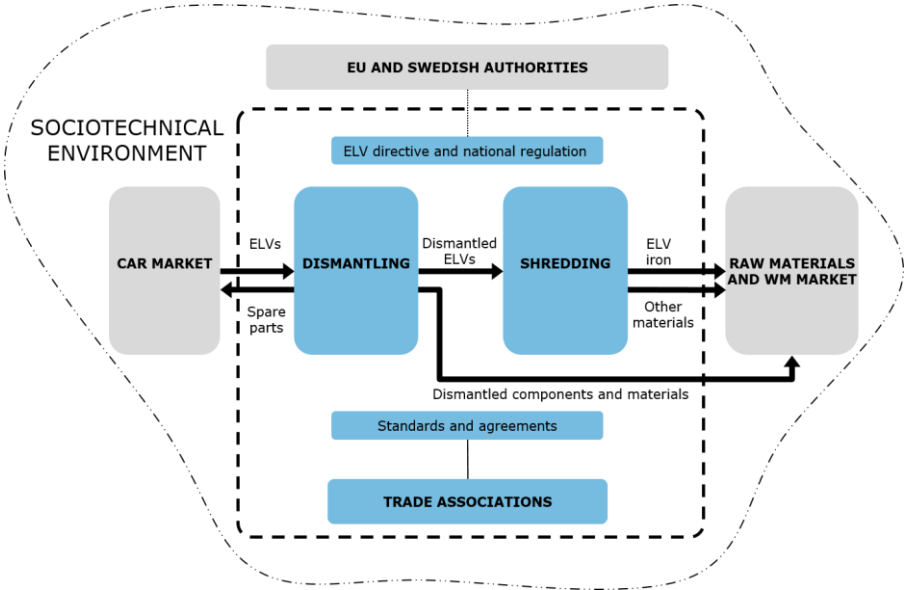


Figure 2. Model used for studying system innovation in Swedish car recycling in 1910-2010. The focal technology is analytically delineated around the capability to transform ELVs to valuable products and raw materials containing iron. WM = waste management.

4. RESULTS AND DISCUSSION

4.1. PAPER I

Estimated annual scarce metal inputs to the Swedish ELV recycling system are presented in Figure 3. Total estimated input amounts to 2 000-3 000 tonnes/year, one percent of total ELV input mass.

Input magnitudes vary significantly from a few kilograms to thousands of tonnes. Ranges for individual metals also vary substantially, indicating that content of specific metals varies between car models, despite cars being of the same brand and production period. Specific car designs thus likely influence metal input considerably.

Mix of metals within specific main application categories varies significantly. Electric, electronic and magnetic components are identified as the sole main application category of thirteen metals (dysprosium, erbium, gallium, gold, indium, neodymium, praseodymium, rhodium, samarium, silver, tantalum, terbium and ytterbium), while six (cobalt, gadolinium, lanthanum, lithium, palladium and yttrium) are found in one additional category. Three (magnesium, molybdenum and niobium) are allocated to metal alloys only, and two (cerium and platinum) only to catalytic components. Manganese is the one metal allocated to three categories.

The number of reported applications per metal in the used data-set, ranges from 1 to over 1000 (Supplementary material to paper one, Table S1), indicating that some metals are concentrated to one component, while others are dispersed throughout the car. Consequently, input magnitude, application and dispersion patterns significantly precondition the recycling possibilities of each metal.

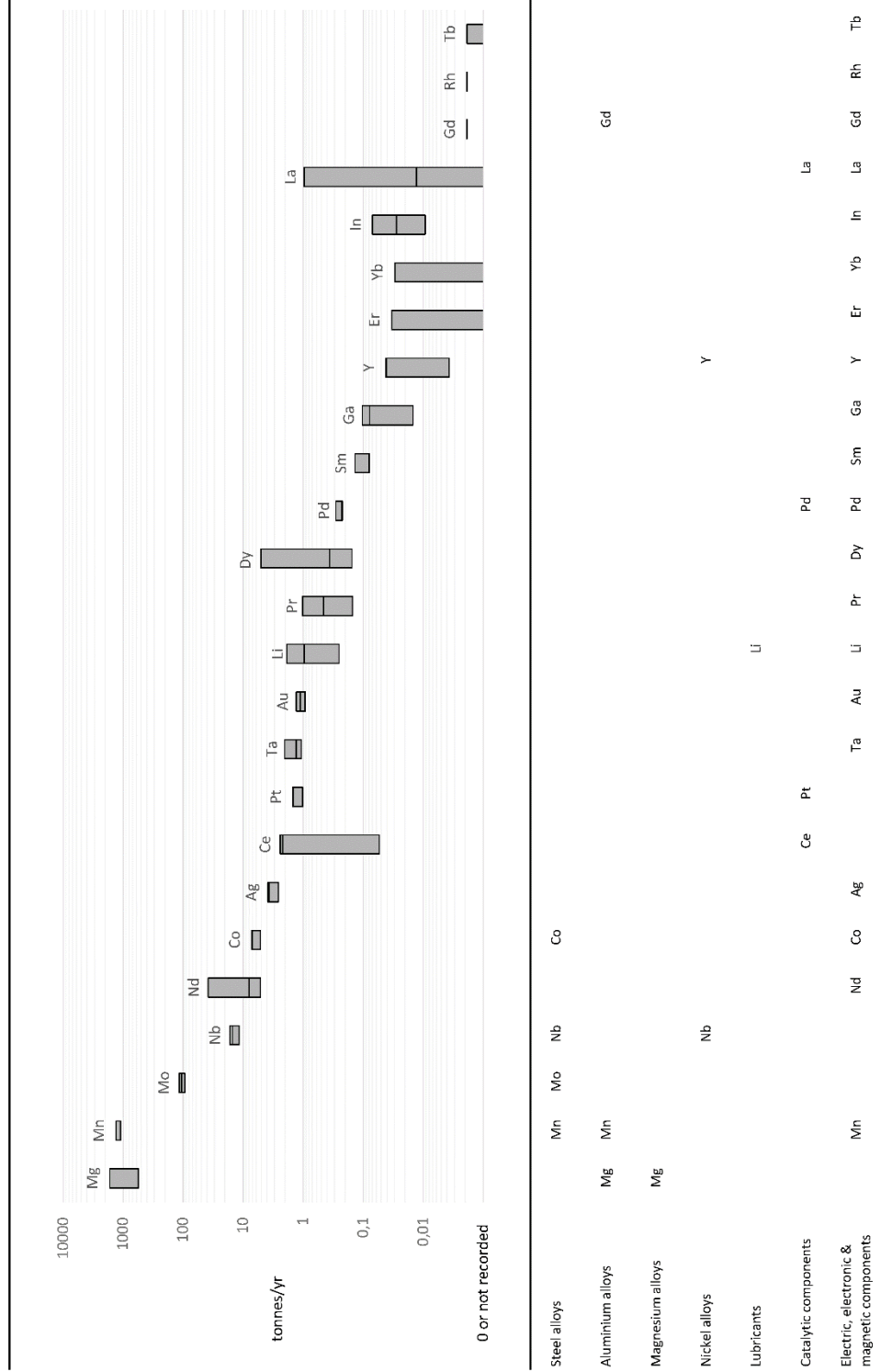


Figure 3. Estimated annual input of some scarce metals to Swedish ELV recycling and their main application categories. Upper, in-between and lower values correlate to metal contents of three model cars used in the study (See paper one, Section 2.1, and Supplementary material to paper one, Section S1).

Results of MFA modelling are represented by the Sankey chart of Figure 4, where sub-systems (A-F) correspond to identified key system processes (see paper one, Section 2.2). Figure 4 illustrates that Swedish ELV recycling involves many material flows, estimated to vary significantly in magnitude. ELV input amounts to 230 000 tonnes. Dismantling (A) recovers and diverts 25% of input as spare parts and as components and materials sent to dedicated processing (B). The remaining 75% continues as dismantled ELVs to shredding (C), where the most salient outputs are ferrous fractions used by domestic or foreign steel production. Remaining mass is distributed between minor streams. The abundance of system processes and flows implies that main application categories may take multiple pathways, both in and outside Sweden.

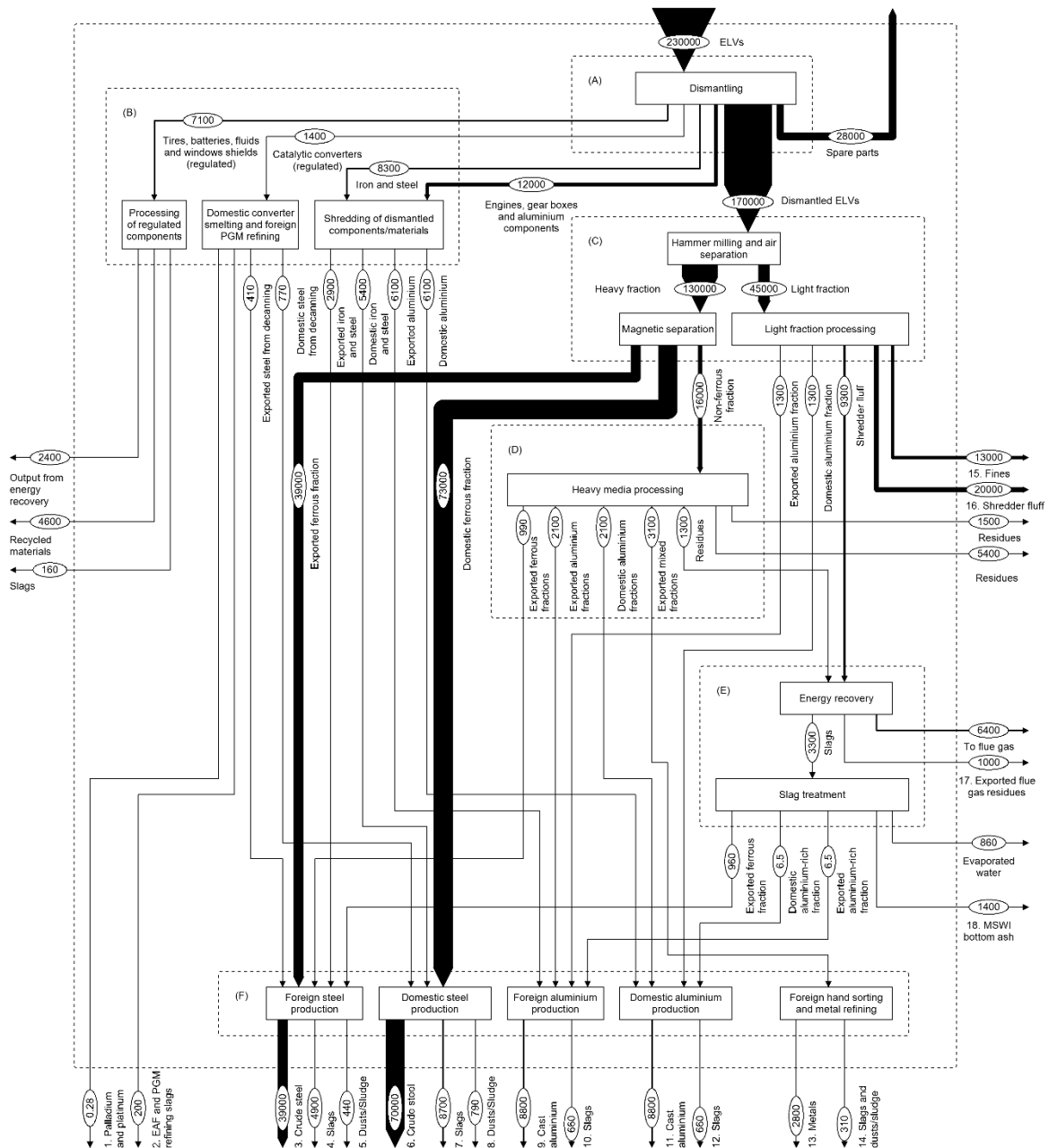


Figure 4. Processes and material flows in Swedish ELV recycling. Flows 1-18 are outputs from system processes to which identified pathways of scarce metal application categories lead.

The potential for functional recycling of metals varies, and will depend on pathways of application categories and subsequent fates of individual metals (paper one, Sections 3.2-3.3). Notably, potential for functional recycling can be identified for platinum in its one main application. Potential for functional recycling of cobalt, gold, manganese, molybdenum, palladium, rhodium and silver is also identified, but depend on application and pathways, of which some result in non-functional recycling or no recycling. For remaining metals, functional recycling is deemed lacking. Fates and recycling types are unknown for some metals. However, since these metals are not common alloying agents in the metal refining processes to which identified pathways lead, any functional recycling is unlikely. See Figure 5.



Figure 5. Scarce metals (in bright blue) for which potential for functional recycling is identified.

Note that industrial scale technologies for functional recycling of the metals under study is lacking with some few exceptions (Ljunggren Söderman and Ingemarsdotter, 2014). Thus, near-term strategies to improve the potential for functional recycling, would involve diverting metals to processes already identified as capable of functional recycling. Gold, palladium, rhodium and silver in electronic, electric and magnetic applications (Figure 3), may be dismantled and functionally recycled in electronic waste recycling processes recovering precious metals. Potential components are electronic control units (Wang and Chen, 2011), PCBs connected to GPS, radio, CD or user interface equipment, exterior lights and lambda sensors (Sander et al., 2014, Widmer et al., 2015). However, with such strategies, not all scarce metals contained would be functionally recycled.

Another option is batch-wise shredding and post-shredding of dismantled ELVs, combined with extended quality specifications of steel and aluminium fractions to accommodate identification and dedicated use at metal refineries. Conditions for functional recycling of cobalt, manganese, molybdenum and niobium in steel alloys and of gadolinium, magnesium and manganese in aluminium alloys (Figure 3), could then be improved.

4.2. PAPER II

Results of paper two indicate that the key system-building processes that led to current capabilities for ELV iron recycling, may be viewed as continuous or intermittent exogenous and endogenous forces of a TIS. These forces strengthened functions of the TIS, and built system components so to enable capabilities. Forces stemmed from large-scale societal developments and actions taken by numerous actors, rooted in or outside the secondary steel production value chain. More specifically, current capabilities for ELV iron recycling seemingly are the result of evolution of the ELV recycling system with the system demand side, supply side and public policy. See Figure 6 for a simplified graphical representation of the development observed in paper two, based on the model of Figure 2. See paper two, Table 2, for a corresponding detailed overview, where the observed development is divided into sequences. For each sequence, the observed exogenous and endogenous forces are summarised, and the strengthened functions and built system components are noted.

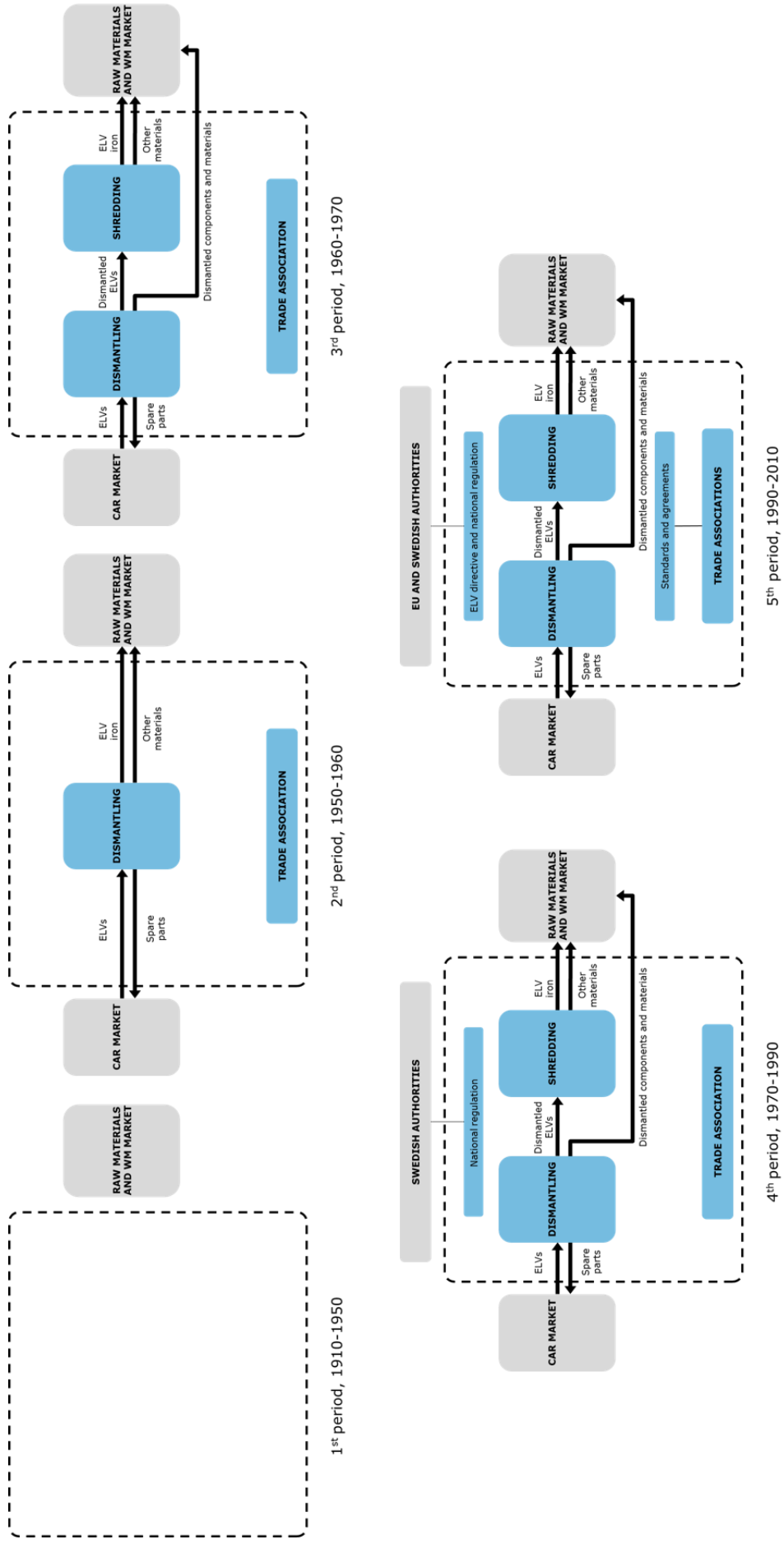


Figure 6. Schematic representation of Swedish car recycling during 1910-2010, based on the model of Figure 2. Each sub-figure represents the state at the end of each period.

Paper two illustrates, in 12 sequences, the build-up and refinement of dismantling and shredding system components. Both contribute to iron recycling; dismantling, by removing unwanted components or materials from the ELV, and shredding, by raising efficiency and quality consistency of iron output. Sequentially, the build-up of both these groups of system components were preceded by structural build-up within the steel industry, which strengthened the market for ELV iron (paper two, Table 2, sequence 1), and by increased access to ELV iron through mounting numbers of ELVs (paper two, Table 2, sequence 2). Subsequently, the continued build-up of these groups were seemingly connected to partially different sequences. Regarding dismantling, dismantlers responded to, and were subjected to, policy initiatives that resulted in both industry and regulatory institutions. These institutions raised requirements for operating in the system and formed barriers to entry, which finally resulted in fewer but institutionally aligned actors and harmonised practices (paper two, Table 2, sequences 3, 6, 9, 10 and 11). Regarding shredding, the build-up related to overcoming initial economic, technical and legitimisation thresholds, in order to make way for shredder technology adoption (paper two, Table 2, sequences 4, 5 and 8). Additionally, the formed collaboration between these two groups, and in the last period also with car produces, seemingly related to three key sequences (paper two, Table 2, sequences 5, 7, and 12) in which networks were built and reinforced. These networks, potentially promoted efficient distribution of some components (such as shredders, see paper two, Table 2, sequence 8), and counteracted sub-optimisation of system capabilities.

Thus, paper two indicates that the sequential order of development was highly relevant, as one sequence put in place system components needed by another, but also that the build-up of dismantling and shredding capabilities related to partially independent development sequences. Finally, it also indicates that the capabilities of the system was increased by strengthened networks.

Of relevance to forming initiatives that may strengthen capabilities for recycling other ELV materials besides iron, some of the observed sequences of paper two may potentially be imitated, by replicating or simulating exogenous forces and putting in place system components. However, respect needs to be taken to temporal order, since some sequences require some level of structural maturity. Note that the discussed sequences of paper two are not necessarily dependent on whom they are performed by. Nevertheless, some may not be within direct reach of all actors. For instance, institutional formation by public policy making is naturally reserved to policy makers alone, while a wide range of actors may form advocacy coalitions for such policy, or work for softer institutional formation, such as certification schemes and industry norms. See Table 2, for a shortened summary of initiatives discussed in paper two.

Table 2. Potential initiatives that may strengthen capabilities for recycling ELV materials, which currently are recycled at low or non-existent rates.

INITIATIVE(S)	MAIN STRENGTHENED FUNCTION(S)	IMPACT DESCRIPTION OF INITIATIVE(S)
<ul style="list-style-type: none"> -Demand side procurement and negotiation platforms where material standards are negotiated, set, and communicated. -Policy support for secondary raw materials trade (e.g. subsidised transports). -R&D funding aimed at raising production efficiency of secondary materials production. 	<ul style="list-style-type: none"> - Market formation 	<ul style="list-style-type: none"> -Promotes clear market conditions. -Works against trade thresholds. -Increases competitiveness of secondary materials production so to potentially raise demand for secondary raw materials.
<ul style="list-style-type: none"> -Coordinated waste streams. -Product design adapted to recycling. -Policy support (e.g. taxes, subsidies, labelling) for directing consumption patterns toward products adapted to recycling. 	<ul style="list-style-type: none"> - Resource mobilisation (of material resources) 	<ul style="list-style-type: none"> -Raise access to, i.e. mobilise, material resources for system actors, and promote bridging the value chain gap between input (ELV material) and output (secondary raw material).
<ul style="list-style-type: none"> -Networks (formed by setting stringent ELV recycling targets or intentional creation), which utilise certification schemes related to good practice dismantling. -Specified and enforced compliance of good practice as part of ELV regulation. 	<ul style="list-style-type: none"> - Legitimation (of good practice) - Influence on the direction of search 	<ul style="list-style-type: none"> -Network certification schemes and regulated dismantling procedures may legitimise good practice, and influence direction of search to or from the system. Potentially suitable for materials that may never be economically/technically feasible to treat automatically, e.g. small components holding scarce metals.
<ul style="list-style-type: none"> -Venture capital to promote investments in technical systems. -R&D and demonstration projects. 	<ul style="list-style-type: none"> - Resource mobilisation (of financial resources, physical equipment and knowhow) 	<ul style="list-style-type: none"> -Work against investment, technical and legitimation thresholds related to implementing readily available, but capital-intensive, automated technical systems that may raise system efficiency. If such systems are lacking, R&D and demonstrations projects may be critical.
<ul style="list-style-type: none"> -Networks for system actors holding unique competencies. -Regulation that emphasises shared value chain responsibilities (e.g. through stringent recycling targets, or procedural specifications that promote coordination of actor competencies) 	<ul style="list-style-type: none"> -Development of positive externalities 	<ul style="list-style-type: none"> Potentially suitable for large material streams, likely requiring large-scale automated technical system, e.g. plastics. -Promote networks between system actors holding unique competencies, so to counteracted sub-optimisation of system capabilities.

It can be noted that increased ELV material complexity, most evidently coming into play in the fifth studied period (paper two, Table 2, sequences 9 and 12), motivated changes that likely raised system capabilities in general. However, it also indicates initial system lock-in, as it points to a challenge for system capabilities to deal with new materials. A challenge seemingly springing out of the increased specialisation of the system at the time. Thus, given a future in which a greater range of products rely on material complexity, specialisation to single material streams may not suffice, and care should be taken not to drive industry development in that direction. Rather, specialisation to a range of materials or to adaptability may be key.

4.3. A SYNTHESISED PERSPECTIVE

Papers one and two provide two perspectives on the issue of how to manage ELV recycling. Paper one discusses that some improvement of recycling may be achieved by implementing new procedures that make use of currently available recycling technology; dismantling some specific components that may be processed in WEEE recycling, and dedicated shredding of dismantled ELVs together with new quality specifications for enhanced utilisation of high-quality ELV steel and aluminium in current refining plants. Paper one notes that losses would still occur, as there is a lack of dedicated technology available that targets all individual metals. Paper two indicates that the implementation of both work procedures and already available technology hinges on the evolution of the ELV recycling system with the system demand side, supply side and public policy. Consequently, increasing capabilities for recycling ELV materials that currently are recycled at low or non-existent rates (e.g. plastics and scarce metals), may depend on similar evolution to form new value chains (see Table 2). Some of these value chains may never be economically feasible, and may require policies that strengthen economic incentives. Furthermore, the high degree of material entanglement in ELVs may imply that material losses are highly likely. Consequently, striking a balance between profitability and material resource strategy when forming such value chains may be key. Clearly, it seems unlikely that the formation of such value chains can be orchestrated by a single actor, or in an immediate future.

Furthermore, when shifting to a long-term outlook, additional challenges emerge related to new car material configurations or transmaterialisation of cars, and the capability of the ELV recycling system to adapt and survive under such material uncertainty. Paper two indicates that it may be difficult to readapt recycling systems to changing material compositions. Thus, it is possible that mismatches between the material composition of input flows and system recycling capabilities will be the normal case, rather than an exception. If so, material streams to landfills, and material dispersion to other material flows or the environment are likely. In such a case, there may be need for a long-term societal vision of which key secondary material flows that need dedicated supply chains. For these, long-term support would likely be needed for orchestrating, and continuously readapting, supply and demand sides, recycling system internal components, and public policy, which seem instrumental for building such supply chains, as indicated by paper two. Key material flows may be e.g. those detrimental to environment, to human health, those containing scarce metals and those material flows for which purity is highly desired.

5. CONCLUSIONS

The results of this thesis imply that if the breadth of car materials are fully accounted for, the Swedish ELV recycling system is not tuned to the differences in scale and complexity of materials constituting current and future discarded cars. If scarce metals and other materials from cars are to contribute to resource security and secondary materials production, metal and material specific strategies are likely needed. Such strategies may hinge on large-scale evolution of the ELV recycling system with the system supply and demand sides, and with public policy. Given that the material composition of ELVs may change over time, uncertain recycling market conditions may be the normal case rather than an exception. Thus, long-term policy is likely needed for orchestrating continuous and adapting evolution around some key material resources that society deems desirable.

6. RESEARCH CONTRIBUTIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Paper one contributes empirically by raising the resolution of the Swedish ELV system and by exploring material flows which have previously not been extensively treated in literature. Theoretically, contributions are made by providing an approach for assessing recycling of flows given limited data.

Paper two contributes empirically by providing new empirical material to innovation and sustainability transitions research. Theoretically, by adapting the technological innovations systems framework to the waste management field.

Regarding suggestions for further research related specifically to ELVs, paper one indicates that continued data collection and mapping of individual elements and materials, e.g. scarce metals and plastics, are needed both in terms of how such elements and materials are situated in ELVs and how they distribute in material flows of ELV recycling systems. Paper two indicates that much knowledge is needed of how supply chains may be formed around aforementioned elements and materials.

In more general terms, paper one strongly indicates need for further system-wide mappings of material flows of specific elements in waste management research, and advancements of methods for performing such mappings and analysing implications for recycling, given limited data availability. Paper two hints at that processes and the degree of structural build-up in the sociotechnical environment of an emerging TIS, are highly relevant for understanding how functions work to build TIS components (see Bergek et al. (2015)). For example, processes which may be interpreted as environmental knowledge development within the government organisation, particularly within the Swedish EPA, translated to legitimation and influence on the direction of search for the focal technology, especially during the 1990s in relation to dismantling capabilities. Furthermore, processes which may be interpreted as resource mobilisation within the steel industry, translated to market formation for the focal technology. I.e. the notion that functional transformations may take place between different TIS through particular system structures may be fruitful avenues of research for conceptualising system interactions (also, see Sandén and Hillman (2011)). As such aforementioned processes of the sociotechnical environment may vary in strength, and be more or less tied to focal technology system components, this may also shed light on why focal technology components may lag behind or be well-developed.

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