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Lessons from energy-efficient lighting products

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LICENTIATE DISSERTATION |IIIEE | LUND UNIVERSITY

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Lessons from energy-efficient lighting products

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Abstract

The transition to a low-carbon economy requires enabling technologies including energy-efficient lighting products. It is increasingly recognized that a sustainable economy is not only low-carbon and energy efficient, but also resource efficient. Previous research has highlighted the importance and need for increased collection and recycling of lamps, to reduce mercury emissions, to avoid unnecessary negative environmental impacts, and to recover the critical materials they contain. Extended Producer Responsibility (EPR) policies aim to address these issues by promoting collection and recycling of waste products, closing material loops and providing ecodesign incentives. This licentiate thesis contributed to EPR research with detailed knowledge about the performance of EPR policies for energy-efficient lamps in Europe. Using a theory-based evaluation approach, both the performance in relation to EPR goals as well as challenges perceived by key stakeholders, were analyzed. Factors contributing to high operational performance and best practices in the Nordic countries were identified, as well as the areas for further improvement.

The research also examined opportunities and barriers for closing critical material loops from this waste stream and found that EPR policies have been an important enabler for development of commercial scale recycling of rare earth elements (REE) from waste lamp phosphors in Europe. It is argued that both wider adoption and improved performance of EPR systems are necessary to increase potential secondary supply of REE from this waste stream. However, the feasibility of recycling REE is also dependent on complex considerations of value and contextual factors such as competition with primary supply, material prices, and markets for recycled materials. The value of waste lamps is further mapped and examined from different stakeholder perspectives. These considerations of value are discussed in the context of prior and future EPR research.

Key words: extended producer responsibility, lamps, WEEE, policy evaluation, critical materials, circular economy

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Abstract

The transition to a low-carbon economy requires enabling technologies including energy-efficient lighting products. It is increasingly recognized that a sustainable economy is not only low-carbon and energy efficient, but also resource efficient. Previous research has highlighted the importance and need for increased collection and recycling of lamps, to reduce mercury emissions, to avoid unnecessary negative environmental impacts, and to recover the critical materials they contain. Extended Producer Responsibility (EPR) policies aim to address these issues by promoting collection and recycling of waste products, closing material loops and providing ecodesign incentives. This licentiate thesis contributed to EPR research with detailed knowledge about the performance of EPR policies for energy-efficient lamps in Europe. Using a theory-based evaluation approach, both the performance in relation to EPR goals as well as challenges perceived by key stakeholders, were analyzed. Factors contributing to high operational performance and best practices in the Nordic countries were identified, as well as the areas for further improvement.

The research also examined opportunities and barriers for closing critical material loops from this waste stream and found that EPR policies have been an important enabler for development of commercial scale recycling of rare earth elements (REE) from waste lamp phosphors in Europe. It is argued that both wider adoption and improved performance of EPR systems are necessary to increase potential secondary supply of REE from this waste stream. However, the feasibility of recycling REE is also dependent on complex considerations of value and contextual factors such as competition with primary supply, material prices, and markets for recycled materials. The value of waste lamps is further mapped and examined from different stakeholder perspectives. These considerations of value are discussed in the context of prior and future EPR research.

List of Papers

Paper I — Richter, J. L.[1], & Koppejan, R. (2016). Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops. *Journal of Cleaner Production*, *123*, 167–179.

Paper II — Machacek, E., Richter, J. L.[1], Habib, K., & Klossek, P. (2015). Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resources, Conservation and Recycling*, *104*, *Part A*, 76–93.

Paper III — Richter, J. L. 2016. The complexity of value: considerations for WEEE, experience from lighting products, and implications for policy. *Electronics Goes Green 2016+ Conference Proceedings.*

[1] A statement on the contribution of J.L. Richter as an author for each article can be found in Appendix D.

Other Publications

Plepys, A. & Richter, J.L. (2016). Public Procurement Barriers in Promoting Market Uptake of Innovative LED Lighting. Electronics Goes Green Conference Proceedings.

Richter, J. L., & Leire, C. (2015). Greening the global classroom: Experiences using MOOCs to advance sustainability education. In Global Cleaner Production and Sustainable Consumption Conference Proceedings.

Leire, C., McCormick, K., Richter, J. L., Arnfalk, P., & Rodhe, H. (2016). Online teaching going massive: input and outcomes. *Journal of Cleaner Production*, *123*, 230–233.

Karlsson, R., Kunen, J. Richter, J., Karlsson, T., Will, M. (2016). *D2.8 Final Report on sustainability issues*. SSLerate Project.

Abbreviations

CFL – compact fluorescent lamp

EEE – electrical and electronic equipment

EoL – end-of-life

EPR – extended producer responsibility

EU – European Union

GDL – gas discharge lamp

IPR – individual producer responsibility

LED – light emitting diode

LCA – life cycle assessment

MFA – material flow analysis

MSW – municipal solid waste

PoM – put on market

PRO – producer responsibility organization

PSS – product service system

REE – rare earth element(s)

RoHS – restrictions on the use of hazardous substances

WEEE – waste electrical and electronic equipment

1. Introduction

> *But I note, with wry satisfaction, that the lampmaker's use of rare earths is visually the most spectacular of all - that of generating brilliant colored lights to see by. The rare earth ion being a sheltered place, inside, safe from disrupting influences of its environment, it can take a bit of absorbed energy, shape it, and spit it out in one of the purest forms of visible light we know. These pure, brilliant, colored lights (termed spectral colors or spectral lights) show enormous promise for general illumination.*
>
> – W.A. Thornton (1981) *Industrial Applications of Rare Earth Elements*

The history of light bulbs, or lamps, is itself a case study of the many facets of development, innovation and sustainability. By the end of the 19th century, electric lighting was one of the first public applications of electric power and it became another symbol of societal progress and development. The tungsten filament lamp itself became an icon in the 20th century, symbolizing new ideas and inventions (Institute for Energy Research, 2014). Lesser known is that the lamp also became one of the first examples of planned obsolescence. The major lighting producers formed the Phoebus cartel and agreed to codify the life of a lamp to 1000 hours despite the technological capability for longer lifetimes (Krajewski, 2014). The cartel also agreed to standardization of lamps (by wattage, shape and screw-in mounts), with the argument that standardization ensured quality for consumers (OSRAM, 2006). Besides the cartel, there were other lighting industry alliances, including the "Patentgemeinschaft" (Patent pool) that influenced production quotas through its control of the patents needed to make the core lighting products and the "Internationale Glühlampen Preisvereinigung" (International Incandescent Lamp Price Association) that endeavoured to control lamp prices in Europe (Krajewski, 2014). The early development of lighting technology highlights some of the tensions and barriers to innovation.

Ultimately, World War II broke the alliances with an urgent demand for longer life and more energy-efficient products. This need spurred further development of fluorescent lamps with longer lives and better energy efficiency in lamps (Bright & Maclaurin, 1943). Fluorescent lighting saw an increased uptake in the commercial and industrial applications and linear fluorescent lighting saw uptake in the residential market in Asia (Lefèvre, de T'Serclaes, & Waide, 2006). The uptake for compact fluorescent lighting in residential applications was relatively slow until the 1990s, with the Western European market leading the way with compact fluorescent lighting (Mills, 1993). Turning off the lights and switching to compact fluorescent lamps became tangible actions promoted by environmental campaigns around the world. This continues today in the form of initiatives such as Earth Hour and UNEP's En.lighten initiative. With lighting accounting for approximately 15% of global power consumption and 5% of worldwide greenhouse gas (GHG) emissions, more efficient lighting is argued as one of the most effective and economically advantageous methods to address energy consumption and climate change (UNEP, 2012). However, the switch to more efficient fluorescent lighting has also attracted criticism and challenges of trade-offs in the switch to more complex technology utilizing mercury even as this substance is being phased out in other applications (see e.g. Sandahl et al., 2006).

Life cycle assessments (LCAs) confirm that there is substantially less overall environmental impact from energy-efficient lighting compared to traditional incandescent technologies. This is mainly due to the use phase dominating the life cycle environmental impacts. However, the impacts in this phase can also be influenced by the assumptions about the energy mix. When a large share of renewable energy is considered, other stages of the life cycle become more significant. This is in part due to the changing nature of these products from the simple incandescent bulb to the mercury-containing fluorescent, or gas discharge lamps, to the essentially electronic light emitting diode lamps (LEDs), which require increasingly advanced and complex manufacturing processes. The change in technology to gas discharge lamps also introduced hazardous materials like mercury into the products, which can have a high local environmental impact if large enough quantities are released into the environment (Wagner, 2011) or result in high mercury emissions if filter technology is not used for incineration (Silveira & Chang, 2011). The fragility also makes the health of handlers a concern when handling waste gas discharge lamps (Kasser & Savi, 2013; Sander et al., 2013).

Despite these concerns, there is little formal research about the end-of-life management of energy-efficient lamps, with that which has been done mainly focussed on state level actions in the U.S. (Silveira & Chang, 2011; Wagner, 2011). In Europe, extended producer responsibility (EPR) systems for waste electrical and electronics equipment (WEEE) have been implemented under the WEEE Directive (EU 2002/96/EC and its recast 2012/19/EU). This Directive and the overall EPR systems for WEEE have been the focus of research and evaluation studies (e.g. Hischier, Wäger, & Gauglhofer, 2005; Huisman, 2013; Huisman et al., 2008; Khetriwal et al., 2011; Román, 2012; Tojo, 2004; van Rossem, Lindhqvist, & Tojo, 2006; van Rossem, 2008, Ylä-Mella et al., 2014). Specific product groups are given attention in WEEE-related EPR research, but most focus on computers, phones, and televisions and there has been very little attention in research specifically on energy-efficient lighting products[2] (also see Pérez-Belis, Bovea, & Ibáñez-Forés, 2014 for an overview of WEEE literature).

While much of the general WEEE research is relevant to the case of lamps, this product category also has unique characteristics compared to many other WEEE streams. For example, collection and recycling of lamps is currently a relatively high cost compared to the value of the product with a low or negative value of the recovered material from lamp waste. The high cost for lamps is tied to necessary recovery of hazardous materials increasing recycling costs, but also to challenges in collecting lamps that are lightweight, small, and dispersed. While clearly it is of societal value to avoid mercury contamination, this is an externality that is difficult to quantify in economic terms (Magalini et al., 2014). Lamps represent a classic product group for EPR policy as it was originally designed, i.e., they represent a net cost for treatment, and treatment clearly avoids environmental harm – which necessitates the need for policy to ensure sound end-of-life management (Huisman et al., 2008). However, with WEEE Directive targets that are based on the weight of WEEE overall, in particular for the 4 kg/capita targets before the 2012 recast, it can be argued that the WEEE Directive gave less incentive to focus on this waste stream than others. With most research focused on WEEE in general, there is limited knowledge about how effectively the EPR systems in Europe are performing in regard to energy-efficient lamps in particular.

The need to ensure proper treatment of hazardous and critical materials in waste lamps, particularly for gas discharge lamps, has spurred some interest in quantifying the magnitude of lamp waste flows e.g. the amounts of fluorescent lamps that will end up as waste in China and Japan (Asari, Fukui, & Sakai, 2008; Tan & Li, 2014; Tian et al., 2016). There is also interest in waste lamps for the recovering the critical materials they contain, such as rare earth elements (REE) in the phosphors needed to produce warm white light. The EU Commission's report on Critical Raw Materials for the European Union (EU Commission, 2014), considers the REE as having the highest supply risk among various critical raw materials; and REE have received increasing attention in the last few years with rising prices and concern about supply restrictions from China, where over 90% of production takes place (Binnemans et al., 2013). For these reasons, lighting products as a source for recycling of rare earth elements has been given considerable attention by the researchers writing about technical recycling processes (Dupont & Binnemans, 2015; Langer, 2012; Liu et al., 2013, 2014; Tan, Li, & Zeng, 2015; Tunsu et al., 2016; Tunsu et al., 2015) as well as researchers in geology and industrial ecology writing about material criticality (Guyonnet et al., 2015; Moss et al., 2013; Reck & Graedel, 2012; Rollat et al., 2016).

[2] Currently lighting products are category 5 (gas discharge lamps category 5b). In August 2018 new product categories will see energy-efficient lighting consolidated in category 3.

Only a couple of these studies have sought to estimate the potential for closing critical materials loops with lamp recycling, and acknowledge that there are great uncertainties about the actual collection and recycling practices (Binnemans et al., 2013; Rollat et al. 2016). While many researchers and other stakeholders alike call for improved collection and recycling of lighting products (Asari et al., 2008; Binnemans et al., 2013; Hu & Cheng, 2012; Huisman et al., 2008; Lim et al., 2013; Tähkämö et al., 2014; Tian et al., 2016; UNEP, 2012; U.S. Department of Energy, 2013; Wagner, 2011), there is little research about how policy could develop to increase opportunities for closing critical material loops.

1.1 Problem Statement

The transition to a low-carbon economy requires enabling technologies including energy-efficient lighting products. It is increasingly recognized that a sustainable economy is not only low-carbon and energy efficient, but also resource efficient (European Environment Agency, 2016). An integrated policy approach towards energy-efficient lighting includes end-of-life management of the waste products to reduce mercury emissions and avoid unnecessary negative environmental impacts (UNEP, 2012). It is also increasingly recognized that energy efficient lighting products contain critical materials essential for continued technological innovation. Previous research on recovery of critical materials has often highlighted the importance and need for increased collection and recycling of energy-efficient lamps; however, it has not been connected well to existing knowledge from the waste management and policy research. For example, while there has been some attempt at predicting the potential supply from recycling rare earth phosphors from lamps (Binnemans et al., 2013; Rollat et al., 2016), these predictions have made general assumptions about the collection and recycling systems without examination of the current state of implemented policies, performance of these systems and challenges to realizing this potential.

Energy-efficient lighting products are a product category covered by the WEEE Directive in the EU and some other EPR policies have been implemented in Switzerland, the U.S. (in some states, e.g. Maine and Washington), and Taiwan. New EPR legislation is also proposed or being discussed in other countries, for example India and China, where the large-scale introduction of fluorescent lighting could present a problem if not properly managed at end-of-life (see e.g. Pandey, Hooda, & Mishra, 2012; Tan & Li, 2014). Even in countries with EPR legislation, these policies are still rather new (implemented in the last 10 years) and there is little detailed knowledge about how these policies perform in practice.

More detailed knowledge of this WEEE stream is important to better inform current research on EPR policy for WEEE, both to improve existing policies and to inform policies being developed now. EPR policy is also integral to circular economy strategies and it is known that energy-efficient lighting products contain critical materials and there is research aiming to increase our knowledge about potential material flows and technological processes to recover this material from energy-efficient lighting products; however, there is a gap between this research and the research on current EPR policy and practice. It is necessary for research to address this gap in order to truly gauge the performance and potential of EPR policy for lighting products in advancing circular economy strategies.

1.2 Research Aim and Questions

The aim of the thesis research has been to address the gap in knowledge of existing EPR policies as they relate to lighting products specifically. The research aimed to evaluate these policies to identify best practices and challenges, with particular regard to the issue of critical materials and closing materials loops. The particular contribution of this research has been to address the need for increased collection and recycling of end-of-life lighting products with analysis of the actual performance of current policies, identifying factors in best practices as well as other influential factors, and to discuss the challenges. The research also aimed to be policy relevant; therefore the implications of the findings for future policy are also considered.

The research questions guiding this study are:

RQ1: How have existing EPR policies in Europe addressing collection and recycling of energy-efficient lighting products been performing?

RQ2: What are the factors explaining countries with high operational performance for the collection and recycling of lamps?

RQ3: What is the practice and potential for closing material loops, particularly for critical materials, in energy-efficient lamps in Europe?

This research is framed by the research project "Policy instruments and business models for closed material loops" financed by the Swedish Energy Agency (project number 37655-1). The original research proposal was written by Dr. Thomas Lindhqvist and Dr. Naoko Tojo, and reviewed and approved by this Agency. The more detailed research design was then developed for this research independently with guidance from academic supervisors. This licentiate dissertation gives an overview of the approach and methods used in the research resulting in the two published research articles and conference paper. It summarizes and discusses the main findings from these research papers but also includes additional background to the research process and findings that were not included in these papers. The papers served as a starting point for development of other components of the research project, including a Master's thesis exploring EPR for lamps in the Netherlands and UK (Phadtare, forthcoming). This dissertation research is the first part of PhD research and therefore has an aim to explore the merits of the product-specific and case-specific approach to evaluation of the WEEE Directive performance. It has also served to identify important remaining research gaps, which are discussed in the context of further research in the concluding section. In this way, this licentiate dissertation also serves as reflective input for continuation of the PhD research.

1.3 Scope and Limitations

The geographical focus of the research is mainly limited to European countries, which reflects the scope of the Swedish Energy Agency research project. However, relevant examples from the U.S., Japan and other countries were obtained through involvement in conferences, events such as the Global Efficient Lighting Forum, and as other contexts came up in the issues reviewed in the literature. This is also the case with the focus on lighting products – while, the focus on this research was scoped to lighting products as much as possible it was often the case that WEEE, critical materials, or EPR in general was the topic of literature or discussion. Inclusion of the more general literature helped in identifying where the findings could be more generalized.

The WEEE Directive is the main focus of this research. It is noted that the Restriction on Hazardous Substances in EEE (RoHS) Directive (2002/95/EC and 2011/65/EU) is also part of the EU's EPR policy package (van Rossem et al., 2006) and its effect on design has been discussed in prior research (see e.g. Gottberg et al., 2006) and it is not a focus of this research. The EU Ecodesign Directive (2009/125/EC) also has an indirect effect on EPR policies and significantly influences energy efficiency (and possibly more design attributes in future) of lighting products (OECD, 2014). The role of the Ecodesign Directive is also not a focus; however, it is discussed in the context of future research.

The most significant limitations with this research were encountered with the data quality for collection and recycling statistics, particularly in Eurostat and earlier data. Also data on costs were not made available, even upon request, which limited the ability to examine cost effectiveness of different EPR programs for lamps. It was also difficult to obtain reliable cost estimates for externalities addressed in the value considerations of primary versus secondary material supply. These issues are also discussed in Paper I.

1.4 Structure of Thesis

This thesis presents in Chapter 2 an overview of relevant concepts and theories underpinning and developed in this research. Chapter 3 presents a brief summary of the research design and methods. Further details of the design and methods can also be found in the appended papers. Chapter 4 presents and discusses the findings of the research overall and some of the particular findings from the published papers. Lastly, Chapter 5 revisits the research questions and discusses the implications of the conclusions for future research. The appendices of this thesis contain further details on methodology, including details of interviews and correspondence, as well as the published papers.

2. Theories and Concepts

This chapter gives a more general background to the fundamental concepts and theories underlying the approach and analysis of the research in this licentiate dissertation. These include life cycle thinking, extended producer responsibility, and policy evaluation.

2.1 Product Life Cycle and Value Chains

The focus on lighting products as a case for evaluating EPR policy necessitated development of deep knowledge about lighting products and the materials that are used to manufacture and to potentially later be recycled from such products. A life cycle thinking approach helps conceptualize environmental problems as system-level issues by considering all of a product's environmental aspects from cradle to grave or cradle to cradle. Life cycle thinking is also important when considering unintended consequences of improvements leading to shifting environmental impacts from one life cycle phase to another (Mont & Bleischwitz, 2007). Life cycle assessment (LCA) is a useful tool for demonstrating how and why this might occur and LCAs of lighting products were a starting point for understanding the environmental impacts of lighting products and the importance of end-of-life management. Such understanding underlies the concept of EPR.

A simplified life cycle of a product in Figure 1 shows that end-of-life management of a product involves choices and potential interactions with other life cycle phases. For example, there are choices in whether and how end-of-life products are collected and put back into the value chain as used products, components, or materials, burned for energy recovery, or landfilled. Economic considerations are also involved along the life cycle of a product that can be examined as the value chain. There may also be additional considerations of value beyond economic that can influence decisions along the value chain as well.

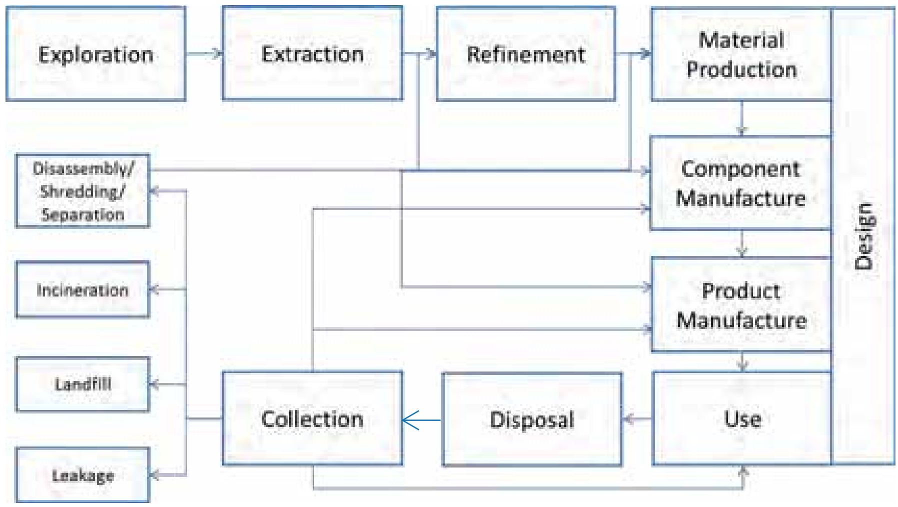

Figure 1. Generic life cycle / value chain of product

2.2 Extended Producer Responsibility

The principle of EPR is defined as ''a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to take-back, recycling and final disposal of the product'' (Lindhqvist, 2000, p. 154). Lindhqvist (2000) further illustrates that EPR entails different types of responsibilities: liability, physical, financial, and provision of information (i.e. informative).

The Organisation for Economic Cooperation and Development (OECD) defines EPR as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle", which is characterized by:

> 1. *the shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities;*
> 2. *the provision of incentives to producers to take into account environmental considerations when designing their products.*
>
> \- (OECD, 2016)

The definition illustrates the range of issues from ecodesign to waste management that can be integral to EPR policies; involvement of national states, private producers, and local municipal actors; as well as the range of responsibilities that can be allocated. These responsibilities can be distributed differently amongst actors in different EPR interventions, but it is argued that placing financial responsibility on the producer is an important mechanism for creating incentives to minimize costs and environmental impacts, which is a core component of EPR (Kalimo et al., 2012).

It should be noted that, in the case of EU WEEE Directive, there is evidence of ecodesign changes in anticipation of the legislation (Tojo, 2004), however, it has also been argued that the full potential of design incentives have not been fully realized in the actual transposed legislation or practice (van Rossem et al., 2006), which has led to some debate about whether they can actually be practically achieved (Huisman, 2013). However other researchers have noted the potential of EPR to achieve these aims and have argued that such aim is at the core of EPR (Kalimo et al., 2012; Tojo, 2004).

2.3 Policy Evaluation

Policy analysis and evaluation has been important in framing this research. The term evaluation can have different and even controversial definitions. This research took as its starting point evaluations as defined in Vedung (2009): "careful retrospective assessment of the merit, worth and value of administration, output and outcome of government interventions, which is intended to play a role in future, practical action situations"(p. 3). Policy evaluation can be considered as a practice, but increasingly also as a discipline in itself (Scriven, 2003). Theory-based evaluation[3] includes a modelling of how intervention (program) should theoretically function, as opposed or compared to how it actually functions in reality (Bickman, 1987). This involves reconstruction of an intervention theory – i.e. breaking down the policy to its inherent assumptions about actors and actions that lead to immediate, intermediate and long-term outcomes (Vedung, 2009).

When the theory is mapped, empirical checks can be made that the assumptions and actions are indeed occurring. Another level can also involve empirical checks that these are occurring *because* of the intervention (i.e. confirming causation). In this way, theory-based policy evaluation using intervention theory and empirical checks can be argued to be akin to process tracing. Process tracing is a case study research technique for capturing causal mechanisms to derive or test theories and explanations (Bennett & Checkel, 2015). In the case of policy, it is the intervention theory which is being tested and the causal mechanisms being traced. The strength of using this technique to guide the empirical checking of intervention theory is its emphasis on collecting evidence from different sources

[3] Alternative terms include program theory or theory-driven analysis

and also widely considering alternative explanations. This in turn, can help make the conclusions drawn from the policy evaluation more robust.

Using intervention theory can also help to focus the scale (or multiple levels) of the policy (for example, from national to local) and identify stakeholders addressed by the evaluation (Mickwitz, 2003). It is worth noting that there can also be several intervention theories as different stakeholders can hold varying views on the intended outcomes of an intervention (Dahler-Larsen, 2001; Vedung, 2009). A stakeholder approach to the evaluation elaborates upon the basic intervention theory with the perspectives of key stakeholders. Identifying the primary stakeholders crucial to the intervention implementation also highlights sources for empirical checks. Intervention theories from the perspective of different key stakeholders can also be reconstructed to identify similarities, differences, and disagreements (Hansen & Vedung, 2010).

3. Research Design

This chapter gives an overview of the research approach and process. The first part gives insight into the epistemological framing of the research. Then the analytical framework for the evaluation of EPR policies is presented as well as a more detailed background description of the case selection in Paper I and the value analysis in Paper II. Lastly, a brief description of data collection methods is provided to supplement the descriptions in the appended papers.

3.1 Research Approach

This research is framed by critical realism, an epistemological framework that encompasses a wide range of ontologies, which has been argued as a necessity for interdisciplinary research and when researching complex sustainability issues (Bhaskar et al., 2010). The starting ontological approach for critical realism is that the world is "structured, differentiated, stratified and changing (Danermark et al., 2001, p. 5). The critical realist approach is arguably rooted in the positivist view of a world independent of human consciousness but also acknowledges in part some aspect of a subjectivist view of a world socially constructed because our view of the world is influenced by our own perspectives and limitations in understanding its true nature. Thus, critical realism views science as a continuous endeavour to improve our understanding of a changing, multi-level world. Danermark et al. (2005) also describe the particular emphasis critical realism puts on researching the causal mechanisms of events and reasoning to gain better understanding, as well as, the need for mixed methods.

This research can also be characterized as being situated between an interdisciplinary and transdisciplinary approach. The distinction between the two in academic discussions is often not clear as both deal with complex "real world" problems, but the main difference is the level of integration between disciplinary perspectives and cooperation amongst different actors (see e.g. Stock & Burton, 2011). A commonly highlighted characteristic of transdisciplinary research is that it works towards "co-producing solution-oriented and transferable knowledge through collaborative research" and "(re)integrating and applying the produced knowledge in both scientific and societal practice" (Lang et al., 2012). A transdisciplinary approach also includes the involvement of non-academic partners, which could take place throughout the research process, but also in the communication and discussion of results (Stock & Burton, 2011).

The approach taken in this research is reflective of the interdisciplinary background of the researcher, but also the complex sustainability issues at the core of the research problem. An interdisciplinary or transdisciplinary approach is argued as an appropriate approach for sustainability issues as they tend to be complex, containing different causes and outcomes on multiple levels (Bhaskar et al., 2010; Høyer & Naess, 2008; Stock & Burton, 2011). Both interdisciplinary and transdisciplinary research tend to start with the societal or "real world" problem (Lang et al., 2012; Stock & Burton, 2011).

Engagement and collaboration with non-academic actors added further transdisciplinary characteristics to this research. The research process involved not only more formal interviews, but also dialogues, workshops, and communication of results with many of the key stakeholders. Some of these were specifically organized for the research project "Policy instruments and business models for closed material loops" funded by the Swedish Energy Agency. There was also interaction, discussion and sharing of research results with relevant EU projects including SSLerate and Lighting Metropolis – both dealing with the uptake and demonstration of solid state lighting, where sustainable development and issues about resource efficiency and end-of-life management were also relevant. While results were reported and discussed with stakeholders, including the Swedish Energy Agency, the independent development of the research design attempted to avoid a possible pitfall of transdisciplinary research, namely an "epistemic drift" that can result from the influence of non-academic stakeholders on the research itself (Tranfield & Starkey, 1998).

3.2 Analytical Framework

3.2.1 EPR evaluation

The WEEE legislation regarding lamps, and its resulting transposition in the selected member state cases, is evaluated with a focus on environmental effectiveness. This is a common criterion for evaluating policy, and very relevant when the legislation has clear targets and aims (Mickwitz, 2003; Vedung, 2009). However, it should be noted that the goals of the WEEE Directive and the legislation transposed in the member states refer to WEEE collection overall, with few product level specifications. Moreover, while data is available about the collection and recycling of gas discharge lamps, as mentioned earlier, the quality of this data was a limitation in this research. When relevant data or explicit goals are lacking or untrustworthy, intervention theories are used to support the evaluation of the policy (Kautto & Similä, 2005).

The intervention theory of the WEEE Directive has been used in earlier research by Tojo (2004) and Manomaivibool (2011). The identified goals of the Directive are also rooted in EPR theory and include: 1) ecodesign of products to prevent waste, 2) efficient use of resources and the retrieval of valuable secondary raw materials, and 3) improved waste management systems (Lifset, Atasu, & Tojo, 2013; Lindhqvist, 2000; Manomaivibool, 2009; Tojo, 2004; Van Rossem et al., 2006). The basic framework in these works (Figure 2) is the starting point for the intervention theory mapped out for lighting products in the case countries.

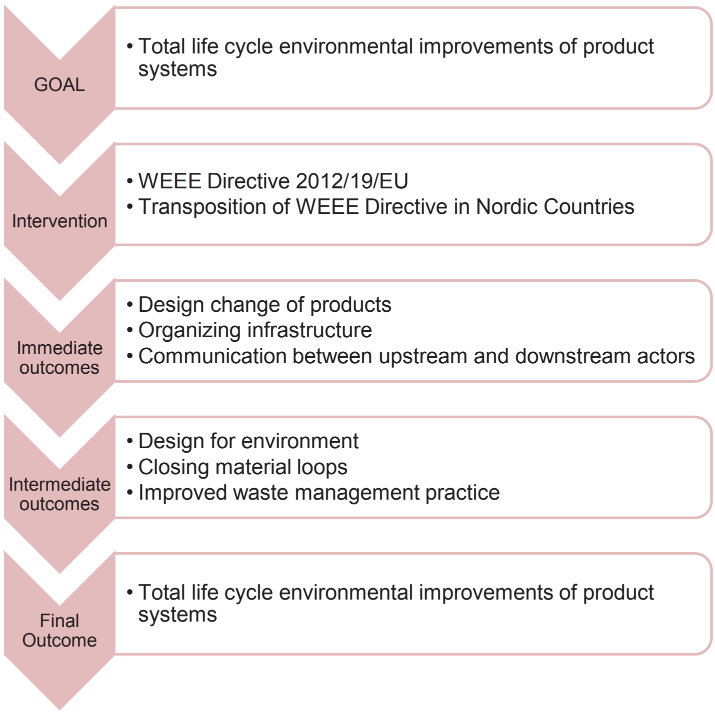

Figure 2. Simplified Intervention theory for EPR policies used in Paper I, based on Tojo, 2004.

3.2.2 Case studies

As is often common to case study research, the process in this thesis has been iterative (George & Bennett, 2005). As mentioned, most existing literature focusses on WEEE in general rather than lighting specifically. An initial review identified the Nordic countries as high-performing countries in regard to WEEE collection and recycling (Román, 2012; Ylä-Mella et al., 2014). Other countries identified through literature and background interviews included Austria, Belgium, Germany, the Netherlands, and Switzerland. The statistics for gas discharge lamps for these countries were then examined, which added Latvia as a possible case because of its very high collection and recycling rate for gas discharge lamps. Figure 3 shows the comparison of country data for gas discharge lamps based on collection in kilograms per capita (aligning with the original WEEE Directive target methodology) while Figure 4 shows country comparisons based on tonnes collected compared to an average of the previous three years put on market[4] tonnes (aligning with the recast WEEE Directive target methodology).

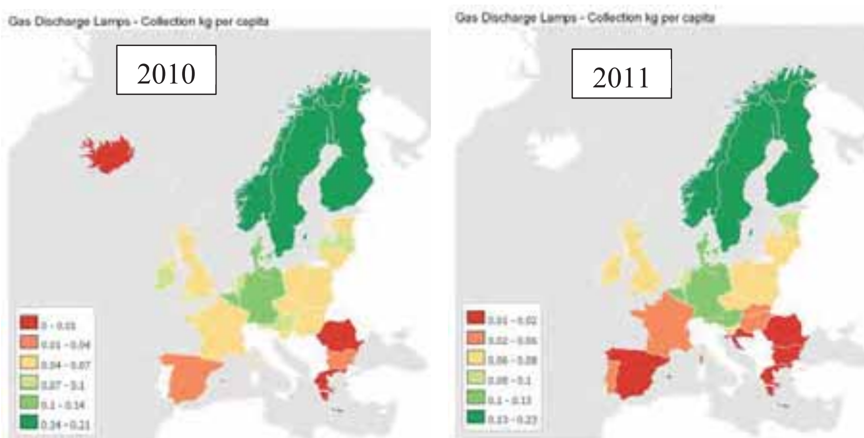

Figure 3. Gas discharge lamp collection kilograms per capita (2010-2011). Source: Eurostat data

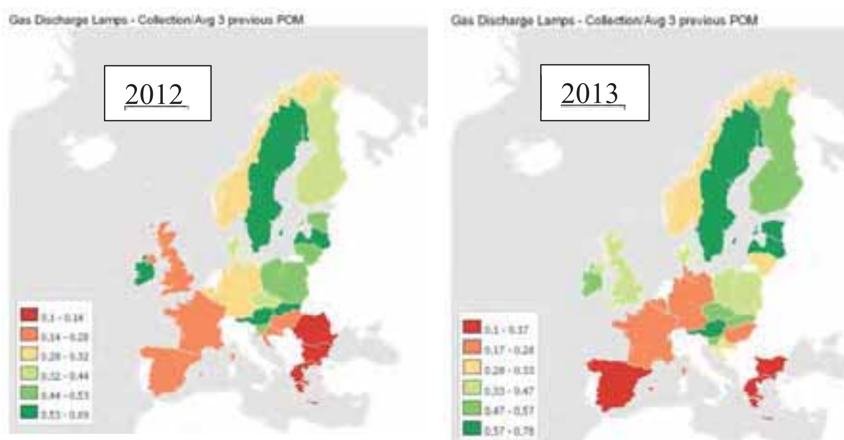

Figure 4. Gas discharge lamp collection collected tonnes compared to an average of the previous 3 years put on market tonnes (2012-2013). Source: Eurostat data

[4] Defined as " supply of a product for distribution, consumption or use on the market in the course of a commercial activity, whether in return for payment or free of charge" (Balde et al., 2015).

Following examination of the data, (generally grey) literature was used to map out the basic EPR systems for lamps in these countries. After the initial comparison, the Nordic countries were selected as cases for more in-depth research for Paper I. This case selection also allowed for comparison to the earlier research (Román, 2012; Ylä-Mella et al., 2014) which highlighted these countries as best practice examples for WEEE, identifying factors such as the high per capita collection rates as well as the collection/recycling network and infrastructure. Selection of the same cases allowed for testing of whether this performance was similar when examining lamp waste in particular, rather than overall WEEE level.

This case selection is indicative of a "most similar" case selection (George & Bennett, 2005) as these countries share similarities in many respects, but with key differences in the WEEE and lighting EPR systems that made for an interesting comparative study. The more similar the cases being compared are in the EPR system aspects, the more likely it was to be able to see any differences in effectiveness that could be attributable to behavioural aspects independent of the EPR systems. A more heuristic case study approach was initially used to identify and confirm variables that contributed to effectiveness. First the dependent variable of environmental effectiveness needed to be defined and unpacked in terms of EPR. The WEEE Directive targets and measurement of country performance in relation to the targets, which focus on collection and recycling rates, could be argued as a reasonable proxy of effectiveness.

While the Nordic case selection was the focus of the research for Paper I, the overall project and thesis research also looked at other countries with indications of high performance (from statistical data), for example Switzerland, Latvia, Austria, Germany, Netherlands and the UK -the latter two the cases selected for research by Phadtare (forthcoming). In these country cases the basic EPR systems were examined based on the framework developed for the Nordic cases and findings compared to the Nordic case findings.

3.2.3 Value analysis

Paper II reflects the economic geography background of the lead author in framing the global value chain research approach. In this approach establishing what "value" is in the value chain is dependent not only on the processes of upgrading materials into components and products, but also on the interactions and choices of actors along the value (for a full exploration of this, see Machacek, 2016). The discussion of value for secondary supply stems from a wider consideration of costs and benefits, in which externalities are considered but also the social construction of value in the value chain (Foster, 2006). This discussion is then continued in Paper 3 which examines the question of "shared value" as argued by Porter and

Kramer (2011) in which productivity along the value chain can be viewed in light of not only a firm's view of value, but also society's and there can be strategies for increasing both. The idea of a firm and societal value is further expanded to a general stakeholder perspective of value. To conceptualize this, a simplified version of a value mapping tool, based on the research of Bocken et al. (2013), is used to consider the value of end-of-life lamps between and amongst different stakeholders, including network actors (e.g. firms, suppliers, etc.), customers, society and the environment.

3.3 Data Collection

Data for this research was collected from a variety of sources and using different methods, often referred to as triangulation, to increase robustness of the findings. A brief overview is presented here, in addition to details provided in the appended papers.

3.3.1 Literature review

Several stages of literature reviews were conducted for this research. The initial literature review focused on the current state of knowledge about EPR systems more generally, as well as specific studies about the end-of-life management of lamps. This included reviewing previous doctoral theses and other academic literature on WEEE and EPR, consultant reports, company reports (from stakeholders identified in the intervention theory), and LCA literature on lamps.

Subsequent literature reviews were more focused on the selected cases and specific issues that had been identified, most notably the issue of critical material use and recycling of lamps.

3.3.2 Quantitative data

Quantitative data was collected from publicly available statistics from Eurostat, existing survey data, data from national authorities, and reports published by entities such as producer responsibility organizations (PROs)[5] and municipal waste organizations. Collecting from multiple sources revealed disparities in data, which then required follow up and checks to determine validity.

[5] Producer Responsibility Organizations are cooperative industry associations that act on behalf of its member companies to meet their EPR obligations. Generally PROs bear the operational responsibility of managing WEEE.

3.3.3 Interviews

Key stakeholders identified in the initial intervention theory analysis were contacted and interviewed when possible (a list of interviews can be found in Appendix A). These included the administrative/government authorities, Producer Responsibility Organizations, national and municipal waste organizations, recyclers, and retailers for each case. In each case, stakeholders were interviewed with a core protocol developed for their stakeholder group (see examples in Appendix B). The questions for these protocols are derived from the factors and questions identified above, after further refinement of the variables. The interview format was most often semi-structured to allow for additional comments and in the case that the respondent identifies further factors or variations of factors. Where possible, the interviews were also in person and this also enabled observations of EPR systems (particularly in Denmark and Sweden, to a lesser extent in Norway, Germany, and Switzerland).

4. Findings and Discussion

This chapter presents and discusses findings from the appended papers, but also additional research findings that came as background or continuation of research in the papers. The chapter begins with general findings about the uncertainties of performance of the EPR systems for lamps based on statistics alone. Then the findings of the theory-based evaluation are presented.

A general example of mapping out the intervention theory for the cases is shown in Figure 5 below. This chapter summarizes these findings, but also includes additional findings not included in the papers. An overview of the findings on each of the three intermediate outcomes (i.e. improved waste management, efficient use of resources, and ecodesign) is given in this section, with particular focus on the underlined issues identified.

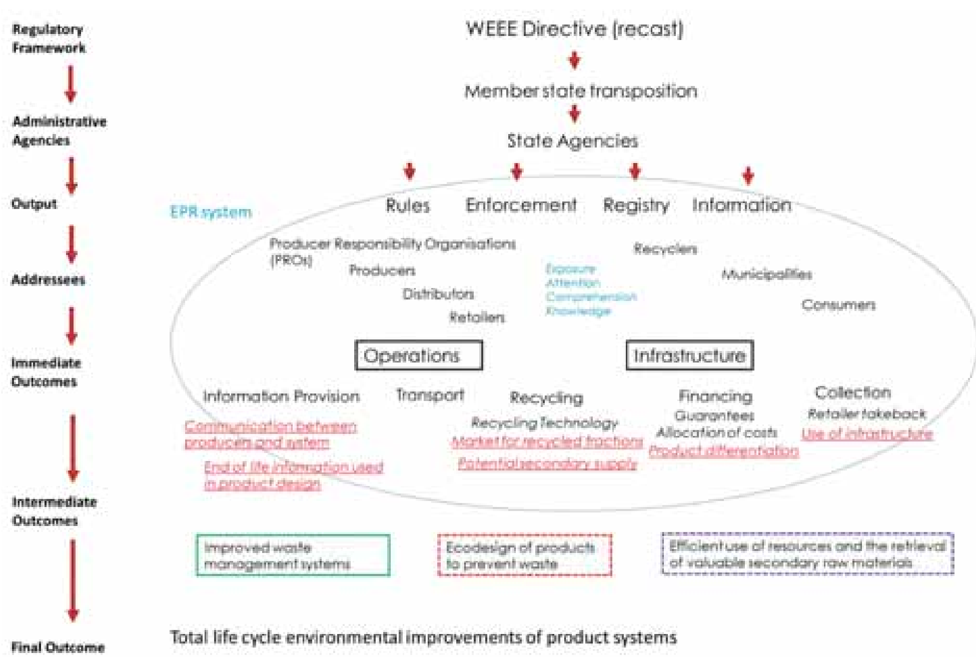

Figure 5. Mapping out WEEE Directive intervention theory

4.1 Measuring Performance by Statistics

The analysis of the effectiveness of the lamp EPR systems began using reported Eurostat collection and recycling figures, but the limitations of this data and the importance of not drawing too many conclusions based on this data alone became increasingly clear. First, the data required checking with producers and authorities, particularly if trying to get a better picture of household versus business waste. Differences were found in how countries could estimate put on market and collection figures and how these were reported to Eurostat or the member state countries. For some countries, major differences were found when changing the methodology of collection statistics, e.g. collection versus average of previous three years put on market, historical (assuming six year average lifetime) or waste generation modelling. In this regard, the Nordic countries had more consistent figures than many other countries.

Even when figures were confirmed, there could be alternative explanatory factors for the apparently high operational performance of a system. For example, based on the Eurostat data, Latvia appears to have a very high performing collection and recycling system. The numbers were confirmed by different stakeholders, however, there were also different explanations found. The lamp PRO in Latvia, Ekogaisma, explained that they had to reach a collection rate of 50% measured in pieces same year, which changed in 2014/15 to 50% measured in weight) (J. Bielefeldt, personal communication, 24 November 2014). This is effectively a collection target specifically for lamps and could be a motivating factor. Another explanation was that while Latvia does appear to have good lamp recycling facilities and was also processing lamp waste from Estonia and Lithuania, the lamp waste that had been collected was primarily historical waste from closed factories rather than new waste (R. Bendere personal communication, 3 October 2016). Ekogaisma literature confirmed current challenges with consumer awareness of proper disposal, but there were also efforts to address this and to increase convenience of the system (see Ekogaisma, 2015). Ekogaisma is required to have three collection points in each of Latvia's ten regions (J. Bielefeldt, personal communication, 24 November 2014), but it was remarked that the level of convenience for the average consumer is still low (N. Belmane and R. Bendere, personal communication, 3 October 2016). So while there appears to be good recycling capacity in Latvia, it remains to be seen how the collection infrastructure, particularly for households, develops and it would be worth revisiting this country as an in-depth case in the future.

The initial experience with explaining collection and recycling data in Latvia illustrates the shortcomings of relying on this type of data alone as a measure of effectiveness. The research approach based on EPR evaluative framework and theory-based evaluation enabled a much richer evaluation of effectiveness.

4.2 Improved Waste Management

Paper I presented the detailed findings about the performance of waste management for lamps in the Nordic countries. While counterfactual scenarios are difficult to reconstruct, there was evidence from government documents (e.g. from the Swedish Chemical Agency – see Kemikalieinspektionen, 1998) describing the small-scale voluntary collection and recycling, mainly of business lamp waste, and concluding that this performance was inadequate and in need of improvement. In addition, stakeholders interviewed observed the improvement of collection and recycling of lamps in response to EPR legislation, confirming that without EPR legislation there would not be a good system for lamp collection and recycling due to the costs of such operations. The stakeholder interviews and literature both reiterated the importance of EPR for collection and recycling of this product group to avoid environmental harm and for resource recovery.

Mapping of the intervention theory also helped identify the factors and best practices that contribute to high collection and recycling rates in the Nordic countries. These are shown in the top half of Figure 6 and provide a descriptive framework for identifying factors in well-performing EPR systems.

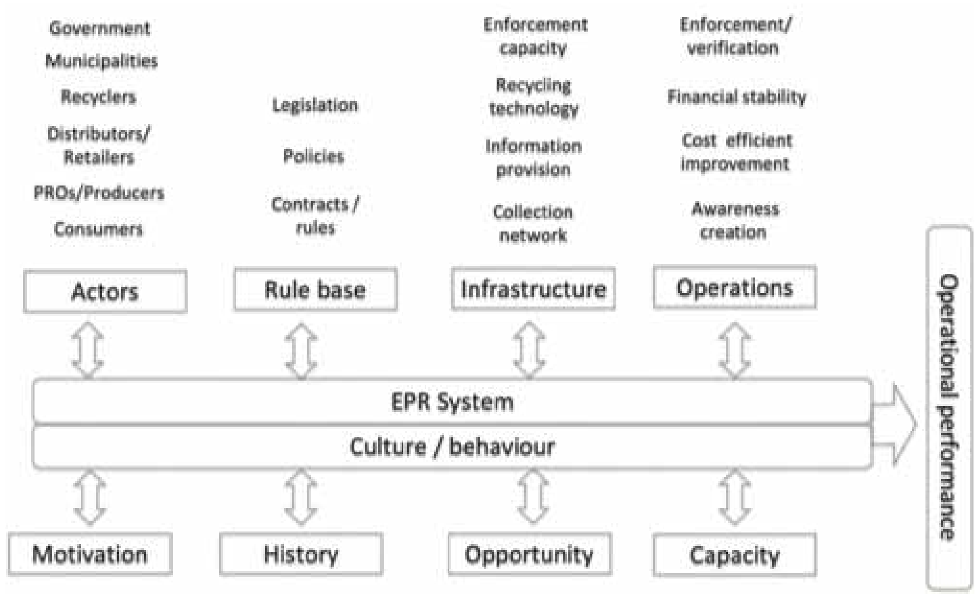

Figure 6. Common identified factors contributing to effective operational performance of an EPR system.

4.2.1 Culture and behaviour

A recycling "culture", "behaviour" or "history" was mentioned often in the stakeholder interviews as an explaining factor for highly effective operational performance of EPR systems in the Nordic countries. These were often perceived as independent of the EPR system. These factors were not as well identified in the intervention theory analysis, but could be a potential alternative explanation for high operational performance. Paper 1 presented a version of Figure 6 with only "culture/behaviour" as identified factors. Subsequent research following the article included a literature review of previously identified determinants of recycling behaviour to further unpack these factors and explore the relationship between these factors and the EPR system factors.

In literature recycling behaviour has been explained in many ways, most relying on the theory of planned behaviour, which hypothesizes that intentions are influenced by attitude, subjective norms and perceived control. Previous studies of recycling behaviour have most often utilized quantitative methods with more or less explaining factors of the determinants of recycling behaviour, most commonly covering attitudinal/motivational aspects, situational contextual factors, capabilities and awareness, and habits and routines (see e.g. Darby & Obara, 2005; Meneses, 2015; Saphores, Ogunseitan, & Shapiro, 2012; Sidique, Lupi, & Joshi, 2010; Tonglet, Phillips, & Bates, 2004; Vesely, Klöckner, & Dohnal, 2016; Wang et al., 2011).

Melissen's review with a focus on recycling behaviour of small electronics (Melissen, 2006) provided a more simplified synthesis of important factors for this behaviour using the Poiesz triad model (1999) of motivation, opportunity (i.e. having access to recycling), and capacity (i.e. the knowledge and awareness about how to recycle). These broad factors captured the recycling "culture" findings from the research and have been incorporated into the framework shown in Figure 6. The review of literature revealed that many of the identified determinants of recycling behaviour, or recycling culture, are likely influenced by contextual factors such as effective EPR system, and the significant factors in the EPR system are also likely influential in fostering a recycling culture.

In line with Melissen's synthesis, an effective EPR system provides motivation, convenience and knowledge for consumers in the form of enforcement, establishment of a convenient collection network, and awareness creation.[6] These aspects are stipulated by EU WEEE legislation, but there can be differences in how they are actualized in the individual member state EPR systems (see e.g. van Rossem et al., 2006). The fact that opportunity is a contextual factor means that this is already covered by the other factors identified in the collection and

[6] This also aligns with previous EPR research and guidance see e.g. Tojo, Lindhqvist, & Davis (2001) who also suggest financial incentives can also motivate consumers.

recycling system, if these are considered in terms of convenience for the consumer and awareness raising amongst consumers. It should also be considered that motivation and capacity of some actors could be intrinsic and based on values (separate from the EPR system) as well as extrinsic (incentivized by the system).

In the initial research, related to values was the reference to a recycling "history". This could be an explanatory factor; for example, how long there has been EPR or related recycling legislation in the country. The influence of this factor from the cases examined is not readily clear. Swedish stakeholders interviewed remarked that the country's earlier adoption of EPR practices were influential in making a high performing WEEE system. The Finnish stakeholders also mentioned that the Swedish system enabled faster learning in setting up an EPR system in that country, despite a shorter history. Lastly, German stakeholders remarked despite the country's relatively long history with EPR systems, there were still challenges in how the system is operationalized that impeded better performance. So, while history of EPR in a country may be a contributing factor to high performance, it is not necessarily always the case.

4.2.2 Incentives for further improvement

Recently the WEEE Directive 2012/19/EU has been recast with revised targets, not on a kg/capita basis, but measuring collection performance (from 2016) based on the ratio between the collected amount and the average weight of EEE put on the market in the three preceding years. The collection target is set at 45% in 2016 and will rise to 65% in 2019 (Art. 7). Elsewhere in the legislation gas discharge lamps are specifically mentioned as a priority WEEE category (e.g. Article 5) Indeed, avoiding environmental impacts from the mercury waste gas discharge lamps has been an argument for "collecting as much as possible and in a safe way (avoidance of breaking) and to treat them properly" (Huisman et al., 2008, p. 281). Despite this, lamps are small, light, dispersed, and costly to treat – which can make them less attractive in meeting general WEEE collection targets.

Article 7(6) of the WEEE Directive also mentioned gas discharge lamps to be considered for an individual collection target. A subsequent report commissioned by the EU Commission examined different scenarios for the economic, environmental and social impacts of setting individual collection targets to WEEE categories (Magalini et al., 2014). The report ultimately did not recommend separate targets, citing the context of many member states already having difficulty in reaching the general WEEE targets. The report instead recommended that such actions take place on a voluntary and individual member state basis. Already France has done this, stipulating lamps should be collected at 45% (of previous 3 years put on market) until 2019 when this rises to 65%. In response, the

PRO for lamps in France, Récylum, has already stated that the 2019 target will be a significant challenge (Récylum, 2015).

The research in this study showed that Sweden already appears to be achieving high rates of return for lamps. The transition of the waste stream towards LED lighting further complicates the question of individual collection target as the mercury in the lamp waste has been a large motivation for the collection of the stream so far. An individual target could be means of further motivating improvements of the operational performance.[7] For already high-performing countries, an individual target at the same level as the general target (as France has done) may not motivate continuous improvements as the target is already achievable. In this case, framing individual targets to reflect an ideal target and taxing the difference might provide more continuous incentives while acknowledging the challenges (e.g. similar to Norway's tax on beverage packaging, which reduces from 25% and does not apply above 95% of collection and recycling – see Infinitum, 2014).

4.3 Efficient Use of Resources and Retrieval of Valuable Secondary Resources

Lamps can technically be recycled at very high rates and the WEEE Directive states that "for gas discharge lamps, 80 % shall be recycled" (Annex V). Article 11 stipulates that the "achievement of the targets shall be calculated, for each category, by dividing the weight of the WEEE that enters the recovery or recycling/preparing for re-use facility, after proper treatment in accordance with Article 8(2) with regard to recovery or recycling, by the weight of all separately collected WEEE for each category, expressed as a percentage."[8] Figure 7 demonstrates that most countries in the EU are reportedly meeting the 80 % recycling target for collected gas discharge lamps.

[7] Furthermore Magalini et al., 2014 found the feasibility of implemented such individual targets in Sweden to be "high" (also in Denmark, while "medium" for Finland).

[8] Prior to 2014 Eurostat asked Member States to use the sum of treated WEEE as the denominator for the calculation of the recycling and reuse rate, as opposed to the collected WEEE. Some member states also distinguished recovery and recycling in gas discharge lamp data prior to 2014.

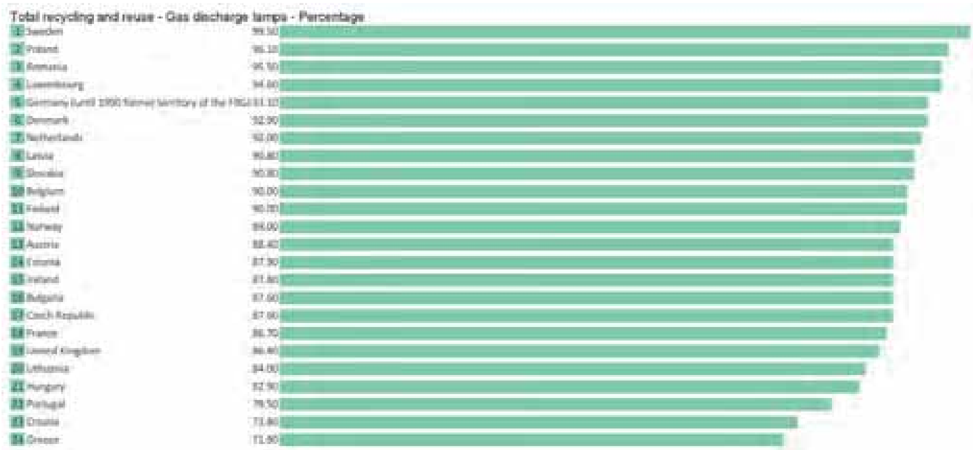

Figure 7. Gas discharge lamp % recycled (of tonnes collected) in 2011.
Source: Eurostat statistics

However, a closer examination of the data shows different interpretations and discrepancies in the reported data. For example, Slovenia has been excluded from Figure 7 because it reported a higher number in tonnes for "total recycling and reuse" (179 tonnes) for gas discharge lamps than what was reportedly collected (162 tonnes). It was necessary to examine recycling activities for gas discharge lamps beyond the data to get a more accurate picture. This is also described in Paper 1. In the Nordic countries it was found that, in the lamp recycling process, glass is the main fraction recycled by weight (around 40% for a compact fluorescent and up to 80% of a tube), followed by metals (approximately 20-30%), plastic (approximately 20%) and mercury/phosphor powders (2-3%) (Nordic Recycling, 2016). The plastics are generally incinerated while the mercury/phosphor powders are generally stored in hazardous landfills (this is further discussed in the next sections). This was later checked with recyclers in Switzerland, Belgium and Austria with similar findings.

Paper 1 presented the finding that there were generally no closed loops for the recycled fractions in the Nordic countries, with the exception of rare earth phosphors. Though producer and PRO material on websites often communicated glass as being used for the production of new lamps, it was found that this was the exception rather than the general practice. Examples found of closed loop recycling of the glass were limited to countries with close proximity to lamp production and to systems where the tubes were processed separately rather than all lamps together in a shredder. For example fluorescent tubes in Belgium and Netherlands reuse the glass tubes using the end-cut method (Phadtare, forthcoming), but even this loop is disappearing as lamp manufacturing is moving out of Europe (J. Ornelis, personal communication, 14 November 2016; also Swico, SENS, & SLRS, 2016).

For the Nordic countries examined in Paper I, it was found that low quality of the glass fraction, possible contamination with mercury, and high transport distances/costs to lamp production facilities were found to be barriers for the use of recycled glass in many applications. In most of the Nordic countries (as well as for mixed fractions in the other EU countries examined) this fraction was mainly used as landfill cover, despite several PRO aims to use as much of the recycled fractions as possible back in the production of new lamps. In this application, the glass fraction is considered recycled, though arguably the use is quite close to what is considered "backfilling" by Commission Decision 2011/753/EU,[9] which is not considered recycling by the Article 3 of Directive 2008/98/EC (referred to in Article 3 Directive 2012/19/EU).

While LEDs currently represent a small fraction of the waste stream, this is growing and already represents unique challenges as LEDs are essentially an entirely different product. Moreover LEDs are rapidly evolving, which makes anticipation of what the waste stream will look like more complicated. For example, LED designs now incorporate increasing use of mixed plastics rather than metals and more integrated LED with luminaire designs. The mixed plastics, in particular, were noted by recyclers to represent a challenge for recycling, particularly at the 80 % recycling target.

4.3.1 Critical materials

The beginning of this research in 2014 coincided with much interest worldwide in the area of critical material strategies and recycling processes for critical materials. Many studies in the last decade worked to characterize the flow of these materials into products and it was known that electronics were a significant application. When looking only at materials flows, one would not expect much attention for lighting products, as they are small end uses with only 7% of rare earth elements (REE) estimated to be used for phosphors. However, the picture changes when looking at the global value chain for rare earths where lighting phosphors represent 32% of the value for the rare earth market (Binnemans et al., 2013; Schüler et al., 2011). Studies found there to be very little recycling of these materials (less than 1%) and despite indications of technical feasibility, it was noted that the small amounts of REE and dispersed nature of the products were significant barriers to recovery of this value (Binnemans & Jones, 2014; Binnemans et al., 2013).

9 According to Article 1(6) of Commission Decision 2011/753/EU: 'backfilling' is "a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials"

Binnemans et al. (2013) and later others, e.g. Guyonnet et al. (2015) and Rollat et al. (2016) provided material flow estimates of the potential supply of rare earth materials from recycled lamp materials. The authors acknowledged there were uncertainties in their assumptions about recycling rates. For example, Binnemans et al. used a high, medium or low scenario that considered the technical efficiency of recovering the REE from phosphors based on the demonstrated efficiency of existing and tested processes (e.g. Solvay's process), but the estimated global collection rates (40%-70%) were not based on observed collection rates or policies. The papers mapping potential supply of REE from phosphors all recommend increased collection of waste lamps, but do not make any further or more detailed policy recommendations. In contrast, Paper II aimed to address this gap by further developing the recycling rate estimates considering the actual reported recycling rates for lamps based on existing policy measures (building upon research for Paper I), as well as, the potential from further policy development. This was then multiplied by the efficiency of the lamp recycling and the efficiency of the REE recycling process (these last two rates had not been considered separately in previous studies).

Considering actual collection rates globally for gas discharge lamps, it became clear that a 40% collection rate assumed in the pessimistic scenario by Binnemans et al. (2013) was in fact still optimistic as this rate was only achieved by countries (or U.S. states) with mandatory EPR legislation in place (and as mentioned, even within the EU there was not uniform performance at this level). Instead we found after examining policies and practices globally that a 15% collection rate would be a better estimate for a low-end collection rate, reflecting slow development from the status quo more accurately. We then developed medium and optimistic scenarios from this base of current policy experience (i.e. projecting EPR policies implemented in other major economies and then high performance of policies based on the best practice examples explored in Paper I). Linking the collection and recycling rates to current policies and practices gave better insight into what policies are needed, where, when, and to what level these policies need to perform in order to achieve the projected potentials.

The research for Paper II also highlighted the important role EPR policy has already played in incentivising collection and creating resource recovery opportunities. Lamps becoming an attractive waste stream for research, pilot projects and eventually commercialisation for the recovery of REE could be considered a positive consequence (at least in part) of the WEEE Directive in the EU. First, the Directive has been the impetus for setting up collection and recycling infrastructures in many countries, and for refining existing systems in others. It highlights gas discharge lamps as a priority for collection (Article 5). It also sets a standard to recycle 80% of the gas discharge lamps collected (Annex V) and requires the removal of mercury in the treatment (Annex VII). The unique characteristics of the lamps and the special requirements for them in the WEEE

Directive (and in transposition into the member state legislation) resulted in lamps being processed separately from the rest of WEEE and with a process targeted for mercury removal, which also happens to be the same fraction as the REE phosphors. Thus the unique characteristics of lamps isolated this waste stream from the general trend of increasingly mixed WEEE being shredded together for recovery of only common metals.

Another unique contribution of Paper II was the modelling of the secondary supply of REE in comparison to the primary supply. This revealed the context of primary and secondary supplies in competition (for the most part as primary met most of the projected demand). While the issue of competing primary and secondary sources is not new, it has not been addressed explicitly by prior models of potential secondary supply of rare earths from recycling lamp phosphors. It is acknowledged that only the primary and secondary supply for lamp phosphors are modelled and that the reality is much more complex; however, the modelling helped to highlight important challenges for secondary supply. Despite the high concentration of REE in lamp waste and high efficiency of recycling REE from the waste phosphors, secondary supply still has lower volumes than primary supply and there are negative externalities in the primary supply and positive externalities in the secondary supply. These are further discussed in Paper II and Paper III as well as Section 4.2.2 of this thesis.

Since publication of Paper II, REE recycling from waste lamps has discontinued due to the only commercial process, operated by chemical company Solvay in France, closing its rare earth phosphor recycling process at the end of 2016, citing economic factors (Leoty, 2016). So while the recycling of lamps to treat mercury continues, the recycling of lamps to recover REE has ceased. The case of lighting products supports the argument for more detailed end-of-life treatment requirements that could incentivize more innovative recovery technologies, in particular for scarce materials (Kalimo et al., 2012). Such requirements could give more certainty and stability to critical material recovery initiatives.

Switzerland has already proposed legislation moving in this direction, with the proposed changes to the Ordinance on the Return, Take Back and Disposal of Electrical and Electronic Equipment (ORDEE) to require recovery of scarce metals from technological equipment wherever feasible. A research project, funded by the Federal Office for the Environment (FOEN) has already begun work investigating the costs and benefits of such efforts on an individual product level. The demonstration project found that indium from monitors could be recovered for a small increase in the advanced recycling fee (ARF) – by approximately CHF 0.2-0.5 / product (EUR 0.19-0.47/USD 0.2-0.49) (Swico, SENS, & SLRS, 2015). However, the report notes the technology for indium recovery is still at an early stage so there are high uncertainties. The Swiss legislation could have interesting implications for critical materials in lighting, particularly REE in fluorescent lighting (which is arguably a more mature process than the indium recovery from monitors reviewed in the FOEN project) as well as indium and gallium in LEDs. It is likely that the "feasibility" of recovery of these materials will also depend on who is willing to pay and how much, which is discussed further in the next section.

4.3.2 Value considerations

Paper II discussed the value considerations for secondary supply of REE from lamp phosphors, highlighting that the value is dependent on which stakeholder perspectives are being considered. The case of Solvay, for example, identified the potential value of closing material loops for REE in lamps from a strategic supply chain management perspective. This discussion was the point of departure for Paper III, which then examined the case of lamps in comparison to prior research in examining WEEE and aimed to explore the stakeholder perspectives of value more systematically utilizing a value mapping tool developed by Bocken et al. (2013).

Paper III considers that there is potential value to producers in meeting recycling targets under legislation, but also revenue from sold recycled fractions. There was evidence that closing material loops for lamps also had value to producers and producer responsibility organisations as demonstration of corporate social responsibility. Similar to Solvay's case in Paper II, there could also be potential value from security of supply for critical materials essential for particular products. This would have value not only for Solvay as a supplier of high purity rare earth for phosphors, but also producers of lamps. This value was demonstrated by the interest of producers like Osram and Philips in developing their own phosphor recycling processes during the high REE prices in 2010 (and the limit of this value as interest waned following the falling REE prices).

The environment could be considered in many ways to be the primary stakeholder in EPR legislation through avoiding adverse effects from disposal of waste lamps in nature, an externality with contested value (i.e. multiple valuation methods can be used) in traditional economic analysis. While the environmental and social externalities of mining in China for primary supply receive attention in research and media (see e.g. Ali, 2014; Kaiman, 2014; Liu, Tan, & Hu, 2016; Packey & Kingsnorth, 2016), they appear to factor less in actual value decisions about secondary supply of material from recycling.

There is also value of the materials for society in general, in creation of a domestic urban mining industry for strategic materials deemed critical for the economy and technological development (EU Commission, 2014; Graedel et al., 2011; Magalini et al., 2014). There is a value in developing the capacity to recycle these elements, as evidenced by the EU funding towards research and development in this area as well as EU funding that assisted Solvay in setting up its commercial recycling process. However, the conclusion of many of these projects as “uneconomical” makes it clear that these incentives are not enough to overcome all the challenges with secondary supplies competing with primary supplies. Whereas recycling of REE from lamp phosphors is shutting down in the EU, it appears to just be starting up in the U.S. where Rare Earth Salts, a REE separation company and Rare Earth Recovery Sciences, a buyer of retorted compact florescent lightbulb phosphor powder, have signed a five year commercial agreement to produce separated rare earth oxides from retorted lamp phosphors in the United States. Paper II also found strong REE recycling activities in Japan. It would be worth future research to unpack the value propositions in these cases to better understand how they differ from Europe.

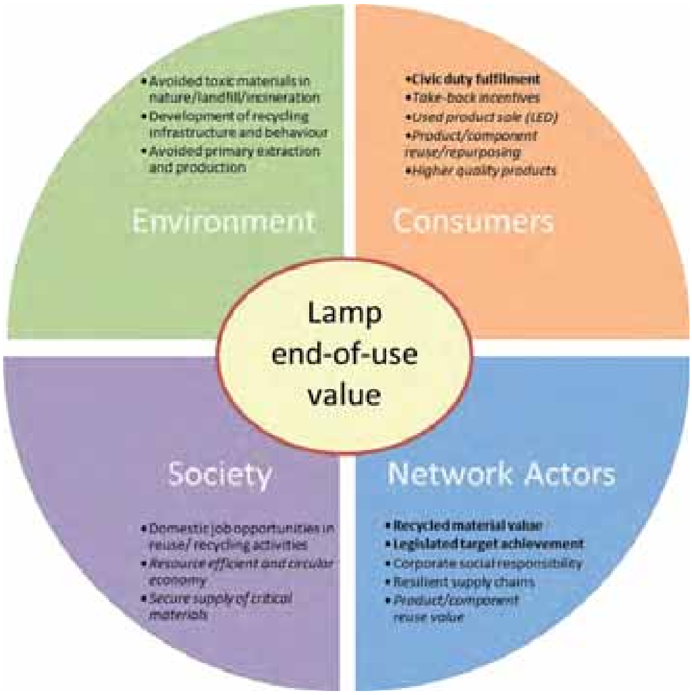

Figure 4. Value mapping for the value of lamps at end-of-use

Bold text refers to value that is considered currently, regular text to value considered at least partially now, and italicised text refers to value currently not considered generally

For consumers, there may be value in honouring obligations (if legislated that way) to return end-of-use products to the official system. Currently, individual benefits for a consumer are generally tied to the identity of the consumer as a citizen (Tojo, Lindhqvist, & Davis, 2001 also discuss the possibility of financial incentives for the consumer, but these are not implemented for WEEE or lamps). In this way, the value for society and the environment is what is used to appeal to the "citizen-consumer"[10]. It is argued as well that the framing of this value can matter and that as products become "greener" there is a need to shift from recycling presented to avoid environmental harm to a framing of recycling as a means of conserving resources (Baxter et al., 2016). Currently there is little material or reuse value for the consumer directly for lamps at the end of use. As LED technology evolves there is already evidence that some lamps will reach their end of use by a consumer before end-of-life (Gassmann et al., 2016). This may give rise to situations where LEDs at end of use of its first user do have reuse or repurpose value. In this case, lessons learned from other valuable WEEE may be relevant. New business models of lighting as a service may see the value of lighting products for consumers being purely functional with the material and product value remaining with the producer (see e.g. McKinsey & Company, 2014).

The research found that the value to one stakeholder was not always clear to other actors. For example, Paper II found that values such as longer-term resilience played a role in the Solvay's decision to recycle REE from lamps. Eventually this was not enough to maintain the operation with low prices for the end-product and based on the model of paying recyclers for the powders. However, PROs expressed a value for the recycling of REE as a positive corporate social responsibility story for producers and some felt that this was not recognized by the recyclers (both of lamps and REE) because they were not asked if and how much they would be willing to pay for this service.

Paper III discusses how even when value is recognized, for example the value of avoided mercury contamination by recycling fluorescent lamps, it is not always clear how this value should be used in decision making. This was evident in the study reviewing Article 7(6) of the WEEE Directive (Magalini et al., 2014) where environmental benefits of recycling were quantified by the value of recovered materials and avoided CO_2 emissions. The treatment of the mercury was quantitatively included in the costs of higher collection and treatment, and the avoidance of mercury emissions was qualitatively assessed. It was not clear in the final comparison of costs and benefits what weight the qualitative benefits were given, except that from the final judgement of "medium" relevance of individual targets for lamps that the qualitative benefits did not outweigh the costs.[11] This further underscores the complex reality where both value and costs can be split amongst different actors.

[10] The concept of the citizen-consumer and their role in environmental policy is explored in an overview by Berglund & Matti, 2006.

[11] It should also be noted that in this cost benefit analysis that the availability of recycling technology to recover rare earths was deemed low, which was most likely an outdated assessment since recycling of phosphors from lamps is one of the most mature technological processes for REE (Rollat et al., 2016; Tsamis & Coyne, 2014). See Table 5.1, p. 73 of Magalini et al., 2014 for an overview of the assessment for different WEEE categories.

4.4 Ecodesign

As discussed in Paper I, design incentives through EPR for lamps had been a subject of prior research by Gottberg et al. (2006). The authors found EPR policy did not incentivize design changes in the lighting industry, as the marginal costs were not sufficiently high to impact the producer. This may also depend on whether it is the producer or customer bearing the costs. In the case of lighting the demand is relatively inelastic and thus costs can be passed on to consumers. Additionally the costs affected all producers equally because, as the authors note, producers incur costs as part of collective compliance schemes (PROs), which then gives little opportunity or benefit to individual design improvement affecting end-of-life recyclability. Though the authors do not reference it, this situation in the implementation of EPR in practice has been criticized and motivates an argument in favour of individual producer responsibility (IPR) in EPR literature. Some research has proposed changes to the transposition of the legislation to ensure IPR remains at the member state level while other have proposed to enhance individual incentives within collective schemes (see e.g. Mayers et al., 2013; van Rossem et al., 2006).

There have been some opportunities for IPR with lighting waste as this stream is collected and treated separately from other WEEE. There were even processes developed for individual brand recycling of fluorescent tubes (mainly B2B lamps) and this was motivated by the high REE prices and the incentive to recycle the phosphors. Producers not only recycled their own brand, but developed processes to separate fluorescent lighting by type of phosphor used (Binnemans et al., 2013). This level of separation allowed the producer to reuse rather than recycle the REE phosphors – a much simpler process than the chemical processes needed to recycle REE back to its constituent elements. However, there was little incentive to separate household lamps in this way.

It is unclear whether the separate treatment of waste lamps seen currently will remain the case as LEDs become more prevalent in the lamp waste stream. Currently LEDs are generally collected and recycled with other lamps. The financing of WEEE systems also reflect this, with the member states examined having the fee for retrofit lamps, regardless of gas discharge or LED with the argument being that both types of lamps are in reality collected and processed together and so incur the same costs. Systems based on current market shares[12] (most often the case in the countries examined for this research) also generally mean that old technologies are financed by the new technologies. While this was

[12] Whereby the costs WEEE managements is allocated or charged to producers based on allocate costs of WEEE management to producers proportionate to their market share when those costs occur. For example, producers could pay a flat fee when placing a product on the market (usually annually) or PRO fees based on market share calculations (see also van Rossem, 2008).

accepted as necessary by most PROs, there are indications of some LED producers who do not think this is a fair system (Take-e-way, 2015). The Commission is also proposing to encourage better product design by differentiating the financial contribution paid by producers under extended producer responsibility schemes on the basis of the end-of-life costs of their products (EU Commission, 2015). France has already started moving in this direction with modulating fees for LED lighting (€0.12 instead of €0.15 for conventional lighting bulbs) owing to the absence of mercury and the long life cycle.

It was found that there is general scepticism of the consumer's ability to distinguish between lamp technologies when disposing of waste products. There are currently projects working on automatic separation of gas discharge lamps and LEDs.[13] Once separated, there are some projects working to demonstrate recovery of materials such as indium and gallium from LEDs but there is also a chance that LEDs, with their electronic components more closely resembling other types of EEE than previous lamp technologies, will then be added to a large shredder with other WEEE. This is perhaps indicative of trade-offs between a high-scale, efficient, lower-cost WEEE system and one with optimized benefits and incentives for ecodesign and circular flows for critical materials.

It has been argued that more detailed treatment requirements could be used also as a means of creating design incentives (Kalimo et al., 2012). From 2018, LEDs will be designated under product group 3 of the 2012 recast of the WEEE Directive with other lamps (Annex III and IV) and have a target of 80% recycling (Annex V). With higher return share of LEDs in the future and the trends in design now seeing replacement of metals with mixed plastics, meeting these targets could be a challenge without innovation of both technology and product design. As mentioned earlier, Switzerland is also proposing legislation with recycling requirements for critical metals. How the "feasibility" requirements will work in practice remain to be seen, but lighting products could be a very good candidate for testing such requirements as technical recovery processes for REE from waste lamps are more mature but the timeframe is short with the transition to LEDs.

There are still some barriers to incentivizing ecodesign with EPR with the case of lighting products. Lighting products are evolving quickly and becoming much longer-life products. This is problematic in the fact that by the time they are being recycled, design has already moved forward. This is already seen in the evolution of LEDs in which the first generation had much higher amounts of metals than what is currently being designed. LEDs are also much more complex, increasing the likelihood that different components fail at different times. Furthermore, there are already indications that LED products are becoming waste before end-of-life (i.e. still functional but either not fashionable or compatible with a newly installed

[13] For example, the EU FP/ funded project Illuminate: http://cordis.europa.eu/project/rcn/110301_en.html

lighting system for instance). This highlights the need to also consider reuse potential and applications for LEDs. This potential can be increased with more modular designs (Hendrickson et al., 2010).

While incentives should be strengthened within the WEEE Directive, there is likely also a need for some ecodesign incentives to be placed within the Ecodesign Directive to address rapidly evolving technologies like LEDs and ensure end-of-life management is part of the design consideration. For example, the link between end-of-life management and production could be enhanced with the recognition of the need of products not only to be designed *for* the end-of-life, but also to be designed *with* the end-of life (i.e. recycled components and materials) as well. The need for better quality and consistent volumes of these materials is acknowledged, but efforts to design with reused or recycled materials also need to be incentivized and rewarded, just as with efforts to design for end-of-life.

An emerging opportunity for more IPR for lighting waste could be servicizing. Philips, for example, has already indicated to be moving towards a pay per lux model, at least with business clients (McKinsey & Company, 2014b; Philips Lighting, 2013, 2014). In theory then the producer would retain ownership of the products throughout the life cycle, including the end-of-life. In practice, it remains to be seen whether the end-of-life lamps are managed by the producer directly or whether they will continue to utilize the collective schemes for this waste as well.

5. Conclusions and Future Research

The stated aim of the thesis research has been to address the gap in knowledge of existing EPR policies as they relate to lighting products specifically. Chapter 4 presented the findings evaluating specific EPR policies in Europe. Factors in high operational performance and best practices from the Nordic country cases were presented. Continuing challenges with data were discussed as well as challenges found for ecodesign incentives, closing material loops, and increasing operational performance for EPR systems for lamps. In this chapter the research questions are revisited to summarize the main findings of the research. Based on this, possible areas for future research are also discussed.

5.1 Research Questions Revisited

RQ1: How have existing EPR policies in Europe addressing collection and recycling of energy-efficient lighting products been performing?

Eurostat and PRO data on collection and recycling rates in EPR systems for energy-efficient lamps reveals a mixed performance throughout Europe. This research confirmed that there are limitations to this data and a need for improvement. A more detailed examination of EPR systems is necessary to fully understand and explain high or low performing systems. The evaluation framework revealed a more detailed and complex analysis of the performance of the Nordic systems in relation to EPR objectives, i.e. ecodesign of products to prevent waste, efficient use of resources and the retrieval of valuable secondary raw materials, and improved waste management systems.

Design incentives for lamps remain a challenge. France has started to modulate fees for LEDs, but the collective PRO and market share system in most member states means that fluorescent lighting waste is financed by LEDs, despite the lack of mercury in these products. Though there are gains in separating the LEDs from fluorescent lighting in the waste stream, it is difficult to do this at source. Doing so in the future would allow for LEDs to be treated separately and incur more accurate costs. With the increasing life of LEDs and complex designs, modular design as well as reuse and repurposing need to be explored further. Individual producer responsibility could further enhance incentives for better design.

While operational performance was generally high in the Nordic countries and identification of specific factors in this area revealed, there also some areas identified for further improvement. The technical process for recycling lamps is mature and energy-efficient lamps are recycled with high efficiency by weight, but this obscures a more complex picture in which critical materials are still landfilled and recycled materials struggle to find markets.

RQ 2: What are the factors explaining countries with high operational performance for the collection and recycling of lamps?

The research revealed several detailed factors for the high operational performance for lamp EPR systems, which could be categorized as belonging to the system (e.g. relating to stakeholders/actors, rule base, infrastructure, and operations in the system) or behavioural/cultural aspects (e.g. history, motivation, capacity, and opportunity). Based on the cases and literature examined, it is argued that the latter behavioural and cultural aspects are influenced by the EPR system and vice versa.

In terms of policy relevance, incentives for increased collection could begin with specific targets for the lamp waste stream. France is already moving in this direction, having separate targets for lamps that align with the general WEEE targets. This may also be necessary in countries already performing above the overall WEEE target. Such incentives might then incentivize further work in understanding the most influential factors to improve EPR systems for lamps.

RQ 3: What is the practice and potential for closing material loops, particularly for critical materials, in energy-efficient lamps in Europe?

This research found that collection and recycling rates alone do not reveal how recycled materials are used in practice, and that often the available grey literature may communicate potential rather than actual practice in this regard. In practice recycled materials often struggle to find markets and have difficulties competing with primary resources. This challenge will likely only increase if LEDs continue to develop with increased complexity and integration of materials.

The research revealed significant opportunities for recycling critical materials from energy-efficient lamps. Secondary supply of REE from waste phosphors is largely influenced by the collection rate of waste fluorescent lamps, which in turn, can be influenced by EPR policy. Adopting EPR can improve collection, however, not all EPR systems perform equally well, so consideration should also be given to factors of best practice to further increase collection rates, and thereby increase the volume of potential phosphors available for recycling. The recycling process for REE from phosphors has been demonstrated by prior research to be very efficient and technically feasible; leaving low collection rates as one of the bottlenecks in closing this loop.

The research also demonstrated that potential volumes of REE from recycled phosphors need to compete with larger volumes from primary supply. Despite the higher concentrations of REE in waste lamp phosphors than primary ores, primary supply continues to be more competitive since the fall in REE prices after 2011. The mapping of the value in the case of lamps showed that value is dynamic, multidimensional, and there are several identified externalities that should be considered.

There are still questions of how policy can better address externalities and different value considerations between producers, recyclers, consumers, the environment, and society. One possibility is that EPR policy could be more detailed in treatment requirements for critical materials and waste lamps are a good candidate for assessing the feasibility for doing so. There are already indications of this happening on the national level in Switzerland. It remains to be seen how the economic feasibility of this approach will be determined.

5.2 Future Research

Many of the findings in this research confirmed prior EPR research, particularly concerning some of the big level issues like ecodesign incentives. The factors for high operational performance added a more detailed framework that could be further tested and developed in future evaluations of EPR systems. A quantitative approach would be appropriate for testing the significance of different factors and the correlation with high collection and recycling rates, however, the questions about data quality revealed in this research would need to be addressed first to make such a study robust. Also, a quantitative approach would be less likely to deal with possible alternative explanations. A case study approach testing the importance of different factors would be appropriate for further developing this framework.

This research also contributed to the discussion of how EPR policies can begin to consider valuable WEEE and value for waste more generally. A better understanding of how, when, why, and to whom waste becomes valuable is fundamental for the design of future EPR policies if they are to contribute towards a transition to a circular economy. The case of lamps demonstrated that the factors and context for value arising can be very specific to the products, materials, and systems considered. It is therefore worth pursuing the issue of valuable waste with further cases that can be used for a more systematic examination of valuable waste products. For example, mobile phones are a product group that has been researched in this regard and the experience from this product can be compared with lamps, generally perceived to lack value (but as demonstrated by this research, this is rather simplistic). How policy should deal with the different value considerations of WEEE is still underexplored in the EPR research field. It is important not only to consider clear options for waste with traditional, i.e. market, value, but to also consider waste with societal value. It is also important for research to tackle these questions now for several product streams where this value is still uncertain, for example with LEDs and solar photovoltaics, which have recently been added to the scope of the WEEE Directive.

This research focussed on EPR policy and the WEEE Directive more specifically. However, the case of lamps could be useful for researching further how different policies work together to transition towards a low-carbon and resource efficient economy. For example, the Ecodesign Directive currently drives standards on energy efficiency and durability (i.e. lifetimes) for lighting. Evaluating how different policies affecting light products interact could also be an interesting area of research to further understand how policies interact in a mix, possible trade-offs and synergies, as well as potential improvements.

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Appendix A: List of Interviews and Correspondence

	Name	Organisation, position	Stakeholder Group	Interview date	Note
Denmark	Jan Bielefeldt	Lyskildebranchens WEEE Forening (LWF), Adminstrative Director	Producer Responsibility Organisation	26 August 2014	In person interview, semi-structured
	Jonas Engberg	Ikea, Sustainability Manager Denmark	Retailer	26 August 2014	In person interview, semi-structured
	Hardy Mikkelsen	Reno Djurs, Environmental Manager	Municipal Waste Organisation	4 December 2015	Phone interview, semi-structured
	Lotte Wammen Rahbek	Forsyning Helsingør , Waste planner	Municipal Waste Organisation	15 December 2014	In person interview, semi-structured
	Niels Remtoft	Dansk Affaldsforening, Special Consultant	National Waste Association	15 December 2014	In person interview, semi-structured
Finland	Senja Forsman	SOK Grocery Chain, Compliance Manager	Retailer	4 December 2014	Phone interview, semi-structured
	Timo Hämäläinen	Finnish Solid Waste Association, Development Manager	National Waste Association	19 December 2014	Phone interview, semi-structured
	Jorma Koskinen	Ekokem, Sales Group Manager	Recycler	29 January 2015	Email questionnaire, structured
	Jesse Mether	Rautakesko Ltd, Sustainability Manager	Retailer	19 December 2014	Email questionnaire, structured
	Perrti Raunamaa	FLIP, Administrative Director	Producer Responsibility Organisation	8 December 2014	Phone interview, semi-structured
Norway	Ellen Halaas	Avfall Norge, Advisor for framework and law collection, sorting and recycling	National Waste Association	9 December 2014	Phone interview, semi-structured
	Guro Kjørsvik Husby	El Retur, Information Officer	Producer Responsibility Organisation	24 November 2014 8 January 2015	Email questionnaire, structured
	Bjørn Thon	RENAS, Administrative Director	Producer Responsibility Organisation	30 January 2015	Phone interview, semi-structured
Sweden	Carina Andersson	IKEA of Sweden, Product Laws & Standard specialist - Producer Responsibility	Producer	13/15 May 2015;	Email questionnaire, structured; in person unstructured
	Peter Arnesson	Nordic Recycling, General Manager	Recycler	24 October 2016	In person, unstructured

	Jessica Christiansen	Avfall Sverige, Education Manager /Controller Technical Advisor WEEE	National Waste Association	16 December 2014	In person interview, semi-structured
	Jonas Carlehed	IKEA, Sustainability Manager Sweden	Retailer	30 January 2015	Phone interview, semi-structured
	Lars Eklund	Natursvardsverket (Swedish EPA), Advisor Environmental Enforcement	Government authority	2 December 2014	Phone interview, semi-structured
	Göran Lundholm	Nordic Recycling, General Manager	Recycler	13 August 2014; 27 October 2014	In person interview, semi-structured; phone interview, semi-structured
	Dolores Öhman	Hässleholm Miljö, Head of Waste Collection and Customer Service	Municipal Waste Organisation	3 Septembe r 2014	In person interview, semi-structured
	Anders Persson	SYSAV, CEO	Municipal Waste Organisation	9 Septembe r 2014	In person interview, semi-structured
	Mårten Sundin	El-Kretsen AB, Marketing Manager	Producer Responsibility Organisation	5 December 2014	In person interview, semi-structured
	Hans Standar	Svensk GlasÅtervinning AB, CEO	Glass recycler	4 December 2014	Phone interview, semi-structured
	Joseph Tapper	Elektronikåtervinning i Sverige, CEO	Producer Responsibility Organisation	5 December 2015	In person interview, semi-structured
Other	Stephan Riemann	LightCycle, CEO (Germany)	Producer Responsibility Organisation	17 October 2016	Email questionnaire, structured
	Knut Sander	Researcher, Ökopol (Germany)	Researcher	25 April 2014	In person, unstructured
	Ruta Bendere	Chairperson, LASA (Latvia)	National Waste Organisation	3 October 2016	Phone, semi-structured
	Nameda Belmane	Waste Management Consultant (Latvia)	Other	3 October 2016	Email, semi-structured
	Armands Liukis/ Jan Bielefeldt	SIA Ekogaisma (Latvia)	Producer Responsibility Organisation	24 November 2014	Email, unstructured
	Thomas Hoffmann	SuperDrecksKëscht, Head of Communication (Switzerland)	Recycler	25 October 2016	Email questionnaire, structured
	Jozef Ornelis	Indaver, Product Manager (Belgium)	Recycler	17 November 2016	Email questionnaire, structured
	Cameron Davies	Rare Earth Salts, Chief Operating Officer (USA)	REE Recycler	27 October 2016	Email questionnaire, structured

Appendix B: Interview Guides

Sample interview protocol for producer responsibility organisations

1) In other countries there are different situations regarding a separate PRO for lamps. What are the advantages and disadvantages having a PRO focussed solely on lamps? What else distinguishes [organisation] from other PROs operating in [country]?
2) How does the general WEEE system affect the take back of lamps? Would you characterise the system as competitive or cooperative for collection between the PROs?
3) What do you find to be the particular challenges to take back of lighting products? For example, collection, transport and recycling for lamps have been described as very expensive compared to other WEEE categories but the costs are different in each country context. What are the main cost factors and how is [organisation] working to make the system as cost efficient as possible?
4) There are statistics from Eurostat regarding recycling in [country]. The collection rates vary depending on how you count, for example historically versus same year as well as how you divide product categories. How does [organisation] measure collection and recycling effectiveness for lamps and are there challenges to collecting good information (e.g. from producers).
5) How does your organisation communicate with other stakeholders like producers, producer responsibility organisations and government authorities - is there a specific forum for this?
6) Is there any information or communication with producers regarding the end-of- life/recyclability of products? How do the producers respond?
7) Do you have information about how recycled fractions from collected and treated products are used? Is there interest/action on using these fractions in particular ways (e.g. in lighting products).
8) Do you differentiate fees in any way depending on the product? Is there likely to be any differentiation between CFL and LEDs in the near future?
9) How are producers active in the system through your PRO?
10) The EU is considering a separate target for gas discharge lamps. What is your organisation's view about this?

11) In the media in some countries, it has been highlighted that there are still lamps ending up in incineration and glass recycling. Is it an issue in [country]?
12) Transporting hazardous waste such as lamps could pose risks from mercury for waste handlers. Is handling mercury-containing waste products or broken lamps an issue in [country]?
13) There is the website and some material from [organisation], are there any other ways [organisation] is working with education and information to raise awareness about WEEE recycling?
14) Are there strengths or weaknesses you perceive to the [country] WEEE system compared to other Nordic countries?
15) Nordic countries are often cited as the best practitioners of WEEE recycling - what do you think are the main factors in success?
16) Improving collection and recycling is a continuous challenge, what do you think are the main areas that still need significant improvement? Is there more that can be done with critical materials recovery for instance?

Sample interview protocol for national waste management associations

1) What are the main issues in producer responsibility for WEEE where your organisation is involved on the member's behalf?
2) How does your organisation communicate with other stakeholders like producers, producer responsibility organisations and government authorities - is there a specific forum for this?
3) Are there any issues with working with the relationship between municipalities and PROs in [country]? Is it a contract or other agreement on how the responsibility is allocated and managed for collection points and collection?
4) Would you characterise the system as competitive or cooperative for collection between the PROs?
5) Transporting hazardous waste such as lamps could pose risks from mercury for waste handlers. Is handling mercury-containing waste products or broken lamps an issue in [country]?
6) From [organisation] reports there are still some lamps found in residual waste. Are these and other small electronic waste perceived as a particular problem?
7) How are municipalities and/or your organisation working with increasing collection of lamps and other small WEEE? Are there any pilot projects or innovative examples to further optimise the WEEE system in this respect?
8) There is the website and some material from [organisation], is there more [organisation] is doing to educate about hazardous waste like gas discharge lamps?
9) The EU is considering a separate target for gas discharge lamps. What is your organisation's view about this?
10) Are there strengths or weaknesses you perceive to the [country] WEEE system compared to other Nordic countries?
11) Nordic countries are often cited as the best practitioners of WEEE recycling - what do you think are the main factors in success?
12) Improving collection and recycling is a continuous challenge, what do you think are the main areas that still need significant improvement?

Sample interview protocol for lamp recyclers

1) What process you use for lamp recycling and what are the advantages/disadvantages of this process?
2) Are you able to sell glass fractions from recycling? What are they used for? Is there any interest in using glass for new lamp manufacturing? Why or why not?
3) What happens to the other fractions, i.e. plastics, metals, etc.?
4) There is a lot of interest in recycling critical materials. What happens currently to the rare earth phosphors in the lighting? Are the phosphors ever sent to Solvay in France for processing? Are there any new developments with phosphor recycling?
5) Do you separate LEDs from mercury lamps or recycle all together?
6) Do you communicate with producers? Are they generally interested in using materials from the recycling process?
7) Is there any development or changes to the process being made as LED waste rises?
8) Do you see the need for a separate system for LEDs in the future, or should they go with regular electronics?
9) Lamps have been a waste stream with a high net cost for collection and recycling (compared to some other WEEE). Do think there is any scenario where lamps in the future would not be a net cost for recycling? Why or why not?

Appendix C. Workshops and Education

The research project in which this research is situation conducted two workshops in March 2015 and October 2016 in which stakeholders were invited for discussion of lighting specific issues (the focus of the 2015 workshop) and EPR trends and issues related to lighting, WEEE and other categories more generally (the focus of the 2016 workshop). These workshops also provided a venue for further discussion with participants about the findings of the research at these stages. Such discussions were valuable for both input and in shaping the research.

There were also several workshops and conferences outside the direct project that were forums for sharing findings from this research, but also conversing with other researchers and practitioners in the fields of EPR and WEEE, rare earth applications and recycling, and lighting applications. Events attended included:

- Electronics Goes Green Conference, 7-9 September 2016, Berlin, DE (presenter)
- "Secret Life of Lighting Products: a focus on environmental impacts and policy", Lund University Environmental Psychology Dept. (invited seminar speaker)
- ReClaim Workshop. 1-2 June 2016. Mechelen, Belgium (participant)
- Circular Materials Conference. 11-12 May 2016. Gothenburg, Sweden (participant)
- Videncenter for Mineralske Råstoffer og Materialer (MiMa) critical materials workshops. 4 February 2016; 6 October 2015. GEUS, Copenhagen, DK. (participant)
- Waste@LU Seminar series, seminar 1. 28 April 2015. Lund, Sweden (Presenter)
- Light Symposium, KTH Lighting Laboratory. Stockholm, Sweden 2015 March 19-21 (participant)
- Lund University Multidisciplinary Light Research Seminar events, 2015 February 4-5 (participant)
- UNEP Global Efficient Lighting Forum. 2014 November 10-11. Beijing, China (volunteer/participant)
- ISWA Beacon Conference on Waste Prevention and Recycling: Resource efficiency - Closing the Loops. 16-17 June 2014 (participant)
- WEEE 2.0 Forum, Brussels 2014 March 20-21 (participant)

Another valuable forum for discussion of this research was in teaching in Masters courses and thesis supervision. The research was used as a basis for teaching seminars, guest lectures, and a practical course component involving surveying local citizens in Denmark and Sweden about their knowledge and disposal behaviours for waste lamps (the results of which were presented and discussed with stakeholders in the project workshop in 2014). I was also involved in supervising student research tasks on topics related to EPR for lamps in the U.S. and Africa. Lastly, I supervised three Masters theses in the area of EPR (one in EPR for lamps specifically).

Teaching and communicating about my own research as well as discussing issues in the research field more generally allowed for valuable reflection on the approach as well as the contribution of the findings. In addition to these activities, coursework also provided an arena for discussion and critical reflection. In particular, the E-Waste Academy organized in November 2014 by StEP in Shanghai and the EREAN (rare earth) summer school at Leuven, Belgium in August 2014 were opportunities to present and discuss my research design with other researchers with deep knowledge of the topic areas.

Appendix D: Co-authorship statements

Co-authorship statement

All papers/manuscripts with multiple authors which is part of a PhD thesis
should contain a co-author statement, stating the PhD student's contribution to the paper.

1. General information	
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2.Title of PhD thesis
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3.This co-authorship declaration applies to the following paper/manuscript:
Title: **Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops** Author(s): **Jessika Luth Richter, Rob Koppejan** Journal: ***Journal of Cleaner Production*** Vol./page: **123 (2016) 167e179** DOI: **10.1016/j.jclepro.2015.06.131**

4. Contributions to the paper/manuscript made by the PhD student
What was the role of the PhD student in designing the study? **The PhD student took the lead role in developing the research idea and design with the main co-author contribution after this stage of the research (following a request from the special issue editor for an industry co-author if possible)**.
How did the PhD student participate in data collection and/or development of theory? **The student independently collected all data used in the article/research from interviews, literature, and statistical databases. The student also reviewed prior literature in the field to develop the EPR theory-based evaluation framework used. The collected data and development of theory in the first article draft was then discussed with the co-author.**

4. Contributions to the paper/manuscript made by the PhD student
Which part of the manuscript did the PhD student write or contribute to? **The student initially wrote all parts of the article. A draft of the article was then discussed with the co-author and parts of the discussion rewritten based on feedback and input from the co-author. This feedback and input from the co-author included comments on findings and discussion dealing with uncertainties with product lifetimes, data quality issues, as well as input on Figure 4 (factors in operational performance).**
Did the PhD student read and comment on the final manuscript? **The student read, commented and edited the final manuscript. She was solely responsible for preparing the manuscript for submission and for final edits in response to peer review comments.**

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Co-authorship statement

All papers/manuscripts with multiple authors which is part of a PhD thesis should contain a co-author statement, stating the PhD student's contribution to the paper.

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3.This co-authorship declaration applies to the following paper/manuscript:
Title: Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties Author(s): Erika Machacek, Jessika Luth Richter, Komal Habib, Polina Klossek Journal: Resources, Conservation and Recycling Vol./page: 104/ 76-93 DOI: 10.1016/j.resconrec.2015.09.005

4. Contributions to the paper/manuscript made by the PhD student
What was the role of the PhD student in designing the study? Jessika Richter participated in all initial discussions with the co-authors and was involved in further developing the study design and approach for demonstrating and arguing the overall potential contribution and barriers involved in the recycling of lamps.
How did the PhD student participate in data collection and/or development of theory? Jessika's research on recycling of lamps provided data and informed the methodology underlying the recycling rates for the secondary supply scenarios. Other data she researched and analyzed for this articled included LED market data from McKinsey & Company, recycling literature (for lamps and REE), WEEE statistics and, most important for this study, personal interviews with key actors in the recycling process. Her conducted interviews provided insights which delivered nuances on the valuation of materials, which so far have not been addressed in the literature available on recycling and on rare earth elements. She also researched and cross-checked data influencing the primary and secondary models including lifetime of lamps, proportion of LEDs, and proportion of REE used for lighting. Jessika supported the first author's case study data on Solvay with additional literature. Along with the first author, Jessika

4. **Contributions to the paper/manuscript made by the PhD student**
reviewed literature to support and frame key arguments in the Discussion section of the article, including research on value of secondary resources and data about the environmental costs and impacts associated with primary REE mining (also in Appendix C). She also discussed the main arguments with the first author to develop and refine the overall article.
Which part of the manuscript did the PhD student write or contribute to? Jessika contributed to all elements of the manuscript, with significant contributions in the Introduction, Results (particularly the case of Solvay and explanation of the recycling rates– along with the co-authors), Discussion and Conclusion. She and the first author together wrote the Discussion section in which the potential and challenges for recycling lamps and REE are discussed as well as the article's conclusions and Appendix C. Jessika also contributed to formatting the article and references (and checking/adding references) in adherence to the journal guidelines.
Did the PhD student read and comment on the final manuscript? Yes, along with the first author, Jessika was very much involved in the reading, revision, and editing of the final manuscript.

5. **Material in the paper from another degree / thesis :** *Articles/work published in connection with another degree/thesis must <u>not</u> form part of the PhD thesis.* *Data collected and preliminary work carried out as part of another degree/thesis may be part of the PhD thesis if further research, analysis and writing are carried out as part of the PhD study.*	
Does the paper contain data material, which has also formed part of a previous degree / thesis (e.g. your master's degree) Please indicate which degree / thesis: ____________________	Yes: [ ] No: [x]
Please indicate which specific part(-s) of the paper that has been produced as part of the PhD study:	

The co-author statement should always be signed by the first author, the corresponding-/senior author and the PhD student. If there are two or three authors the statement must always be signed by them all.

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Appended papers

Paper I — Richter, J. L., & Koppejan, R. (2016). Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops. *Journal of Cleaner Production*, *123*, 167–179.

Paper II — Machacek, E., Richter, J. L., Habib, K., & Klossek, P. (2015). Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resources, Conservation and Recycling*, *104*, *Part A*, 76–93.

Paper III — Richter, J. L. 2016. The complexity of value: considerations for WEEE, experience from lighting products, and implications for policy. *Electronics Goes Green 2016+ Conference Proceedings.*

Paper I

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Extended producer responsibility for lamps in Nordic countries: best practices and challenges in closing material loops

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ABSTRACT

Extended Producer Responsibility (EPR) schemes are adopted not only to promote collection and recycling of waste products but also to close material loops and incentivise ecodesign. These outcomes are also part of creating a more circular economy. Evaluations of best practices can inform how to further optimise systems towards more ambitious collection, recycling and recovery of both hazardous and critical materials. Gas discharge lamps in particular are a key product category in this regard, considering both the presence of mercury and of rare earth materials in this waste stream. Nordic countries in particular are known for advanced collection and recycling systems and this article compares the EPR systems for gas discharge lamps. The EPR systems for lamps are evaluated using theory-based evaluation approaches to analyse both the performance of lamp EPR systems and challenges perceived by key stakeholders. The cases were constructed based on primary and secondary literature, statistical data, and interviews with stakeholders. The findings indicate that the collection and recycling performance is generally still high for gas discharge lamps in the Nordic countries, despite some differences in approach and structure of the EPR systems, but there remain opportunities for further improvement. In terms of EPR goals, there is evidence of improved waste management of these products as a result of the systems; however, there also remain significant challenges, particularly in terms of ecodesign incentives. The key factors for best practice are discussed, including aspects of the rule base, infrastructure, and operations. The particular characteristics of this waste category, including the rapidly changing technology, also pose challenges for EPR systems in the future.

1. Introduction

Energy efficient lighting is an important part of addressing climate change and transitioning towards a green economy with electricity for lighting accounting for approximately 15% of global power consumption and 5% of worldwide greenhouse gas (GHG) emissions (UNEP, 2012). Energy efficient gas discharge lamps (also known as fluorescent or mercury lamps), and now increasingly LEDs, have been gradually replacing traditional incandescent lamps for the last few decades and this trend has accelerated recently due to the tightening of energy efficiency regulations in most regions of the world (see e.g. UNEP, 2014). In Europe for example, EU Commission Regulation EC No 244/, 2009 and EU Commission Regulation EC No 245/, 2009 introduced stricter energy efficiency requirements for lighting products and a similar approach has been adopted through energy efficiency regulations in the U.S. (UNEP, 2014). Lighting represents a key area for achieving the European Union (EU) goal to increase energy efficiency by 20% by 2020 and replacement of inefficient lighting by 2020 is expected to enable energy savings to power 11 million households a year (EU Commission, 2013). The 2009 regulations initiated a phase-out of incandescent lamps (EU Commission, 2014a) and resulted in an increase in gas discharge lamps in the EU general lighting market (accounting for an estimated 43% of units sold in 2011 and 2012 (McKinsey and Company, 2012)). A further increase of both gas discharge lamps and LEDs is expected with the phase out of halogen lamps (originally scheduled for 2016, but now delayed to 2018).

However, in transitioning to energy efficient lighting, an integrated policy approach must also consider end-of-life management of energy efficient lamps (UNEP, 2012). The WEEE Directive (EU 2002/96/EC and recast 2012/19/EU) has implemented Extended

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Producer Responsibility (EPR) for such waste in EU member states and banned landfilling of WEEE covered by the legislation. Gas discharge lamps are covered under category 5 of the WEEE Directive. As a product group, they have special characteristics that make them particularly challenging for collection and recycling. They contain mercury that can be detrimental when released into the environment in large enough quantities (Wagner, 2011) or result in high mercury emissions when incinerated without adequate filter technology (Silveira and Chang, 2011). The fragility of lamps makes safe collection and transportation more complex to ensure the health of handlers (Kasser and Savi, 2013; Sander et al., 2013). Avoiding this environmental harm from waste gas discharge lamps is a compelling reason for "collecting as much as possible and in a safe way (avoidance of breaking) and to treat them properly" (Huisman et al., 2008, p. 281). However, collection and recycling of gas discharge lamps represents relatively high cost compared to the value of the product (Philips Lighting, 2012) and the low or negative value of the recovered material from lamp waste (G. Lundholm, personal communication, 13 August 2014). While clearly it is of societal value to avoid mercury contamination, this is a positive externality and moreover, it is a benefit difficult to quantify in economic terms.[1] As such, legislation, targets and other drivers are integral to incentivising end-of-life management (Huisman et al., 2008; G. Lundholm, personal communication, 13 August 2014). The high cost for lamps is tied to necessary recovery of hazardous materials increasing recycling costs, but also to challenges in collecting lamps. Lamps are lightweight, which means they are a small part of total WEEE and that filling trucks for optimal transportation can be an issue. Lamps are also dispersed in high quantities, geographically and between consumers and businesses. This necessitates the need for an extensive capillary network for collection.

The collection and recycling of gas discharge lamps can also create opportunities to recycle valuable materials. Waste gas discharge lamps contain rare earth elements (REE) in the phosphor layer, which is necessary for producing white light. Nearly all global supply of europium, 85.2% of terbium and 76.7% of yttrium is used for phosphors, and the majority of these are used for lighting applications (Moss et al., 2013; Tan et al., 2014). Despite only using 7% of global REE by volume, due to the high level of purity needed for lighting applications, phosphors represent 32% of the value for rare earth applications (Binnemans et al., 2013; Schüler et al., 2011; U.S. Department of Energy, 2011). The EU Commission's report on Critical Raw Materials for the European Union (EU Commission, 2014b), considers the REE group as having the highest supply risk and REE have received increasing attention in the last few years with rising prices and concern about supply restrictions from China, where over 90% of production takes place (Binnemans et al., 2013; Bloomberg News, 2015). The presence of REE in only small amounts in waste products represents a challenge for recycling, but increased recycling has the potential to address supply risks (Binnemans et al., 2013; Rademaker et al., 2013; Sprecher et al., 2014). However, currently less than 1% of REE is recycled and examples of closing this material loop are rare (Binnemans et al., 2013) but the experience in recycling REE from gas discharge lamps is promising (Dupont and Binnemans, 2015).

EPR systems for lamps have been in place in the EU under the WEEE Directive, but legislation has been present even longer in some countries, like Norway, Sweden, and Austria. Academic literature has evaluated various aspects of WEEE systems in the EU, including the challenges for collecting small WEEE (Huisman et al., 2008; Khetriwal et al., 2011; Melissen, 2006) However, there has been not been a comprehensive evaluation of the best practices and challenges for end-of-life management of gas discharge lamps specifically, despite this product stream having been acknowledged to be of particular relevance both for recovery of critical materials and for avoidance of mercury contamination. The literature that has addressed this waste stream has tended to focus on the set up of EPR systems for lamps in the EU in general (Wagner, 2011, 2013; Wagner et al., 2013) or has emphasised recycling over collection aspects (Silveira and Chang, 2011). Very little is known about how EPR systems for lamps compare or differ from the structure and performance of the overall WEEE systems.

The research presented in this paper evaluates EPR systems for lamps in the Nordic countries of Denmark, Finland, Norway and Sweden.[2] The Nordic countries have been recognised for best practices in the area of end-of-life management of WEEE (Román, 2012; Ylä-Mella et al., 2014a,b) and as such also provide good cases for a deeper analysis of EPR for lamps in particular. Such analysis can provide further insight into how to address the unique challenges for this waste stream and the factors that potentially contribute to better attainment of EPR goals and a more circular economy for this key product category. EPR includes goals to conserve source materials by promoting better waste management, ecodesign, and closing material loops and such goals are also an integral part of a circular economy (EU Commission, 2014c). This article presents analyses of EPR systems for lamps in Nordic countries in relation to EPR goals and discusses the factors that contribute to well-functioning systems as well as challenges still to be addressed in further optimising such systems.

Section 2 describes the methodology used in this policy evaluation and comparative case study methodology. Section 3 presents the findings of the comparative case study and evaluation of the performance of the Nordic EPR systems in relation to the EPR outcomes. Section 4 discusses these findings and presents factors identified as influential to the success of the systems as well as remaining challenges.

2. Methodology

The research approach used embedded multiple cases in which multi-level perspectives were explored simultaneously (e.g. gas discharge lamps, country perspectives, key stakeholder groups, etc.) (Yin, 2003). Comparative analysis of multiple cases particularly suits research evaluating multiple holistic systems and allows comparison of factors influencing performance (Druckman, 2005). The framework for the initial comparison of the EPR systems for lamps was based on important elements of such systems identified by Murphy et al. (2012). Nordic countries are the focus cases in evaluating EPR systems for lamps because they have been described for their best practices in performance for WEEE in general, but they have not been examined in regard to gas discharge lamps. High performing systems can be studied to identify the common elements that could be the key to their effectiveness. It can also reveal context-specific or organisational differences that have or have not influenced effectiveness, as well as challenges perceived about the different systems from corresponding stakeholder groups in each system.

[1] Some studies, for example, Hylander and Goodsite (2006) have tried and estimated a cost of USD 2500 to 1.1 million per kg Hg isolated from the biosphere depending on local factors quantity, nature of pollution, media, geography, technology used etc.

[2] Iceland has been excluded in this research as its context as well as the implementation and experience thus far with WEEE systems has been quite different than other Nordic countries so far. It is expected to further develop and resemble other Nordic country systems in the future (Baxter et al., 2014).

Policy evaluation, using multiple methods of inquiry to generate policy-relevant information that can be utilised to resolve policy problems (Dunn, 1981), framed this research. In terms of focus criteria, the WEEE legislation in regard to gas discharge lamps in the Nordic countries is evaluated primarily for its environmental effectiveness, a common criterion evaluating the policy in relation to its goals (Mickwitz, 2003; Vedung, 2008). While there is data related to collection and recycling rates, more comprehensive information about EPR systems for energy efficient waste lamps is still lacking. Moreover, the goals of the WEEE Directive and the legislation transposed in the member states refer to WEEE collection overall, with few product level specifications. A separate target for gas discharge lamps within the Directive is being investigated until August 2015 (Article 7.6). In such cases where the data or explicit goals may be lacking, the use of intervention theories can support the evaluation of the policy (Kautto and Similä, 2005; Manomaivibool, 2008).

The main policy interventions governing the end-of-life management of gas discharge lamps in the Nordic countries are based on the principle of EPR, defined as “a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to take-back, recycling and final disposal of the product” (Lindhqvist, 2000, p. 154). Moreover, Lindhqvist (2000) argues that EPR entails different types of responsibilities: liability, physical, financial, and provision of information (i.e. informative) responsibilities. Policy mixes can vary in how these responsibilities are realised and distributed amongst actors but there are specific goals and outcomes of EPR that should be common to all EPR programmes. These have been outlined by Tojo (2004) and are shown below in relation to the WEEE Directive 2012/19/EU. While the WEEE Directive is the main focus of this article, it is also acknowledged that the Restriction on Hazardous Substances in EEE (RoHs) Directive is part of the EU's EPR policy package (van Rossem et al., 2006a). The RoHs Directive's influence on design for lamps is also discussed in Section 3.2.1. The EU Ecodesign directive also has an indirect effect on EPR policies (OECD, 2014).

Theory based (also known as program theory/theory-driven) evaluation includes reconstruction of the intervention (program) theory to model how a policy is supposed to function (Bickman, 1987). Using an intervention theory as a basis for environmental evaluations focusses the evaluation in terms of scale and stakeholders (Mickwitz, 2003). Hansen and Vedung (2010) propose that an intervention theory consists of three elements: a situation theory concerning the context of the intervention; a causal theory concerning the implementation and outputs that lead to certain impacts of the intervention; and a normative theory concerning the envisioned outcomes of the intervention. This study includes these elements with the context, implementation and outcomes of the intervention all examined.

In addition, theory based evaluations are grounded in a stakeholder approach (Hansen and Vedung, 2010), but it is a recognised challenge that there can exist competing program theories (Dahler-Larsen, 2001). When dealing with more complex program evaluations, Hansen and Vedung (2010) suggest a “theory-based stakeholder evaluation” that elaborates upon a “raw” intervention theory with the perspectives of key stakeholders. Identifying key stakeholders stems from the intervention theory and from this the primary stakeholders crucial to its implementation and likely to have in-depth knowledge of the intervention are selected. The intervention theories from the perspective of these key stakeholders can then be reconstructed to identify similarities, differences, and disagreements (Hansen and Vedung, 2010) or the distinction between the “espoused theory” and the “theory-in-use” (Friedman, 2001). The latter distinction is included in this paper while stakeholder perspectives of success factors and continuing challenges for EPR systems are discussed.

Both the evaluation and cases used data collected from publicly available statistics from Eurostat, national authorities, and producer responsibility and municipal waste organisation reports. This data was supplemented and triangulated with peer-reviewed and grey literature as well as semi-structured interviews with key stakeholders and additional email correspondence (based on interview protocols). For each country case, similar stakeholders were interviewed with identical protocols. When possible, interviews were recorded and in person, though they were also conducted by telephone. Extensive notes were taken and when necessary, clarified again with the interviewed stakeholder via email correspondence. Lighting producers themselves were not interviewed as earlier research has examined EPR from the perspective of lamp and lighting sector producers (see Gottberg et al., 2006). The focus of this study is instead on stakeholders downstream from producers involved in the practical implementation of the EPR systems for lamps. These stakeholders included managers of producer responsibility organisations (PROs) in each country dealing with lamp collection, lamp recyclers responsible for recycling lamps in Nordic countries, and managers of WEEE issues in national waste management associations representing municipalities and municipal waste management companies in each country. In addition, a few specific Nordic retailers and municipal waste management companies with initiatives for lamp collection were also interviewed. A list of organisations and representatives interviewed is included in the appendix as well as sample interview protocols. Where specific information from an interview is presented, the interviewed person is identified, but where there was general consensus amongst a group of interviewed stakeholders, the group is identified.

3. Findings and analysis

It has been demonstrated and generally accepted that end-of-life management of WEEE is environmentally beneficial and benefits can be better realised through increased collection and recycling rates (Hischier et al., 2005; Khetriwal et al., 2011). In the first version of the WEEE directive collection rates differed widely between member states, with ten countries failing to meet the 4 kg per capita target in 2010 but most exceeding and the Nordic countries well exceeding the target (EU Commission, 2013). Ylä-Mella et al. (2014a) and Román (2012) describe the performance of WEEE systems in the Nordic countries as exemplary, citing their high collection rates in Nordic countries (ranging from 8 kg/capita/year in Finland to over 20 kg/capita/year in Norway) despite low population densities and high transport distances, especially in the northern parts of Norway, Sweden, and Finland. Such per capita collection rates rank Nordic countries all in the top five performing countries in Europe. Aside from system architecture, Ylä-Mella et al. (2014a) attribute the success of the Nordic WEEE systems in part to high awareness of environmental issues among Nordic citizens and further argue that one of the strengths of the WEEE recovery systems in Nordic countries is the strong civic support of environmental protection and willingness to use the WEEE systems in place.

While this measure of performance has been consistent with historic WEEE Directive targets measuring performance in terms of kilograms per capita, the WEEE recast brings new targets which measure collection rates in comparison to product put on market in the previous three years. In the recast the target is 45% of the sales of products in the three preceding years with an increase to 65% by 2019 (or 85% of generated WEEE). This has implications for Nordic countries where there is a high level of EEE products put on the market, reflecting both the challenging climate conditions and high living standards that make EEE and information technology an important part of everyday life in Nordic societies (Ylä-Mella et al., 2014a). Despite this, according to Eurostat statistics, Denmark, Norway and Sweden remain in the top five performing countries and are already poised to meet the 45% collection target of previous three years EEE put on market, which is in place from 2016 to 2019. Sweden is already meeting the 65% target that will be in place from 2019. However, Finland, having collected only 36% in 2012 compared to the previous 3 years EEE put on market, still has improvements to make to meet this target. However, it has also been suggested that Finland's lower figures have more to do with collection reporting rather than actual collection being low (see Baxter et al., 2014). Another important change with the recast of the WEEE Directive has been the increased responsibility for retailers and this is examined in further detail in relation to the specific cases.

3.1. Comparing Nordic country cases

In our analysis, we compare the systems for gas discharge product group specifically, though of course the overall WEEE design has a large influence on how this waste category is collected. As described earlier, EPR consists of financial, informative, and physical responsibility for waste products and these responsibilities can be allocated differently in different systems. Table 1 below outlines the basic components and context of the WEEE systems for lamps in the Nordic countries.

3.1.1. System architecture

With the exception of Denmark, each Nordic country has transposed the WEEE Directive with the financial responsibility for collection, transportation, and treatment being the responsibility of producers. In Denmark, municipalities are currently financially responsible for collection of WEEE from households and cover this cost by fees charged to households. Physical responsibility has been extended to retailers in the recast of the legislation in Finland and Sweden and was already part of the responsibility in Norway prior to the recast. In practice, municipalities in all Nordic countries are responsible for most of the household collection of WEEE, including gas discharge lamps. Municipal waste organisations and municipal stakeholders interviewed in these countries reported that financial compensation for municipal collection of WEEE did not cover the full costs of the services provided by the municipalities. The financial compensation in Sweden is negotiated as a contractual arrangement every few years between municipalities and the main producer responsibility organisation, El Kretsen. In Norway and Finland, contracts are negotiated between individual municipalities and individual PROs. As such, the individual arrangements often reflect the negotiating power of the municipality (i.e. in larger urban areas there are often other waste service providers who can compete with the municipalities and thus these municipalities often receive less compensation for their services than rural municipalities). In Denmark, though municipal waste organisations have requested financial compensation for collecting WEEE, they

Table 1
Comparison of EPR for lamp systems in Nordic countries.

			Denmark	Finland	Norway	Sweden
Context	Population 2013 (mil)		5.6	5.4	5.1	9.6
	Area (km^2)		43,094	338,424	385,178	449,964
	WEEE/lamp legislation beginning		2005[a]	2004	1998	2001/2000
System architecture	Legislated responsibility (italics responsibility in practice)	Lamp scope legislation	Filament bulbs excluded[b]	Filament bulbs excluded[b]	All lamps covered	All lamps covered
		Physical responsibility	Producer/ municipality[c]	Producer/ *municipality*retailer	Producer/*municipality*/ retailer	Producer/*Municipality*/ Retailer
		Informative r esponsibility	Producer/ *municipality*	Municipality	Producer/recycler/ municipality/retailer	Producer/ municipality
		Financial responsibility	Producer/ municipality	Producer *Municipality (part)*	Producer *Municipality (part)*	Producer *Municipality (part)*
		Retailer take-back	Voluntary	1:1; 0:1 (≥1000 m^2 grocery stores/200 m^2 EEE	All selling EEE	1:1; 0:1 (≥400 m^2 EEE sales space)
	Recycling stations		Yes	Yes	Yes	Yes
	Kerbside collection		Limited (2 municipalities)	Mobile collection a few times/year	Mobile collection a few times/year	1.5 million households
	Permanent collection sites 2013		398	526[d]	~2700	~2600
	Main PROs dealing with lamps		LWF (lamp specific)	FLIP (lamp specific); Elker Oy	RENAS, Elretur	El Kretsen
Collection and recycling	Avg. tonnes Put on Market (POM) 2009–2011		1670	1926	3018	3203
	Collected tonnes 2012		706	850	890	2165
	% Recycled of collected 2012		93%	90.1%	92.7%	100%
	2012 collected/avg. 2009–2011 POM		42%	44%	29%	68%
	kg per Capita collection 2012		0.126	0.157	0.177	0.227

[a] Since 1998 the Danish Environmental Protection Act included a section about ecodesign for producers.
[b] Inevitably some filament bulbs are collected and recycled with gas discharge and LED lamps.
[c] Municipalities have responsibility for collection from households only, while producers are responsible only for collection from municipal collection to recycling (not from households directly).
[d] Does not include retailer collection locations which were implemented in 2013.
Sources: Dansk Producent Ansvar, 2015; Elker Oy, 2014; El Kretsen, 2014; Elretur, 2014; Eurostat, 2014; RENAS, 2014; "*Danish WEEE legislation*", 2014; "*Swedish WEEE legislation*", 2014; "*Norwegian WEEE legislation*", 2015; "*Finnish WEEE Legislation*", 2014; personal communication with the following organisations: Dansk Affaldsforening; Avfall Sverige; Avfall Norge; JLY Finland (see interview information in Appendix A).

have so far been unsuccessful in this endeavour and do not foresee any changes in the near future due to a recent agreement between the government and industry regarding ecodesign (N. Remtoft, personal communication, 15 December 2014).

In all Nordic countries, producers are solely responsible for transport and treatment of the waste lamps collected by municipalities and retailers, though the exact details of the financial and physical responsibility for transport of lamps from retailers in Sweden remains to be seen with this aspect remaining vague in the recast legislation. Annex V of the WEEE Directive specifies a target of 80% of collected gas discharge lamps to be recycled and Annex VII specifies that treatment should include removal of mercury.

The duty to provide information to consumers about the WEEE system for lamps is distributed differently in the Nordic countries, with different emphasis on the roles of PROs, municipalities, and retailers. PROs interviewed generally felt that adequate information was being provided while municipal organisations were more likely to acknowledge that this was an area that could still be improved. While consumer knowledge about WEEE in general was perceived as high, there were different perceptions about consumer awareness of disposal requirements and environmental impact of waste discharge lamps in particular. In Sweden, lamps were specifically targeted in information campaigns by the main PRO (El Kretsen) and the national waste management association (Avfall Sverige). In Denmark, the provision of this information was seen to be more the responsibility of the lamp PRO, and it did run awareness campaigns every few years. In Norway, the national waste management association (Avfall Norge) began an awareness campaign for small WEEE, including lamps in 2014. In Finland there have not been lamp-specific campaigns, and better information provision, particularly from retailers with new responsibilities under the recast, was seen as an area for improvement.

The organisation of PROs also differs between the Nordic countries. Lamp-specific PROs, like those found in Denmark and Finland, were initiated by the lamp producers who were aware that they were putting a product that contained a hazardous substance on the market and who wanted to ensure the hazards were managed properly at the end-of-life phase for these products and thus not jeopardise market acceptance of these products. Larger umbrella PROs run the risk of having decisions dominated by other waste streams and not ensuring the interests of lamp producers (J. Bielefeldt, personal communication, 26 August 2014). Examining the boards of larger PROs in Norway, it is the case that there is no representation by lighting producers or organisations on the boards of two largest PROs handling lamps and luminaries (see RENAS, 2014; Elretur, 2014).

The competing nature of PROs in Norway has resulted in general issues with collection of WEEE with incidences of PROs refusing to collect from municipalities once they had reached their targets, requiring intervention from authorities. This situation has improved, but the lack of a clearinghouse structure in Norway remains a perceived challenge (E. Halaas, personal communication, 9 December 2014). Lamp-specific PROs and national waste management associations reported more cooperation than competition amongst the several PROs in Finland and Denmark and perceived this as strengths of the systems.

In Sweden, a representative of the lighting industry is a present on the board of the largest PRO, El Kretsen, though the lighting association is only one of over twenty owning industry associations (El Kretsen, 2014). Environmental management of waste gas discharge lamps has also been given priority in Sweden the past few years by Swedish Environment Minister Lena Ek, who has pushed for increased collection of this waste stream from 2011 when meeting with El Kretsen and the national waste management association, Avfall Sverige, about improvements to lamp collection (Pehrson and Balksjö, 2011, 2012; Von Schultz, 2013). This led to a pledge to increase lamp collection by 2 million pieces in 2013 and an information campaign focussed on lamps from households (Avfall Sverige, 2013). In response to this pressure for increased collection of lamps as well as other small WEEE, El Kretsen also initiated a project to make collection of lamps even more convenient with in-store "Collectors" ("Samlaren" in Swedish). The Collectors are closed cabinets positioned most often next to reverse vending machines for beverage packaging in grocery stores. The pilot program with them in Gothenburg, Sweden, was deemed a success. At 14–20 SEK/kg (1.5–2.1 Euro/kg) the Collectors were found to be more expensive than other forms of collection but became more cost effective with time as consumers became more aware of this option and collection increased (El Kretsen and Sörab, 2011). Collectors are currently being deployed first in major cities and increasingly in municipalities throughout southern Sweden where over 60 Collectors have been placed in grocery stores in 2014 and early 2015. The initiative is being led by municipal waste companies and is partially financed by producer compensation to municipalities for collection of WEEE (A. Persson, personal communication, 9 September 2014).

3.1.2. Collection and recycling performance

The general WEEE system architectures in the Nordic countries are described as best examples and perform well in relation to the WEEE Directive goals (Román, 2012; Ylä-Mella et al., 2014a). The general architecture also encourages high performance in the category of gas discharge lamps with the Nordic countries among the top five in Europe in 2012 (Fig. 2) when measuring collection in terms of kilograms per capita.

However, when considering the collection rate compared to the amount of gas discharge lamps put on market, a different situation is found. Nordic countries performed better than the overall EU average of 37% in 2012 (see Table 1), with the exception of Norway. It should be noted that statistics for this product category are highly variable for countries with small amounts of gas discharge lamps recorded (for example, Eastern European countries). When countries with larger lighting markets are compared (Fig. 3), Sweden,

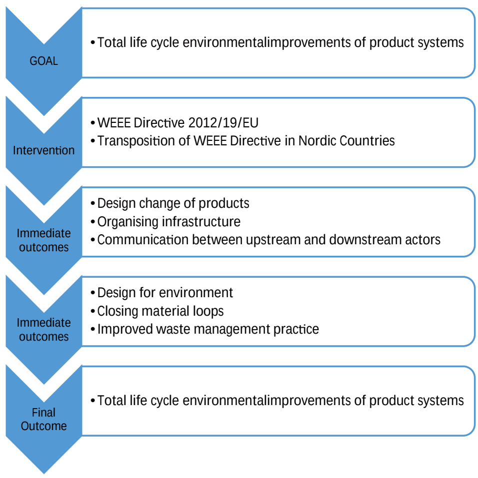

Fig. 1. Simplified intervention theory for EPR programmes and specifically the WEEE Directive, based on Tojo (2004).

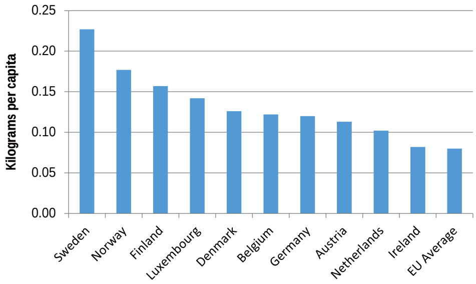

Fig. 2. Top 10 performing European countries, kg per capita collection of gas discharge lamps.
Source: Eurostat, 2014.

Denmark and Finland show consistent collection rates that compare well with other countries and again indicate advantages to the WEEE systems in these countries. The same cannot be said for Norway, for which statistics indicate a consistently lower performance than the EU average. In terms of recycling, all four countries have high treatment rates for the collected lamps, exceeding the minimum 80% recycling in the WEEE Directive (see Table 1). Additionally, all Nordic countries comply with the requirement to remove the mercury in recycling process for gas discharge lamps.

In the absence of specific information about a possible target for the collection of lamps under the WEEE Directive, it is difficult to gauge how Nordic countries will perform if one is introduced after the review in 2015. In relative terms to other countries though, it can be anticipated that Nordic countries are well-positioned to meet such a target, though Norway may need to improve if the target takes into account put on market data for collection rather than weight per capita. However, regardless of any specific targets, increasing the collection and recycling of gas discharge lamps results in environmental benefits that should make continuous improvement of collection and recycling a goal.

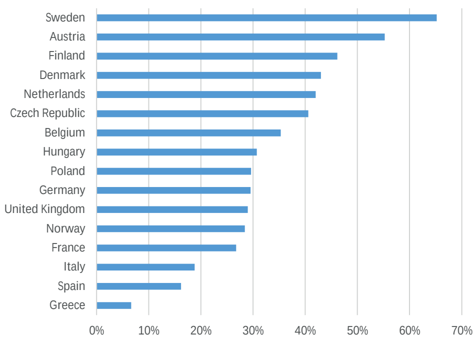

Fig. 3. Collection % for countries with market over 1000 tonnes based on 2010–2012 average collection % of gas discharge lamps (GDLs) compared to put on market 2007–2011 based on Eurostat (2014). Note: Netherlands data estimated based on 2012 (tonnes) Eurostat (2014) put on market data and Huisman et al. (2012) estimates of per capita lamps put on market 2010. Collection % from 3 years (2010–2012) were averaged to account for higher variability when looking at this product category. Note that GDL data in practice often contains LEDs and other light sources and can be deemed an estimate only.

3.2. EPR outcomes for energy efficient lamps in Nordic countries

In general, EPR interventions should produce three intermediate outcomes that lead to the policy goal of total life cycle environmental improvements of product systems (Fig. 1 and Tojo, 2004): 1) design for environment, 2) closing material loops and 3) improved waste management practice. The performance of the Nordic EPR systems for lamps is considered in light of these outcomes.

3.2.1. Design for the environment

Interestingly, gas discharge lamps are one of the only EEE product categories whose lifespan has increased in recent years (Bakker et al., 2014). Additionally, levels of mercury in gas discharge lamps have also decreased and LED technology now becoming more competitive can eliminate mercury altogether in new energy efficient lamps. These developments have significant implications for the end-of-life impact of energy efficient lighting products. In some cases, such developments are likely also to have been motivated by other EPR-related legislation, for example the Restriction on Hazardous Substances (RoHS) Directive which limits mercury content. In other cases factors beyond EPR are likely also influential, for example, the Ecodesign Directive phasing out less efficient light sources, competitive technology development, company culture, etc.

Earlier research by Gottberg et al. (2006) explored the impact of EPR legislation in the lighting sector, including several Swedish producers, and found little evidence of ecodesign in response to the financial responsibility of EPR. Despite initial concerns by lighting producers about the costs of EPR legislation being higher than relative to the product price (Philips Lighting, 2012), lighting products are also characterised by inelastic demand that has allowed producers to more easily pass on compliance costs to consumers. The cost of EPR compliance depends at which point this cost is being considered. EPR compliance costs have been found in some cases to be a small percentage in relation to total product costs and in others quite high. Despite the wide range, Gottberg et al. (2006) argued that the cost of EPR was a small economic driver for ecodesign changes in relation to other product requirements. In all Nordic systems, undifferentiated fees (fixed in Sweden, but by market share in the other countries) are faced by all producers and this also gives little financial incentive or comparative advantage for improving products. For example, there is no differentiation among the producer responsibility organisations in the fees charged for LEDs in comparison to gas discharge lamps, despite the presence of mercury only in the latter. One challenge to doing this is the reality that LEDs and gas discharge lamps in Nordic countries are collected, transported, and treated together so they incur the same costs, though it is unclear whether LEDs, if separated, could be recycled in a more cost efficient process. LEDs do not contain mercury, but do contain some hazardous materials such as lead (see Lim et al., 2013). Another concern with differentiation expressed by PROs interviewed is that if LEDs were differentiated that treatment for gas discharge lamps would be left underfinanced.

In their research Gottberg et al. (2006) consider EPR mainly as an economic instrument and only the financial responsibility as a motivation for product design improvements. However, EPR is also about information flows between consumers, recyclers, and producers. Interviewed producer responsibility organisations and recyclers for lamps reported different levels of communication with producers about the end-of-life attributes of their products. In cases where the recycler or producer organisation had information to provide in this regard, it was reported that the contacts with the producers were generally not in the design department, which was often located in another country. Such anecdotal evidence indicates a possible prerequisite for design change may be missing; namely, communication between upstream and downstream participants may not be taking place in a way that facilitates relevant information from downstream reaching those working with producers who have an influence over design decisions. However, even if this information does reach product designers, its usefulness may be limited due to the (increasingly) long life of lighting products. Indeed, other drivers including market competition and company culture were found to also be able to explain design improvements in the lighting sector and causation to EPR legislation alone could not be established (Gottberg et al., 2006). This is not surprising given the challenges for design incentives for lamps and these are further discussed in Section 4.2.

3.2.2. Closing material loops

In theory, almost all the material from gas discharge lamps can be recycled and some components even re-used, for example the glass tubes if using an end-cut method (Nordic Recycling, 2014) or phosphor coating if reused by the same type of lamp and manufacturer (Binnemans et al., 2013). Table 2 illustrates the possible end uses or disposal options for fraction from gas discharge recycling processes; however the actual end use of fractions is highly context specific.

In practice, materials from the recycling process in Nordic countries are not used again in the production of new lamps. Currently, most waste lamps in Nordic countries are shredded together in a wet process (as opposed to the end cut method, for example) (Nordic Recycling, 2014). In Finland, collected lamps are recycled at one location in Finland (Ekokem, 2014). PROs in Norway and Sweden (and at the time of writing, also Denmark) send waste lamps to be recycled in one location in central Sweden. While this arrangement helps to increase economies of scale in treatment, the recycler faces challenges in returning glass and other materials long distances to lamp manufacturers and this is part of the reason these materials are not recycled in a closed loop.

It is also difficult to transport the glass fractions long distances to glass recyclers in Sweden and Europe as the cost for the transportation will decrease profit. For this reason, much of the glass is currently used as construction material in landfill cover; though higher level alternative uses are being actively sought (G. Lundholm, personal communication, 26 October 2014). The lamp PRO (LWF) in Denmark had been sending crushed lamps for recycling in Germany where more fractions could be used for new lamps, but the recycler has since closed, forcing it to use the same recycler as PROs in Norway and Sweden (but in a new tender process at the time of writing). In Finland the glass fraction is delivered to a nearby glass recycler who can use it to produce foam glass, as well as glass powder (Uusioaines Oy, 2014).

Other fractions, such as the metal, are easily sold and used by local metal recyclers. The small fraction of plastics is generally incinerated in the Nordic countries. In many EU countries the mercury containing phosphor layer is landfilled or stored in salt mines rather than recycled (Solvay, 2014). Solvay Rhodia in France began the first commercial scale recycling of lamp phosphors, separating rare earth oxides for use in new phosphor powders in 2011 (Walter, 2011). It buys fractions from recyclers based on the amount of rare earth material and deducting for the amount of mercury, glass, and other impurities. The recycling process used for Swedish, Danish, and Norwegian lamps produces a phosphor fraction of high enough quality that it can be sold for this recycling. Though not at a large profit, this further recycling also avoids the cost of hazardous landfill. This is made possible both by the recycling process and the scale of the centralised treatment. By contrast the Finnish recyclers have studied the use of phosphor but it is currently produced in such small quantities, and in a less useful form, that it does not make sense to recycle the phosphors (J. Koskinen, 29 January 2015, personal communication).

3.2.3. Improved waste management practice

The collection and recycling of gas discharge lamps represents a significant improvement in waste management practice compared to a situation where there is no legislation or policy for collection and recycling. Even before EPR legislation, the mercury present in gas discharge lamps did make them a concern in countries like Sweden. Voluntary programs for collection and recycling were set up in Sweden, mainly for business end-users (who were the majority of the users in the early stages of the technology). Between 1993 and 1998 the collection rates for gas discharge lamps in Sweden was roughly estimated between 10 and 25% and this was perceived as inadequate in light of the risks of mercury emissions associated with the waste products (Kemikalieinspektionen, 1998). OECD countries with some waste legislation or voluntary programs, but lacking mandatory EPR legislation, also have very low collection and recycling rates of lamps. For example, it is estimated that 95% of fluorescent lamps in Australia are landfilled (Lighting Council Australia, 2014), while Canada, Japan, and Mexico are estimated to collect and recycle less than 10% of waste lamps (EU Commission, 2008). The United States has some, mainly state level, legislation for management of waste lamps, focussed on end user (primarily business) responsibility. However, enforcement is low and the collection and recycling rate is estimated around 23% (Silveira and Chang, 2011).

EPR systems in Nordic countries continue to evolve, with Finland and Sweden using the recast to include new retailer take back options for consumers. Increasing the collection of small WEEE in particular requires increasing attention to factors which influence recycling behaviour, for example motivation, convenience and capacity and the available recycling infrastructure can influence all three of these (Melissen, 2006; Wagner, 2013). Using more retailers to take back waste lamps regardless of purchase (prior, retailers were required to take back a product if an equivalent product was purchased) is a way to further increase the number of convenient return options for household consumers. Such retailer take-back has been successful at the municipal level in the U.S. (where other recycling options for households are not

Table 2
Fractions and end uses from waste gas discharge lamps.

Fractions	Possible part (compact fluorescent – fluorescent tube)	End use/disposal
Aluminium/other metals	18–30%	Reused or recycled
Mix of plastic and metal	20%	Recycling; energy recovery; landfill
Glass	45–80%	Reused for fluorescent tubes; lamp glass; glazing; glass wool insulation; fusion agent with black copper foundry; abrasive sand for cleaning, under layer for asphalt; sand replacement; silicon substitute, landfill cover
Rare earth powder, also containing mercury and small glass particles	2–3%	Separated and reused as mercury or phosphors in new lamps, separated and recycled after rare earth processing; powder and Hg landfilled as hazardous waste

Sources: Nordic Recycling, 2014; WEEE Forum, 2011.

provided), achieving recycling rates of over 36% from near 0% previously (Wagner et al., 2013). However, because of the existence of established and better known recycling centres in municipalities in Nordic countries, the impact of retailer take back is anticipated by some stakeholders to have a small, but still positive, impact on collection of lamps. In Denmark and Sweden there was also evidence of municipalities collecting waste lamps through kerbside collection for detached households through plastic bags or boxes attached to the top of kerbside recycling bins. While this type of kerbside collection is relatively new and effectiveness has yet to be fully assessed, the initiatives represent attempts to further optimise collection of this waste stream. Another form of kerbside collection, collection small bins in apartment complexes, has been more established in these countries, as is mobile collection from households a few times year.

There were mixed views on whether more market oversight was necessary or whether enforcement was adequate in all countries. In the Nordic countries market enforcement is undertaken by typically small authorities (in terms of resources devoted to enforcement of WEEE legislation) and takes the form primarily of guidance about rules and response in the cases of complaints. Interviewed stakeholders perceived that high levels of cooperation amongst PROs and municipalities were part of why general WEEE systems performed well in the Nordic countries. While there were some concerns about free-riders in the systems, this was not perceived to be a major inhibitor of the function of the system, but rather an area where the system could still be optimised, but requiring greater resources than currently available.

4. Best practices and remaining challenges

4.1. Factors in best practice

In contrast to other waste streams, lamps are small, meaning they can be easily disposed of in residual waste, and represent a net cost to collect and recycle, meaning there is no natural economic incentive in absence of legislation (Huisman et al., 2008). Mandatory EPR legislation for lamps is it appears key for higher collection and recycling of this product group. However, the fact that collection and recycling rates in the EU member states and even amongst the Nordic countries also vary indicates that having the legislation, or a rule base, itself is not enough for excellent collection and recycling rates. From the analysis of the Nordic systems, we identified several common factors that contribute to excellence in operational performance (Fig. 4).

Building on a robust and transparent rule base, the system infrastructure is also essential. Enforcement of the rules needs to be adequate to allow focus on continuous improvement rather than incentivising a focus on lowest costs by avoiding compliance. As is seen in the Nordic cases, the strength and resources devoted to the authorities can be fewer in a situation with high compliance and cooperation. Such voluntary action on the part of actors is key, particularly in areas where the rule base is vague. For example, sound financial management is stipulated by the WEEE Directive (Article 12) but how producers and PROs incorporate end-of-life costs is still open to interpretation (Article 12.6 invites the Commission to report "on the possibility of developing criteria to incorporate the real end-of-life costs into the financing of WEEE by producers…"). With the requirement for a financial guarantee waived in most Nordic countries with the participation in a collective scheme (i.e. a PRO with a sufficient number of members to guarantee financing), the financial stability of the collection system rests upon the financial management of these PROs. Whether the arrangements are adequate remains to be seen and tested with more experience. The recycling technology used in the Nordic countries ensures significant mercury emissions are avoided. In addition, despite being small markets on their own, the high level of collection and recycling of these lamps in Nordic countries, the recycling technology to produce powder fractions, and the development of Solvay Rhodia's capacity to utilise these powders, has made recycling of rare earths from waste lamps a reality. In view of the criticality of rare earths (Koninklijke Philips Electronics N.V., 2011; Moss et al., 2013), this development in closing the rare earth loop from lamps is a significant contribution to a more circular economy in the EU.

Information provision ensures that key actors in the EPR system architecture know their role. It is also the basis for continually improving the system. In Nordic countries, a variety of actors engage with information provision to consumers through a variety of media. While the high collection rates could be indicative of the effectiveness of information campaigns, this is unclear in the case of Norway. The high visibility of waste lamps in the media due to the attention of the Minister for the Environment in Sweden may have been just as effective as the subsequent information campaign from the PROs and waste management organisations. The actual level of awareness and responding behaviour of households in the Nordic countries remains an area for further study.

In terms of the collection system in place in the Nordic countries, it can be seen that there has been a concerted effort to provide multiple means of taking back products and this continues to evolve with retailer-takeback and kerbside collection. Such options further increase the convenience of services offered to households, which in turn are particularly key aspects for optimising collection systems for small WEEE like lamps (Melissen, 2006; Wagner, 2013).

4.2. Remaining challenges

The experience with EPR systems in the Nordic countries reveals well-performing systems, however, with the exception of Sweden, not as dominant as for WEEE in general. The general collection of lamps compared to some other categories of WEEE is consistent with the challenges identified with lamp and small WEEE collection in general. Small WEEE is more easily disposed into other waste streams, and there is some evidence of this still happening, particularly in the general glass recycling and residual waste (see e.g. El Kretsen and Sörab, 2011; Elretur, 2012; Pehrson and Balksjö, 2012). However, the small documented amounts in these streams indicate that knowledge is still missing about how consumers deal with lamps at the end-of-life (for example, they are also small enough to be stored and not ending up in any waste stream for several years). This was noted as a continuing challenge by interviewed stakeholders in all four countries.

Obtaining accurate and useful data for measuring and comparing collection rates remains a significant challenge.

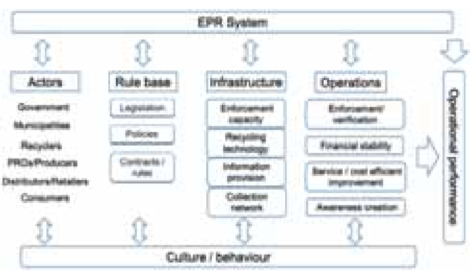

Fig. 4. Common factors contributing to excellence in operation performance of an EPR system.

Producers are required in some countries to report based on amounts (C. Andersson, personal communication, 13 May 2015), which are then converted into kilograms for reporting at the EU level, which in turn leaves room for error and inconsistency. This is particularly the case regarding put on market data, which also utilise the combined nomenclature (CN) codes used for trading and customs. For lighting products these codes are quite general (Wang et al., 2012) and do not align with WEEE product categories. It does not help that lighting technology is also changing at a rapid pace, faster than codes which explains why LEDs can be classified under different CN codes and with which the distinction between lamps and luminaires becomes less obvious (LightingEurope, 2014). With this complexity comes the risk that put on market data can be multiplied though double-counting or codes used erroneously. Additionally, lag times resulting from consumers delaying disposal of waste lamp products could affect the collection data. Also, as lifetimes of lamp products have extended, the three year average from put on market may not be the most relevant measure of collection effectiveness. It has been proposed that at least 6 years is a more accurate measure of the historic collection rate (European Lighting Companies' Federation, 2003). Even if this change was made, it would be a few more years before there is adequate data to measure this robustly (Sander et al., 2013).

Despite the reasons for making collection and recycling of gas lamps a priority, there is still the risk that this product category receives less emphasis in the overall WEEE system with targets still based on the overall weight of collected WEEE. There is some evidence from Denmark and Finland that the presence of lamp-specific PRO may ensure that lamps are adequately emphasised. However, the case of Sweden demonstrates that the emphasis on this product category can also be made by other stakeholders (in that case, the Minister for the Environment) and in fact this may be even more effective in motivating collection. The effectiveness of recent education campaigns in Norway to raise awareness of small WEEE collection, in which lamps are given special emphasis, still has to be gauged, but thus far having neither lamp specific PROs nor a particular emphasis on collection of lamps from other influential stakeholders may help explain the significant difference in performance between this category compared to WEEE collection overall in that country. Interviewed stakeholders also indicated that there was still room for raising the level of consumer awareness about gas discharge lamps to include not only disposal options, but the benefits of recycling these products for the environment and closing valuable material loops.

Further optimisation of materials in closing the loop and improving design requires communication between (the right) upstream and downstream actors. The problems with EPR systems incentivising design change are not unique to lamps, but an overall acknowledged challenge for WEEE systems in general (Huisman, 2013; Kalimo et al., 2012; Lifset et al., 2013; van Rossem et al., 2006b). However, there are challenges also unique to lamps due to the increasingly prolonged life of lighting products. Unlike many other categories of WEEE products in which turnover of products becomes shorter and shorter, new energy saving lamp products have an average lifespan of 8500 h for a CFL and 25,000 h for LEDs (U.S. Department of Energy, 2012), which can correspond from a few years to several decades depending on actual use.[3] The lighting industry has used an average of six years (European Lighting Companies' Federation, 2003), but even this means communicating information to upstream producers as information from actual recycling is often too late to be relevant for the current design of lighting products. Product designers then must be incentivised to design with end-of-life management in mind without empirical knowledge of that management. The challenge of providing such incentives is compounded by the fact that consumers of lighting products do not necessarily respond to environmental design and reward such efforts. Despite new standards and more efficient lighting options available, the least expensive and least environmentally beneficial lighting products continue to dominate the market in Europe (Bennich et al., 2014). In light of these challenges, it may well be that EPR, while part of the means to communicate and incentivise consideration of end-of-life management at the design stage, is not sufficient to overcome the other influences on design. These barriers may need to be addressed through more direct tools to influence ecodesign.

The development of new technology such as LEDs and more integrated products in lighting is increasing in its pace and market penetration (McKinsey and Company, 2012). Such technologies bring a new set of challenges for WEEE system for lamps. It is unknown whether the smaller amounts of rare earth material (in addition to other critical materials like Gallium and Indium) will have the same potential for recycling as the gas discharge lamps. The longer lifetimes of these products may also result in less waste material overall to be collected and recovered. The best ways to deal with hazardous materials as LEDs become the dominant lamp type in the waste streams remains a question as to the best recycling techniques for integrated LED products. The long life of these products and the rapid development of the products may mean that they are disposed before their end-of-life, in which case opportunities for reuse of some components may become possible. Prevention of waste and product design for recycling, one of the key aims of EPR is still a challenge for lamps, and consideration of the new technology will be key to further advancing a circular economy.

5. Conclusion

Collection and recycling of gas discharge lamps should be a priority in a circular economy, in consideration of both the avoided environmental harm of mercury emissions and the potential for recycling of valuable materials. Nordic countries perform well in the collection and recycling of gas discharge lamps compared to other EU countries, and this performance can be attributed to robust system architectures, as a result of the rule base but also other factors. There is evidence that the systems continue to improve in terms of convenience and in closing material loops, with the recycling of rare earths from lamp phosphors a notable development. However, challenges remain to further optimise the systems, particularly in terms of meeting EPR goals for better design and in light of rapidly changing technology.

Acknowledgements

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[3] 8.500 is an average but it should be noted that the use varies significantly. In a professional situation the product would typically be used more intensely than home use, but the users also typically purchase different specifications of lamps (i.e. 6000 h CLFs versus a 15,000 h LFLs). So this could result in a majority of fluorescent lamps being disposed around 6000 h, but with a long tail extending decades.

Appendix A. List of interviewed stakeholders

	Name	Organisation, position	Stakeholder group	Interview date
Denmark	Jan Bielefeldt	Lyskildebranchens WEEE Forening (LWF), Administrative Director	Producer Responsibility Organisation (lamps)	In person interview – 26 August 2014
	Jonas Engberg	Ikea, Sustainability Manager Denmark	Retailer	In person interview – 26 August 2014
	Hardy Mikkelsen	Reno Djurs, Environmental Manager	Municipal Waste Organisation	Phone interview – 4 December 2015
	Lotte Wammen Rahbek	Forsyning Helsingør, Waste planner	Municipal Waste Organisation	In person interview – 15 December 2014
	Niels Remtoft	Dansk Affaldsforening, Special Consultant	National Waste Management Association	In person interview – 15 December 2014
Finland	Senja Forsman	SOK Grocery Chain Management, Compliance Manager	Retailer	Phone interview – 4 December 2014
	Timo Hämäläinen	Finnish Solid Waste Association, Development Manager	National Waste Management Association	Phone interview – 19 December 2014
	Jorma Koskinen	Ekokem, Sales Group Manager	Recycler	Email correspondence – 29 January 2015
	Jesse Mether	Rautakesko Ltd, Sustainability Manager	Retailer	Email correspondence – 19 December 2014
	Perrti Raunamaa	FLIP, Administrative Director	Producer Responsibility Organisation (lamps)	Phone interview – 8 December 2014
	Tuomas Räsänen	Elker Oy, Chief Operations Officer	Producer Responsibility Organisation	Email correspondence – 22 January 2015
Norway	Ellen Halaas	Avfall Norge, Adviser for framework and law collection, sorting and recycling	National Waste Management Association	Phone interview – 9 December 2014
	Guro Kjørsvik Husby	El Retur, Information Officer	Producer Responsibility Organisation	Email correspondence – 24 November 2014 and 8 January 2015
	Bjørn Thon	RENAS, Administrative Director	Producer Responsibility Organisation	Phone interview – 30 January 2015
Sweden	Carina Andersson	IKEA of Sweden, Product Laws & Standard specialist – Producer Responsibility	Producer	Email correspondence 13 and 15 May 2015
	Jessica Christiansen	Avfall Sverige, Education Manager/Controller Technical Advisor WEEE	National Waste Management Association	In person interview – 16 December 2014
	Jonas Carlehed	IKEA, Sustainability Manager Sweden	Retailer	Phone interview – 30 January 2015
	Lars Eklund	Natursvardsverket (Swedish EPA), Advisor Environmental Enforcement	Government authority	Phone interview – 2 December 2014
	Göran Lundholm	Nordic Recycling, General Manager	Recycler	In person interview – 13 August 2014; phone interview – 27 October 2014
	Dolores Öhman	Hässleholm Miljö, Head of Waste Collection and Customer Service	Municipal Waste Organisation	In person interview – 3 September 2014
	Anders Persson	SYSAV, CEO	Municipal Waste Organisation	In person interview – 9 September 2014
	Mårten Sundin	El-Kretsen AB, Marketing Manager	Producer Responsibility Organisation	In person interview – 5 December 2014
	Hans Standar	Svensk GlasÅtervinning AB, CEO	Glass recycler	Phone interview – 4 December 2014
	Joseph Tapper	Elektronikåtervinning i Sverige, CEO	Producer Responsibility Organisation	In person interview – 5 December 2015
Additional correspondence		SERTY (Finland), ERP (Denmark)	Producer responsibility organisations	Email correspondence

Appendix B. Sample interview protocol for producer responsibility organisations

1. In other countries there are different situations regarding a separate PRO for lamps. What are the advantages and disadvantages having a PRO focussed solely on lamps? What else distinguishes [organisation] from other PROs operating in [country]?
2. How does the general WEEE system affect the take back of lamps? Would you characterise the system as competitive or cooperative for collection between the PROs?
3. What do you find to be the particular challenges to take back of lighting products? For example, collection, transport and recycling for lamps have been described as very expensive compared to other WEEE categories but the costs are different in each country context. What are the main cost factors and how is [organisation] working to make the system as cost efficient as possible?
4. There are statistics from Eurostat regarding recycling in [country]. The collection rates vary depending on how you count, for example historically versus same year as well as how you divide product categories. How does [organisation] measure collection and recycling effectiveness for lamps and are there challenges to collecting good information (e.g. from producers).
5. How does your organisation communicate with other stakeholders like producers, producer responsibility organisations and government authorities – is there a specific forum for this?
6. Is there any information or communication with producers regarding the end-of-life/recyclability of products? How do the producers respond?
7. Do you have information about how recycled fractions from collected and treated products are used? Is there interest/action on using these fractions in particular ways (e.g. in lighting products).
8. Do you differentiate fees in any way depending on the product? Is there likely to be any differentiation between CFL and LEDs in the near future?
9. How are producers active in the system through your PRO?
10. The EU is considering a separate target for gas discharge lamps. What is your organisation's view about this?
11. In the media in some countries, it has been highlighted that there are still lamps ending up in incineration and glass recycling. Is it an issue in [country]?
12. Transporting hazardous waste such as lamps could pose risks from mercury for waste handlers. Is handling mercury-containing waste products or broken lamps an issue in [country]?

13. There is the website and some material from [organisation], are there any other ways [organisation] is working with education and information to raise awareness about WEEE recycling?
14. Are there strengths or weaknesses you perceive to the [country] WEEE system compared to other Nordic countries?
15. Nordic countries are often cited as the best practitioners of WEEE recycling - what do you think are the main factors in success?
16. Improving collection and recycling is a continuous challenge, what do you think are the main areas that still need significant improvement? Is there more that can be done with critical materials recovery for instance?

Appendix C. Sample interview protocol for national waste management associations

1. What are the main issues in producer responsibility for WEEE where your organisation is involved on the member's behalf?
2. How does your organisation communicate with other stakeholders like producers, producer responsibility organisations and government authorities – is there a specific forum for this?
3. Are there any issues with working with the relationship between municipalities and PROs in [country]? Is it a contract or other agreement on how the responsibility is allocated and managed for collection points and collection?
4. Would you characterise the system as competitive or cooperative for collection between the PROs?
5. Transporting hazardous waste such as lamps could pose risks from mercury for waste handlers. Is handling mercury-containing waste products or broken lamps an issue in [country]?
6. From [organisation] reports there are still some lamps found in residual waste. Are these and other small electronic waste perceived as a particular problem?
7. How are municipalities and/or your organisation working with increasing collection of lamps and other small WEEE? Are there any pilot projects or innovative examples to further optimise the WEEE system in this respect?
8. There is the website and some material from [organisation], is there more [organisation] is doing to educate about hazardous waste like gas discharge lamps?
9. The EU is considering a separate target for gas discharge lamps. What is your organisation's view about this?
10. Are there strengths or weaknesses you perceive to the [country] WEEE system compared to other Nordic countries?
11. Nordic countries are often cited as the best practitioners of WEEE recycling - what do you think are the main factors in success?
12. Improving collection and recycling is a continuous challenge, what do you think are the main areas that still need significant improvement?

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Full length article

Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties

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ABSTRACT

Rare earth element (REE) recycling remains low at 1%, despite significant uncertainties related to future supply and demand and EU 2020 energy efficiency objectives. We use a global production network framework of REE flows from mine to REE phosphors in energy-efficient lamps to illustrate the potential of closed-loop recycling for secondary supply under different scenarios of primary supply and forecasted demand for LEDs, CFLs and LFLs. We find that different End-of-Life Recycling Rate scenarios for REE secondary supply range between meeting forecasted REE demand and filling primary supply gaps, and competing with primary supply. Our argument centres on diversifying REE sourcing with recycling and the choice between primary and secondary supply. We stress that secondary REE phosphor supply requires further policy support for lamp collection and a discussion of the value of REE phosphor recycling which underlies its economic feasibility.

1. Introduction

With an increase in energy efficiency of 20% to be achieved by 2020 within the European Union (EU), lighting presents a core area of interest. Replacement of inefficient bulbs by 2020 is expected to enable energy savings to power 11 million households a year. In 2009, regulations pursuant to the EU Eco-design Directive introduced stricter energy efficiency requirements for lighting products, which induced a phase-out of incandescent lamps (EU Commission, 2009, 2014a). By 2016 it is expected that a majority of these lamps will be phased out, with similar legislations implemented in other nations including Australia, BRIC countries, Japan, South Africa, and the United States (UNEP, 2014).

The lifetime of incandescent lamps is about four times shorter and their efficiency significantly less than compact fluorescent lamps (CFLs), with 15 lumens of visible light per watt of electricity consumed (lm/W) versus 63 lm/W (Wilburn, 2012). A linear rather than bulb shape characterizes linear fluorescent lamps (LFLs). Fluorescent lamps emit light when voltage is applied to the mercury gas within the glass body, which produces UV light that is transformed to white light by the phosphor powder coating of the lamp (Lim et al., 2013). Light emitting diodes (LEDs) have a lifetime approximately three to six times that of CFLs (Wilburn, 2012). LEDs emit light when electric current passes through a semiconductor chip and they are distinct to fluorescent lights in that they contain minor proportions of phosphor powder and no mercury.

While the market share of LEDs is projected to accelerate, the transition from fluorescent lights will take time partly due to the upfront costs of LEDs in comparison to CFLs and LFLs. McKinsey & Company (2012) expect CFLs and LFLs to remain with a share in the lighting technology distribution until 2020, yet their significance is anticipated to decrease faster jointly with market demand for REE in fluorescent lamps, as envisioned by Solvay and General Electric and illustrated in Fig. 2 (Cohen, 2014). Of central concern to the lighting industry are phosphor powders in these lamps, which contain rare earth elements (REE) used for their luminescent properties and key to producing white light (Binnemans et al., 2013a).

Since the early 1990s, China has gradually emerged as the largest consumer and producer of REE. The country hosts the majority of global mining and processing of these elements and has enacted numerous policies including quotas for mining and export (latter

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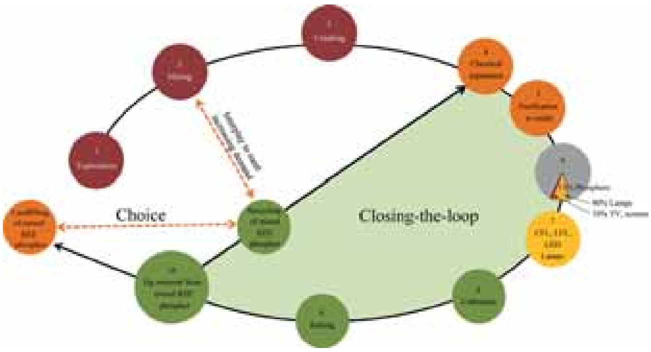

Fig. 1. Global production network of REE phosphor-based, energy-efficient lamps. Source: adapted from Erecon (2014) and Simoni (2013) with % indication of REE phosphor share of total REE market (derived from Castilloux, 2014a) subdivided into estimated 90% of phosphors used in energy-efficient lamps, and 10% for TVs and screens (Balachandran, 2014).

replaced by export licences in January 2015, see Bloomberg News, 2015) and a two-tier pricing system, under which REE cost less in China than in the rest of the world (ROW), introduced by export duties and trading rights, which significantly increases the price of exported REE products (WTO, 2014). Concerns about decreases in REE availability outside China intensified with the price increase of export-destined REE products by up to +600% in 2011 (Massari and Ruberti, 2013). Lawsuits against the REE export policies by China were filed at the WTO (2012) by the EU, Japan and the U.S. and in response to the WTO (2015) Dispute Settlement Body, China removed the application of export duties and export quotas to REEs, and the restriction on trading rights of enterprises exporting REEs. It remains uncertain how subsequent new Chinese industrial policy measures, including new export licences and the ad-valorem tax, will affect the market over the long-term. Strategies to target these concerns address the diversification of REE supply outside China, including re-opening old mines or establishing new mines, and include discussions about whether government intervention would be justified in recognizing the need for integrated value chains (Machacek and Fold, 2014; Tukker, 2014; Zachmann, 2010). Simultaneously, efforts in design to reduce and substitute REE in product components and recycling have surged, aiming to prevent future supply risks.

This study contributes to the discourse on REE recycling with a value analysis of recycled heavy REE europium (Eu), terbium (Tb) and yttrium (Y) from phosphor powders of fluorescent lamps as source of supply at times of EU and U.S. REE criticality classification (EU Commission, 2014b; Richter and Koppejan, 2015; U.S. Department of Energy, 2011). Today, at most 1% of all REE used in different applications are recycled (Binnemans, 2014; Binnemans and Jones, 2014). The role of REE recycling has been explored and critically reviewed in general (Guyonnet et al., 2015; Moss et al., 2013; Schüler et al., 2011; U.S. Department of Energy, 2011) and from the viewpoint of specific REE, laboratory experimentation and product groups (Bandara et al., 2014; Binnemans et al., 2013a; Dupont and Binnemans, 2015; Eduafo et al., 2015; Habib et al., 2014; Kim et al., 2015; Rademaker et al., 2013; Sprecher et al., 2014; Tunsu et al., 2015). While several studies have concluded that recycling of REEs is worthwhile and requires a broader strategy to enable REE processing capacities, including tracing the REE from mine to end of life (EoL) waste (Rademaker et al., 2013; Sprecher et al., 2014), none have provided an in-depth analysis of commercial scale recycling and what is needed to upscale recycling. To this end, this study provides an empirical analysis, using a case study of REE phosphor recycling on a commercial scale and an ex-ante analysis of the market from 2015 to 2020 to assess and discuss the potential for recycling of REE from energy-efficient lamp phosphors. We discuss what factors, including regulatory instruments and rethinking value propositions, are necessary to realize such potential.

2. Methodology

Our conceptual approach involves a qualitatively informed global production network framework to depict value adding, or processing steps from REE-containing ore to REE content in phosphor powders as used in energy-efficient lamps. This is the framework from which we then research the potential for secondary supply and closing the loop for REE in lamp phosphors through a mixed methods approach involving both a case study and modelling. Our case study provides an ex-post analysis of the experience of commercial REE recycling of REE phosphor containing lamps. This and our forecasts of supply and demand of Y, Eu and Tb then underpin the ex-ante analysis of the potential for development of secondary supply of REE phosphors from 2015 to 2020.

2.1. Global production network of rare earths and phosphors

Five steps, depicted in Fig. 1, precede the production of REE phosphors. Investor interest in favourable returns on investment finances prospecting and exploration of REE which enables data

Fig. 2. Forecasted development of the total global lighting market and lamp type shares. *Source*: Adapted from McKinsey & Company (2012).

collection for sequential reporting required for the decision on the granting of an exploitation licence. Mined REE-containing ore is beneficiated by crushing and grinding, mineral separation, adjusted to the REE-mineral type, REE-grade and the mineral assemblage.

Next a cracking process leaches the REE from the REE-minerals resulting in a concentrate of mixed REE solution. A chemical separation into individual REE follows. Most recent estimates partially produced from primary data suggest that REE use in phosphors accounted for 11% of total REE market demand in 2013 and for 19% of REE market demand value in the same year (derived from Castilloux, 2014a). Usually, phosphor manufacturers buy a concentrated REE product (oxides or compounds, see Lynas Corporation, 2014) for direct use in producing various patented phosphor powder compositions (Wilburn, 2012). The 11% phosphors are then used by various phosphor using applications (Castilloux, 2014a), with an estimated 90% for phosphors in energy-efficient lamps, and 10% for TVs and screens (Balachandran, 2014).

REE-based phosphor powders use varying amounts of REE, resulting in a wide variety of powder compositions (Ronda et al., 1998), but primarily phosphor powders contain some proportion of Y, Eu and Tb to generate red, green and blue phosphors (Balachandran, 2014). Almost all global supply of Eu, about 85% of Tb and close to 77% of Y are used for phosphors (Moss et al., 2013; Tan et al., 2014). The high purchase cost of phosphors can be attributed to the high (99.999%) purity requirements (Binnemans et al., 2013a) on the REE used and the lower abundance of these heavy REE, relative to lighter REE, in REE-bearing minerals as explained by the Oddo-Harkins rule (Chakhmouradian and Wall, 2012).

The balancing problem (Binnemans et al., 2013b; Falconnet, 1985) adds to this the challenge of selling all REE mined (if stockpiling is disregarded), as demand does not match the natural distributional occurrence of REE. At the time of writing, supply of light REE (e.g. lanthanum and cerium) is not met by equally high demand while some heavier REE (e.g. dysprosium and europium) are in higher demand than supply (Binnemans et al., 2013b). In addition, REE phosphors are both essential and hardly substitutable in the functioning of fluorescent lamps.

In this article we first examine the relationship between global primary supply and secondary supply of lamp phosphor REE through an empirical case, following Guyonnet et al. (2015, pp.1) who emphasize that *'any global (systemic) analysis of mineral raw material supply should consider both types of sources'*. We also model the dynamics in the global production network of REE linked to demand and supply of Y, Eu and Tb for phosphor powders in fluorescent lamps. The assumptions underlying our forecasts are presented below and uncertainties are addressed in Section 4.

2.2. Demand forecast

REE content varies in CFLs, LFLs and LEDs, see Table 1. The data related to the elemental composition of phosphors contained in LFL, CFL and LED has been derived from Castilloux (2014b) for phosphor (g), and Wu et al. (2014) for REE composition in standard tricolour phosphor. The estimated phosphor composition for all these three lamp types is shown in Table 1.

Table 1
Approximate REO content (g/unit) of various energy-efficient light types.

Range of content	Y_2O_3 (g) 46.9–51.2%	Eu_2O_3(g) 3.9–4.4%	Tb_4O_7 (g) 2.2–2.6%
LFL	1.0975–1.1981	0.0913–0.103	0.0515–0.06084
CFL	0.7035–0.768	0.0585–0.066	0.033–0.039
LED	0.0047–0.0051	0.0004–0.0004	0–0

Sources: Castilloux (2014b); Wu et al. (2014).

In our model we use McKinsey & Company (2012) data on general lighting applications (which encompasses lighting in residential applications and six professional applications, namely office, industrial, shop, hospitality, outdoor and architectural) on the number of lamp types, both new installations and replacements, from 2015 to 2020 for all world regions (Europe, North America, Asia incl. China, Latin America, Middle East & Africa). The number of lamps is multiplied with the averaged total REO (g) as per lamp type in Table 1 to estimate the final demand of Y_2O_3, Eu_2O_3 and Tb_4O_7 for these three energy-efficient lamp types.

2.3. Secondary supply forecast

To enhance our understanding of the future demand of phosphors for lighting purposes and the potential role of secondary supply originating from recycling these waste lighting applications, we model demand for Y, Eu and Tb in energy-efficient lamps from 2015 until 2020. The McKinsey & Company (2012) data estimates a range of lifetimes for the different lamp technologies and we use this combined with U.S. Department of Energy (2012) data to estimate the lifetime of the different lamp technologies in whole years to anticipate availability of lamp waste in the model. We use a lifetime of three years for CFLs and LFLs and of eleven years for LEDs, yet noting that lifetimes are highly sensitive to how the lamps are used (i.e. switch cycles, length of use per day, and other factors). We also conducted a sensitivity analysis for lifetimes as part of the later discussion, provided in Table B.4.

Secondary supply of phosphor from lamps is then estimated with end-of-life recycling rates (EoL-RR), also known as recovery rates (Graedel et al., 2011) which consider a collection rate for lamps as well as an estimate of total recycling of the REE from waste lamps. In the model we use collection rate scenarios of 15–40–70%. The 15% collection rate scenario assumes, in line with status quo and global trends, collection rates in Europe of nearly 40% (Eurostat, 2014) and lower collection rates on the state and sub-state level in the U.S., Canada, and Australia (FluoroCycle, 2014; Silveira and Chang, 2011) as well as more environmentally sound management of waste lamps in developing countries (see e.g. UNEP, 2012). The 15% collection rate also reflects a slow uptake of policies and a lack of collection to date in key regions, for example in China (Tan et al., 2014).

The 40% collection scenario assumes that legislation on extended producer responsibility (EPR) and other supportive legislation will be applied globally in major regions, such as the U.S., China and India. Essentially it reflects the average EoL fluorescent lamp collection rate to-date observed among EU countries, with large disparities between countries but an overall 40% average (Eurostat, 2014). This scenario expects the continuous implementation of legislation related to EoL lamp management on U.S. state and sub-state level (Corvin, 2015; Silveira and Chang, 2011), fruition of plans and pilot projects in India (Pandey et al., 2012), and expansion of China's existing EPR legislation to include lamps (Tan and Li, 2014).

Lastly, the 70% collection rate reflects the EU top-end observed in a few countries (Sweden for example—see Eurostat, 2014 and Table B.5; and Taiwan (Environmental Protection Administration, 2012)) and thus the high end of anticipated global collection. This rate represents a scenario with implemented legislation and well-designed systems in place in major regions around the world.

The efficiency of the recycling process also needs considering to estimate secondary supply. Binnemans et al. (2013a) and Tan et al. (2014) assume an overall recycling process efficiency rate of 80%, and we use this assumption with an amendment. We add a key step to the 80% assumption, namely the *recycling of REE phosphors from the waste lamp powders* between collection and recovery of REE. EoL fluorescent lamps are collected and treated to prevent

Table 2
Components of end-of-life-recycling-rates under three different scenarios.

Scenarios	Collection rate of lamps (%)	REE phosphor recycling rate (%)	Recycling process efficiency rate (%)	EoL-RR (%)
Low ambition—top down calculation of EoL-RR of global REE phosphor capacity eqv. to Solvay's capacity (450 t) compared to global total capacity (11,150 t)	15	55	80	**7**
Medium ambition—top down calculation equivalent to Solvay's capacity (450 t) in Europe, North American and China (1,350 t) compared to global total capacity (11,150 t)	40	59	80	**19**
High ambition—bottom up calculation from best-case Sweden scenario (70% collection as per Sweden and Taiwan; 95% REE phosphor recycling rate in Sweden)	70	95	80	**53**

Sources: EoL-RR concept as per Graedel et al. (2011) and adapted with REE phosphor recycling rate conceptualized by authors. Overall REE recycling process efficiency rate are adopted from Binnemans et al. (2013a) and Tan et al. (2014). Note: The REE phosphor recycling rate is calculated on the basis of informed estimates of the 'collection rate of lamps' and the 'recycling process efficiency rate'.

mercury contamination as there are few other drivers for lamp collection in the first place. For this reason, the EU WEEE Directive explicitly requires removal of mercury for these types of lamps in the recycling process and therefore EU recycling rates for collected lamps are in general over 90% (Eurostat, 2014). *While removal of mercury from lamps involves isolation of the phosphor powder layer where the majority of mercury is present, it does not always involve the further recovery of REE from this powder and this fraction is often landfilled as hazardous waste in the EU* (Walter, 2011; Interviewee C, 2015). Thus, this step leaves a significant gap in the potential for recycling to achieve higher EoL-RR.

In the low-ambition 15% global lamp collection scenario we assume that overall, only 7% REE phosphors are recovered of the lamps collected and recycled. The medium scenario assumes 40% global lamp collection and a tripling of REE recycling capacity worldwide with an EoL-RR of 19%. In the most ambitious scenario, high collection rates like those seen in Sweden are coupled with the recycling process used in that country in which nearly all waste phosphor powders are sent for further recovery of REE at Solvay for a final EoL-RR of 53% (assumptions for each scenario are summarized in Table 2).

2.4. Supply forecast

To calculate the volumes of Eu, Tb and Y available to energy-efficient lamps in 2015–2020, we estimate total primary supply volumes. We use current estimates that 100% of Eu, 85% of Tb and 77% of Y are used for phosphors (Moss et al., 2013; Tan et al., 2014) of which 90% would be available to the production of LEDs, CFLS, and LFLs and the remaining 10% for TVs and screens (Balachandran, 2014).

We assume that total primary supply volumes consist of Chinese rare earth oxide (REO) production, current rest of world (ROW) production and forecasted REO production in the ROW. To forecast future ROW production volumes, we consider a set of ROW developed REE projects with publicly available data including planned production volumes, REO distribution, and costs (see Appendix A). Company-reported dates for starting production provided us with a sequence for their potential market entry, which we modelled with three scenarios that considered delays of one, three and five years in the start of production.

We assume that these projects enter the market when REE prices make the anticipated production start economically feasible. To find these prices we used a price model represented by a REE industry cost curve which is based on the indirectly proportional relation of the supply quantities and prices of individual REO (see Appendix A, more details available from Klossek et al., n.d.). The price model is based on REO prices from March 2015 (Metal-Pages) and current supply volumes of individual REO.

Two approaches guided our calculation of current supply volumes of individual REO for the price model (1) based on the total mining quota in China, (2) based on the Chinese export quota and illegal supply. Approach (1) departs from the phase-out of Chinese export quota by May 1st, 2015, and new export licensing. We assume that the total REO mining quota for 2015 in China could be a proxy for the potential maximum supply volume which could come from China. To calculate total REO supply volumes (for each REO individually) we added the expected REO mining quota in 2015 to current ROW supply volumes.

The second approach uses 2015 REO mining quota in China as a proxy for maximum REO production volumes in China in 2015. As the quota for the 1st half of 2015 increased by 11% (Argusmedia, 2015; Shen, 2015) compared to the quota for the 1st half of 2014, we assume that the total quota in 2015 will be 11% higher than the total quota in 2014. For 2015 we assume the same distribution of REO in the mining quota as in 2014 (Chen, 2014). We estimate current ROW production at 14%, assuming China's share of global production has not changed significantly from the 86% share in 2012 (Tse, 2013 in Wübbeke, 2013). To calculate the volumes of individual oxides we used the same REO distribution as in the total mining quota (which in our view represents an average distribution in a typical hard rock REE deposit).

In the second approach of Chinese export quota and illegal supply, we acknowledge that Chinese REE export quotas have been phased out and replaced with an export licensing system. We expect that in such a situation a part of the illegal export volumes would be sold via official channels; however the total export volumes (consisting of official and illegal volumes) would not change significantly. To estimate the export volumes in 2015 (to be a proxy for the supply volumes coming from China at FOB prices[1]) we considered the REE export quota in 2014 as a proxy for the maximum official export volumes. To find total export volumes we added illegal supply volumes to the export quota (assuming a 40% rate of illegal supply in total export volumes as estimated by Argusmedia, 2015).

The results of these two different approaches to calculate current supply volumes differed slightly. In our view, the Chinese export quota and illegal supply approach is more realistic as it represents maximum REO volumes for export to be sold at FOB prices and considers the domestic REO demand of China, while the first approach assumes that the total REO production of China could be exported which is unrealistic. Our results are therefore showing the

[1] Free On Board (FOB) implies that the seller fulfils her/his obligation to deliver when the goods have passed over the ship's rail at the named port of shipment. This means that the buyer has to bear all costs and risks of loss of or damage to the goods from that point. The FOB term requires the seller to clear the goods for export (WCS International, 2013).

second approach, while the first approach is illustrated in Fig. A.1. Results of these calculations (tonnes of REO) were converted to tonnes of rare earth metals to be compared to the results of the demand and secondary supply analysis.

2.5. Case study

Known as European key player in REE chemical separation, Solvay-Rhodia, hereafter 'Solvay', operates across a bandwidth of industrial sectors including energy, automotive and electronics. It is, jointly with Japanese Shin-Etsu, among the only outside of China capable of chemically separating REE into both light and heavy individual REE products to purities of acceptance for customers on a commercial scale (Interviewee B, 2012; Shin-Etsu Chemical, 2014). Solvay runs REE chemical separation facilities in China and in La Rochelle, France. It is the first large supplier to the lighting market with a commercialized recycling process of La, Ce, Eu, Tb, and Y (Osram and Philips also ran pilot scale recycling projects) (Binnemans et al., 2013a; Moss et al., 2013; Otto and Wojtalewicz-Kasprzak, 2012).

Our case study relies on both literature review and semi-structured interviews with key actors. To enhance reliability of our empirical data, we interviewed representatives of firms involved at different stages of the recycling network, specifically collectors, recyclers and the REE chemical separator and refiner, Solvay, in line with methods as proposed by Kvale and Brinkmann (2009). Our data collection followed an iterative process. Phases of empirical data collection followed desk research for cross-checking available public data and to triangulate industry data with data from regulatory institutions, including from the European Commission, and from scholarly recycling experts. The empirical data served for identifying factors key to recycling REE, such as related to logistics and material components which add to the economic feasibility of REE phosphor recycling. This data also supported our ex-ante modelling.

3. Results

3.1. Closing-the-loop with REE phosphor recycling: The case of Solvay

EU funding through LIFE+ of 50% of the project (equivalent to about EUR 1.1 million for 24 months from June 2012) (EU Commission, 2011) supported Solvay to commercially recycle waste lamp phosphors following four years of prior research and development and industrialization (Solvay, 2014). As Fig. 3 shows, Solvay receives phosphor powder from recyclers and first removes the mercury, glass and other components to physically liberate the rare earth concentrate, which is then sent to the chemical separation plant. There, the halophosphates are removed and the REE phosphors are cracked resulting in a REE concentrate that can be fed, as in a primary process, into a solvent extraction process for individual REE chemical separation. High-tech knowledge of technical staff and internally developed, sophisticated software is applied to manage this solvent extraction process (Leveque, 2014). The REEs are then reformulated into new phosphor precursors for new energy-efficient lamps (Solvay, 2014).

Solvay has developed a flow sheet for the recovery of REEs from a mixture of halophosphate and REE phosphors. According to the patent for the process, the final yield of REE is at about 80% (Braconnier and Rollat, 2010). The objective has been to demonstrate the industrial processing of 3,000 t of lamp waste/year, which corresponds to the forecasted European waste production for 2020 (Golev et al., 2014; Solvay, 2014) and results in 90% waste stream valorisation corresponding to 10–20% of REO (rare earth oxides), glass (by-product) and phosphate (by-product) at Solvay (2014). The REEs lanthanum, cerium, europium and gadolinium, terbium, and yttrium are being recovered (Rollat, 2012). Technical complexities of the recycling process can be better understood in context: Lamp phosphor powder mixtures are the essence of the light characteristics of a fluorescent lamp and different mixtures are used in the powder manufacture (Koninklijke Philips Electronics N.V., 2011) which form the competitive base of lamp manufacturers and they are protected by patents (Li, 2012). Currently Solvay recycles several hundred tonnes of rare earth phosphors each year, primarily from Europe.

While the recycling of phosphor powders is less economical than other internal projects (Walter, 2011), we conclude that it strengthens Solvay's core competence. Depending on global market pricing of REOs, the firm's resources are liberated by sourcing separated REOs externally rather than conducting the chemical separation in-house and thus, the firm's resources are freed-up to pursue high technical sophistication in REE formulation to customer specification. Phosphor recycling reflects an adaptation of Solvay's REE subdivision to overall REE industry dynamics and a diversification strategy in raw material sourcing. Specifically, increasing challenges encountered by Solvay in accessing REE-bearing ore in China (Interviewee A, 2012, 2013) and general REE price volatility initiates quarterly decision-making on whether to chemically separate REEs internally or to purchase them and solely focus on formulation (Walter, 2011). Golev et al. (2014) stress that the annual objective of 3,000 t of waste lamp waste recycling would secure 'Solvay's need for critical rare earths to manufacture new lamp phosphors (. . .).' In-house solvent extraction is the precursor to formulation and production of phosphors, constituting a key process to unique compositions of the phosphor powder. Thus, operating the solvent extraction processes might provide avenues to run process test routes and potentially explore new patents.

To understand the drivers for Solvay's commercialization project it is important to put it into context of the overall REE market. As described in the introduction, particularly between 2009 and 2011 concerns about the supply and price of REE arose as a result of numerous issues including Chinese restrictions on REE exports. This was a driver for increased attention in the EU for possible sources of supplies outside of China, as well as, potential secondary supplies. Lamps were a viable source of waste phosphor powder in the EU for a couple of reasons. First, existing legislation (the WEEE Directive) already mandates the collection of this waste stream. Secondly, the recycling process of this waste stream typically involved isolating mercury in the phosphor powder, so this powder was already an available end fraction of the recycling process (Récylum, 2014). Moreover, the costs of collection and recycling in EU countries is borne by the lamp producers and in some cases by municipalities (such as of collection in Denmark). REE chemical separator/refiner Solvay only needed to pay for the fractions from recyclers and the processing from that point onwards. Both researchers and practitioners argue that without legislation, collection and thus recycling of energy-efficient lamps are unlikely to take place (Huisman et al., 2008; Interviewee D, 2014; Richter & Koppejan, 2015). The role of legislation and market drivers for secondary supply are further discussed later, and we contextualize recycling scenarios within a future market context in our model.

3.2. Future potential for closing loops: Our model

Our EoL-RR scenarios illustrate how closing-the-loop at different REE phosphor powder recovery ratios can contribute to secondary supply of Y, Eu and Tb for new phosphor production to be used in lamps, TVs or screens. We contextualize these EoL-RR scenarios in a comparison with forecasted demand, as per our modelled scenario that stipulates the uptake of different lighting

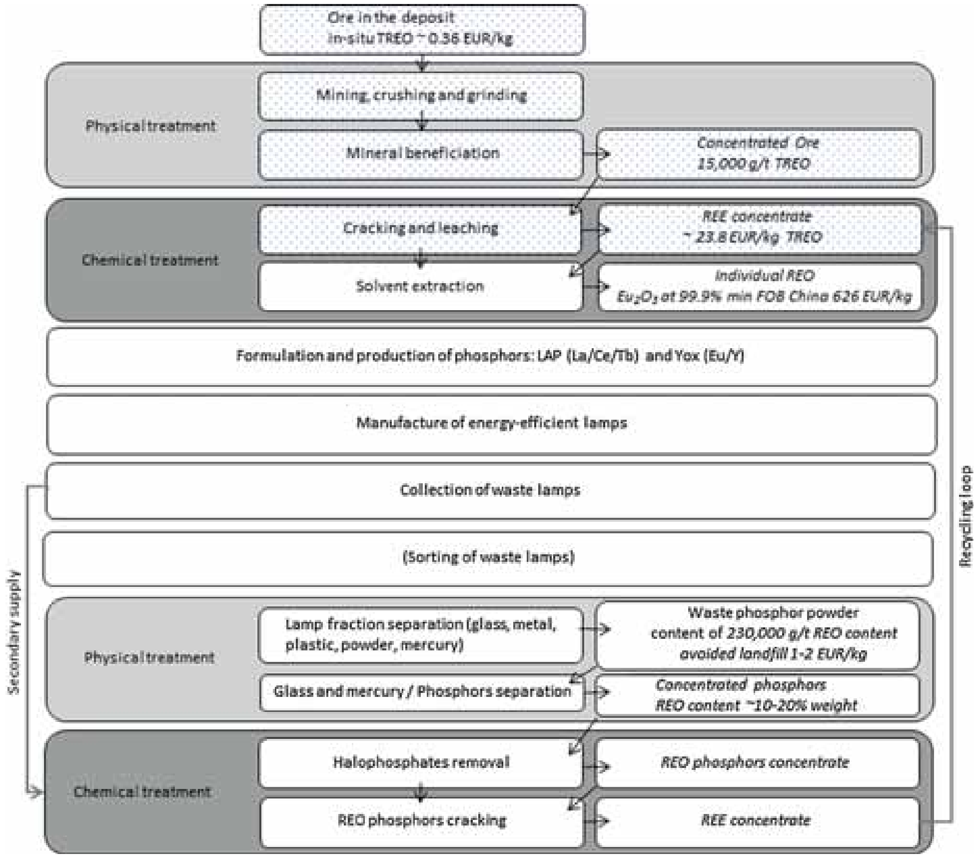

Fig. 3. Primary processing steps from mine to the manufacture of energy-efficient phosphor lamps, secondary supply specific recycling processes of phosphor powders and closing-the-loop with a second run through chemical separation (Tan et al., 2014; Metal-pages, 2015; TMR, 2015; Rollat, 2012). Foregone primary REE processing steps are dotted. Note: Possible variations in the ore grade can impact the ore and REE values in further processing steps. This figure exemplifies a classic REE carbonatite which might provide conservative values when compared to not yet-commercially exploited REE-bearing minerals.

technologies until 2020, and with primary supply as per our supply forecast model.

Our results demonstrate that a global EoL-RR of 53% as per our best case REE phosphor powder recycling ratio modelled in line with to-date Swedish and Taiwanese lamp collection and REE phosphor recycling efficiency could provide secondary supply of Y, Eu and Tb equivalent to our modelled demand forecast of these three REE for LFLs, and an increasing share of CFL demand for Y, Eu and Tb until 2020.

Our EoL-RR of 19% is based on a tripling of REE phosphor recycling capacity for major markets of China and North America in line with our European Solvay case. Such an EoL-RR rate could contribute with secondary supply of Y, Eu and Tb of close to 50% of demand for these REE to be used in phosphors in CFLs.

The 7% EoL-RR corresponds to the estimated current global secondary supply of Y, Eu and Tb. In this scenario, secondary supply of Y, Eu and Tb contributes less than a third of 2020 demand of Y, Eu and Tb and hardly contributes to the demand by the CFL or LFL.

In 2015, the 7% EoL-RR of the three REE phosphors can fill the demand gap with about 7% and can account for up to 9% in 2020. The bandwidth of the 19% EoL-RR to meet demand is at 20% in 2015 and forecasted to more than a quarter of the demand (27%) in 2020. In contrast, and most significant, the 53% EoL-RR enables a secondary supply of the three REE phosphors of more than half of the demand by phosphor-based lamps in 2015 and three quarters of demand by these lamps in 2020 and thus competes directly with primary supply. This 53% EoL-RR illustrates choices about recycling in policy and business decisions which affect future recycling options. It also highlights that these choices require awareness on preferences—whether REE are to be sourced from a host rock or from recycling and why, see Fig. 1.

4. Discussion

The case study and our model demonstrate the potential of secondary supply from waste lamp phosphor recycling to meet some of the forecasted demand, but the question remains about what factors impede and promote closed-loop recycling. The Solvay case demonstrated that market mechanisms as well as legislative drivers are key to making secondary supply viable. Accessibility of adequate quantities of REE phosphor waste lamps, marketability of the recycled REE phosphors, as well as ability to derive adequate value (the right price at the right time) for these products have been argued as key bottlenecks to realize closed-loop systems (Guide and Van Wassenhove, 2009). In this section we first discuss these bottlenecks in the context of market mechanisms and uncertainties inherent in forecasting the future of the REE market. We discuss the factors that enabled REE phosphor recycling so far and what drivers are necessary for REE phosphor recycling to play a substantial role in meeting future REE phosphor supply.

4.1. Uncertainties of demand

REE use in phosphors is dependent on technological and socio-economic developments which impact the market uptake of lighting technologies. The minor REE content in LEDs is noteworthy for demand projections as is the potential redundancy of Tb in a market dominated by LEDs (U.S. Department of Energy, 2011; Wilburn, 2012). While the development of LED technology has progressed faster than anticipated (Danish Energy Agency, Energy Piano & CLASP European Programme, 2015), there are still concerns about the technology being ready to replace all lighting applications (and this was the reason underpinning the recent delay of Stage 6 EcoDesign requirements for lamps in the EU, see Ala-Kurikka, 2015). Also, phosphor powder substitutes might be found which would strongly influence the price customers are willing to pay for products and alternative ROW supplies of REE (Zachmann, 2010). Such a scenario would affect the attractiveness of developing the secondary supply in absence of other drivers.

Recycling can contribute to remedying the balancing problem, described earlier, which affects both primary supply and demand, as argued by other scholars (Binnemans et al., 2013b; Falconnet, 1985). In our supply and demand forecasts we have only considered the phosphors used for lighting and the technological development within this field of application. Yet other applications such as TVs and background lighting screens in tablets, phones and others also currently demand phosphors based on REE (Balachandran, 2014) and there may be growth in this demand by these or future applications (Castilloux, 2014b). Such growth could create new markets for the secondary supply from recycled lamp phosphors. In addition, it is uncertain which technologies will dominate the future lighting market, a factor which will influence the significance of REE lamp phosphor recycling further: For instance, remote phosphor screw-based or tube LED lamps (T8) will demand more REE than regular white LED lamps and LFL tubes (T8) (Castilloux, 2014b).

4.2. Uncertainties for recycled REE phosphor demand

Binnemans and Jones (2014) outlined three possible recycling routes: (1) direct re-use of the recycled lamp phosphors, (2) recycling of the various phosphors by physiochemical separation methods, and (3) chemical attack of the phosphors to recover their REE content. Options 1 and 2 are linked to a reuse of the powder by the same manufacturer, while option 3 allows for the use by a different party (Binnemans and Jones, 2014). The first two options would likely require a take-back system by the manufacturer, or the implementation of "closed-loop supply chain management" (Guide and Van Wassenhove, 2009). To date, closed-loop supply is not unknown, though more typical for industrial goods like machinery, tools, and process catalysts (Graedel et al., 2011). With the first two options, uncertainties as to the quality of the powder would need to be considered. The powder deteriorates over the lifetime of a lamp due to exposure to UV radiation and mercury. In addition, recycling processes will affect the quality of the phosphor powder such as particle size and thus, the recycled phosphor powder will expectedly be inferior to the original product. Our article addresses the third recycling route which reflects the Solvay approach in which the recycled powder is chemically attacked.

Demand for recycled phosphors depends on price, which involves the cost of recycling lamps (which can be relatively high compared to the price of the product) (Philips Lighting, 2012). Key factors include efficient design of the scheme, but also transport distances and end use for the recycled glass, the main fraction by weight of the recycling process (Interviewee D, 2014; WEEE Forum, 2010). Notably, depending on the country, costs for recycling and collection of lamps in Europe can be the responsibility of producers and are not necessarily borne by lamp phosphor recyclers, e.g. Solvay, which only pays the recycler for the separated waste phosphor powder (Interviewee D, 2014). Currently, several externalities are not part of the price of both primary and secondary phosphors. These are discussed later in relation to value.

4.3. Uncertainties of primary supply

The primary supply of REE is uncertain with China possibly further consolidating the industry and using integrated production steps subsidized by the two-tier pricing mechanism for import substitution, expected to be upheld under the licensing regime. Further, alternative ROW supply might need to meet growing Chinese REE demand. High-tech skill requirements at each of the processing steps are obstacles for alternative suppliers and add to alternative REE supply risk (Hatch, 2011). Project feasibility, which is evaluated from the reconnaissance exploration to the mine development stage, is tied to several factors as put forward by Klossek and van den Boogaart, (2015): land title and location of the deposit; experience of regulatory authorities with the deposit type and commodity; REE grade and REE distribution representing estimated values from geological studies; potential for significant volume production (t); presence of radioactive elements combined with environmental legislation; REE mineralogy; opportunities for project financing; business relationships with separation facilities; availability of expertise, technology, and equipment; strategic alliances and off-take agreements with end-users; cost competitiveness; obtaining mining permits and social licences to mine; as well as estimated values of REE and market conditions.

REE deposits are characterized by the different mineralogy of various REE-containing ores, which may require new, tailor-made processing routes to be developed (Jordens et al., 2013), as well as additional financial and human resources, and time in testing their feasibility which could result in significant project delays, which is why we model with a one, three and five year delay. Our modelled three year base scenario is shown in Fig. 4, produced from data presented in Table A.3. A project start delay by one year modelled on the export quota and illegal supply approach, affects primary supply insofar as that primary supply of Eu first meets and exceeds demand by 20 t in 2019 while in a five year delay Eu demand would first be met and exceeded by 50 t in 2020. The one year delay resembles the results of a three year delay regarding Eu primary supply. In none of the delay scenarios, Tb primary supply meets demand and in all delay scenarios, Y primary supply first meets and exceeds demand in 2020. Regulations regarding radioactivity applying to certain deposits, limited access to ROW chemical separation know-how and the capital and operational cost requirements to establish a new separation facility, also represent major bottlenecks for alternative value chains of junior REE exploration projects in the ROW (Golev et al., 2014; Machacek and Fold, 2014). As some projects could become infeasible, future primary REE supply could be lower

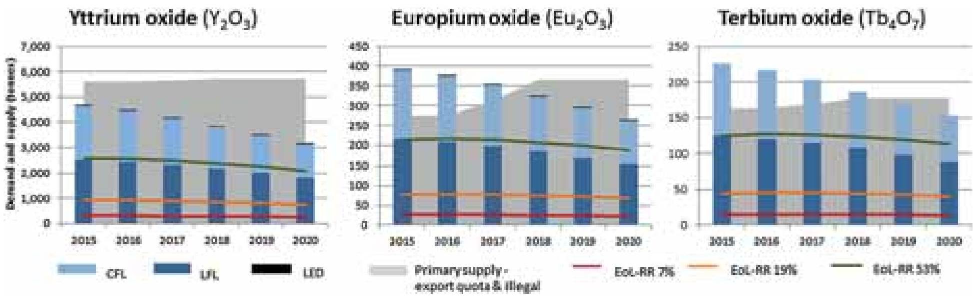

Fig. 4. Potential secondary supply distribution for Y, Eu and Tb based on our three EoL-RR as compared to demand per lamp type (bars) and 3 year delay base case primary supply forecast (grey shading, data in Table A.3) from 2015 to 2020. Please note the different y-axis scales. We use REO as unit to enable a comparison of demand, and primary and potential secondary supply estimates, however, the use of REO in lamp phosphors requires their prior purification to metal, as depicted in Fig. 1, step 5.

or postponed while the commercialization of new physical and chemical separation technologies might increase supply.

4.4. Uncertainties of secondary supply

Our model demonstrates the potential of increased REE powder recycling for REE phosphor powder demand of CFLs/LFLs over the time period in which the general lighting market shifts towards LEDs (and beyond). Even in 2020, the CFL/LFL technologies are expected to account for between 26% (McKinsey & Company, 2012) and a third of the lighting market (Hykawy, 2014). Anticipations on the pace of LED uptake differ: For instance, General Electric anticipates that LEDs will reach a 70% market share in 2020 (see Cohen, 2014; Hykawy, 2014), while Wilburn (2012) emphasizes the role of fluorescent lighting for general lighting in the short to medium term. In our model we tried to find a balance, in line with McKinsey & Company (2012) which anticipates a LED technology market share of 62% in 2020. While LEDs require significantly less REE and a different individual REE mix, such as reduced or no Tb, this lamp technology continues to require small quantities of Y and Eu. Continued heavy REE demand by phosphors used in general lighting (CFL, LFL, LED) and for background lighting (TVs-plasma, LCD, and X-ray intensifying screens) is anticipated (Balachandran, 2014).

Secondary supply is affected by the availability of waste lamps. We have mentioned the uncertainty about actual lifetimes of energy-efficient lamps because this is a function of actual use. If the lamp lifetimes are longer than our modelled assumptions, our sensitivity analysis showed that this would slightly increase the amount of waste lamps available until 2020 (and most likely beyond).

4.5. Promoting secondary supply

As mentioned, our low ambition scenario for recycling is an estimate of the status quo. Achieving higher recycling rates depends on a number of factors, beginning with collection. The case study demonstrated the large role of legislation in making the opportunity for further recovery of REE viable through mandatory collection of lamps (in absence of economic drivers for collection). Our model illustrates that similar timely legislative measures targeting fluorescent lamp collection, could impact end-of-life recycling rates (EoL-RR). The second scenario illustrates a case with more stringent EPR legislation.

The case of Solvay illustrates that such legislation can make REE recycling viable, but it is important to consider the other factors that incentivized Solvay to invest in commercial recycling: First and foremost, the availability of a separation unit at Solvay was a main driver for the decision towards REE recycling. In addition to an available supply of waste lamps, high REE prices and significant supply risk at the time as well as significant EU interest resulted in financial support. The decision to invest was also part of a business strategy that considered the value of the secondary supply differently (this perception of value is discussed in the subsequent section). In absence of price, supply risk, or other value drivers there may be a need for further legislation to drive not only the collection of waste lamps, but also the further recycling of REE. Such legislation, like a business strategy, can be driven by a different perspective of value and alignment with the goals of a circular economy agenda. Ideally, combining either economic or legislative drivers to promote both collection and recycling of REE would further advance the potential contribution of the secondary supply closer to the case we already observe in Sweden, with a high level of lamp collection coupled with subsequent recycling of REE e.g. through Solvay in France.

Timing is significant in the elaboration and implementation of legislative measures that require REE recycling from fluorescent lamp phosphors. At the time of writing, the majority of EoL REE phosphor powder, even from collected EoL CFL/LFL lamps, is still landfilled. While there is evidence of socio-economic value of REE recycling that could already drive recyclers to further process REE, see Balcan (2015) and Ondrey (2014), some recyclers continue to see the small amount of powder as a barrier to act and prefer the small cost of landfilling over a possible change in their operations required to send the powder for further recycling (Interviewee C, 2015). This is problematic and unfortunate from a resource conservation perspective, as the REEs contained in these EoL phosphor powders (Wu et al., 2014) are already enriched, and since they stem from resource-intense concentration processes – physical and chemical beneficiation that involves high energy, water and chemical use – of the mined REE-containing mineral.

4.6. Rethinking the value of recycling phosphors

Aside from the challenges in accessibility and marketability of recycled lamp phosphor powders, which can be addressed, the feasibility of recycling is tied to its economics. We have already discussed that the overall cost factors for recycling REE from phosphors entail both costs for collection and the actual recovery. We now look closer at the overall value of a secondary supply of REE phosphors. Consideration of the overall value of recycling would depart from juxtaposing the processes of a secondary supply loop of recycling lamp phosphor powders with those of primary extraction of REE-containing ore. The latter comprises, as depicted in Fig. 3, mining, mineral beneficiation, and cracking and leaching. These processes involve significant costs for energy and solvents, and operating expenditures comprising future costs for mine rehabilitation, effluent, radioactive material and waste handling. When compared with recycling, even if it involves a second chemical attack of the phosphor powders, the mining and processing costs up to chemical separation associated with the primary supply will not need to be borne.

Researchers have found higher concentrations of REE in the waste lighting products (i.e. anthropogenic deposits, see Mueller et al., 2015); some pointing to more than 15 times higher concentration of Eu, Tb and Y in waste phosphor mixtures as compared to natural concentrations in REE-bearing hard rock minerals (Tan et al., 2014). We would like to stimulate a critical reflection on how it can be possible that recycling of phosphors is not economically feasible despite their high concentration in waste lamps (Langer, 2012; Walter, 2011) and when "only a dozen natural minerals have high enough quantities to be worth the cost of extraction" (Meyer and Bras, 2011). Using a specific process applied to foreign and Canadian EoL phosphor powders with a 98–99% recovery for REE, it has been indicated that REEs could be extracted for as low as USD 6 per kg of mercury phosphor dust (Cardarelli, 2014 in Chemical Engineering, 2014). This cost stands in contrast to the basket value of REE contained, which, averaged on the projects we identified for this study, would amount to about USD 28 per kg (see Table C.1).

With this in mind the focus in *assessing the feasibility of phosphor recycling from waste lamps may need to turn to additional, different value dimensions, beyond the conventional exchange value of the phosphor powder* (from both the primary and secondary processing routes) to include for instance resilience as a factor in business sustainability. Such value propositions could drive business opportunities for closed-loop recycling.

The Solvay business case of closing-the-loop with REE recycling, illustrated how the core competence of the firm is reiterated in a strategy that addresses two objectives: augmenting resilience against supply criticality and further increasing competitiveness. This case has been enabled by EU legislation that has attached societal value to recycling by means of committing producers to collect and recycle waste products, limiting the landfilling of hazardous waste, and promoting closed-loop opportunities. The direct value potential of recycling Eu, Tb and Y used in phosphors of fluorescent lamps is manifested in the addition of a new material stream through phosphor recycling that makes use of existing production capital in a situation of concern and uncertainty over material access and REE supply. As Guyonnet et al. (2015) argue, complementarity between the primary and secondary sources to meet supply requirements is of particular importance in the case of REE for which requirements are increasing. The firm opens up opportunities for value creation as operating its chemical separation plant might facilitate product and process improvements. Use of secondary supply for phosphors is also attractive for its domestic or regional availability as opposed to a dependence on a few key players, primarily China, and the uncertain development of new REE deposits. Secondary supply can augment certainty about short and medium term supply.

Developing the domestic secondary supply of REE can have wider societal benefits while supporting regional and national goals towards more circular economies. The collection and recycling of lamps has a high societal value in the avoided mercury contamination, which is difficult to quantify in economic terms (though some studies, for example, Hylander and Goodsite (2006) have tried and estimated a cost of USD 2,500 to 1.1 million per kg Hg isolated from the biosphere depending on local factors quantity, nature of pollution, media, geography, technology used etc.) At the same time, collection and recycling of energy-efficient lamps represents a cost in terms of overall material recycling (for example, costs for collection and recycling systems of lamp waste in EU have varied between EUR 0.15 per kg and EUR 2 per kg according to the WEEE Forum, 2010). Reconciling different costs and benefits of avoided pollution by collection and recycling is why legislation is often needed to drive this part of the process (Li et al., 2015).

Recycling of phosphors as indicated above, has societal value in the form of forgone costs of protecting human and environmental health and safety as primary REE processing involves the handling of radioactive elements that have been related to higher health risks, for example to cancer (Lim et al., 2013; Weng et al., 2013). It should be noted that the exposure to radioactive material is also dependent on the geology of the mined deposit as well as the method of mining utilised (Ali, 2014).

Closing-the-loop further saves environmental costs associated with the generation and treatment of 63,000 m^3 waste gas, 200 m^3 acidic water and 1.4 t of radioactive waste (all per tonne of REO) (Navarro and Zhao, 2014; Weng et al., 2013). Processes such as in-situ leaching can also result in water contamination and erosion resulting in landslides that potentially endanger lives (Yang et al., 2013) Moreover, the extraction process is very energy intensive, so that REE production is associated with higher greenhouse gas emissions than many other mined metals (Weng et al., 2013). Both the health and environmental effects can persist long after mining operations have ceased (Yang et al., 2013). In this light, regulation to limit these negative effects is needed, yet, only reliable checks will ensure regulatory effects, and thus, governance within the country in which REE minerals are mined, is key.

Ali (2014) stipulated that recycling can avoid many of the negative environmental and health externalities described and that these should be considered in valuing the secondary supply. In addition, there are also potential positive externalities in developing a secondary supply of REE. For example, overall it is estimated that various recycling activities yield potential for the creation of 580,000 new jobs and for R&D and innovation, thus contributing to EU 2020 targets and to sustaining competitiveness (Meyer and Bras, 2011). Finally, the less tangible value potential from investing in recycling lies in its long-term orientation towards adapting the current economic system. This valuation is built on ideas derived from conceptualizing economics of practice (Bourdieu, 1985) and include broader societal value (Foster, 2006) such as from recycling, reducing and reusing, as part of an economic model constructed on waste prevention—and over the long term, a reduction in resource extraction. Legislative targets will be necessary to drive this transition and to emphasize recycling, as is the case within the EU.

5. Conclusion

We have demonstrated that secondary supply has the potential to contribute to supply of phosphors for lamps (and other products). Secondary supply has considerable advantages over primary supply, of which one of the most notable is that it bypasses the extraction phase and many of the environmental impacts and costs involved in this stage. Secondary supply can constitute a source of supply of REE independent of Chinese quotas or licences and as such contribute to supply security of REE phosphors, at least in the short term. Lastly, establishing secondary supplies for recycling is in line with many policy goals in countries that advance closing loops of critical materials for a circular economy.

We have also demonstrated that establishing and encouraging secondary supply requires driving factors. We have pointed to the role of legislation in establishing the collection systems for energy-efficient lamps in Europe and enabling commercial recycling. Our model indicates the rationale for such legislative measures in other regions to increase global recycling rates. Also within Europe energy-efficient lamp collection and recovery of REE from lamp phosphor powders can be improved. The latter step is currently not required by legislation. In absence of legislative drivers, we have discussed the need for rethinking the value in recycling phosphors. Lastly, our article demonstrates the timely essence for drivers to enable REE recovery potential and to close loops of critical materials for a circular economy.

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Appendix A.

Input data for primary supply Tables A.1–A.3
Fig. A.1

Table A.1
Input data for the primary supply analysis (1/2).

Company (REE deposit)[1]	Deposit location	Eu_2O_3 (t/yr)[2]	Tb_4O_7 (t/yr)[2]	Y_2O_3, (t/yr)[2]	Basket Price, USD/t REO	Planned production start[3]	Life of Mine (LOM)	Planned capacity, TREO (tpa)	Total CAPEX, USD	CAPEX Annuity USD/t	Annual OPEX, USD/t	Total annual unit costs, USD/t REO
Lynas (Mount Weld CLD)	Australia	117	20	167	26,780	2015	20	20,000[4]	612,991,200	3,791	14,636	18,427
Avalon (Nechalacho, av.[5])	Canada	44	39	780	36,196	2017	20	10,000	1,068,835,426	12,555	22,536	35,090
Tasman (Norra Kärr)	Sweden	19	34	1,842	43,152	2018	20	5,119	378,000,000	8,674	39,690	48,364
Frontier (Zandkopsdrift)	South Africa	118	34	824	28,416	2015	20	20,000	935,057,016	5,492	12,360	17,851
Quest (Strange Lake, av.[6])	Canada	13	60	2,934	38,656	2020	30	10,424	1631,000,000	16,598	34,248	50,846
RES (Bear Lodge)	U.S.A.	56	11	112	28,641	2017	45	8,500	453,000,000	8,082	16,995	25,077
Matamec (Kipawa)	Canada	14	20	824	39,522	2016	15.2	3,653	360,502,449	17,492	26,057	43,549
Arafura (Nolans)	Australia	77	17	270	28,144	2019	23	20,000	1,084,209,280	6,103	15,670	21,773
Product purity		99.9%	99%	99.999%								

Sources: Reports available on the websites of the companies.
[1] Molycorp is not included in the analysis due to unavailable data on production costs to perform the profitability check.
[2] Calculation of the supply quantities of considered REO, based on the projects' REE production capacities and relative distribution of individual elements in the selected deposits, latter data stems from TMR (2015).
[3] Year when planned capacity is started or expected to be reached.
[4] Lynas is currently producing 3008 t of REO per year (in 2014) and targeting 11,000 t in 2015.
[5] Averaged Nechalacho Basal and Upper values.
[6] Averaged Strange Lake enriched and Strange Lake Granite values.

Table A.2
Input data for the primary supply analysis (2/2).

Market volumes	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3	Total
% In mining quota 2014	27.9%	42.7%	4.7%	15.4%	1.6%	0.2%	1.2%	0.1%	0.7%	4.6%	
Volumes (t)[1]	29,179	44,602	4899	16,096	1667	236	1297	140	717	4798	**104,545**
Mining quota 2014 (t)	**104,545**										
Mining quota 2015 (expected[2]), (t)	**116,550**										
Volumes China 2015 (86%), (t)[3]	32,530	49,724	5462	17,944	1858	**263**	1446	**156**	799	**5349**	**116,550**
Volumes ROW (14%), (t)[3]	5,296	8,095	889	2,921	303	**43**	235	**25**	130	**871**	**18,973**
Total current market volumes 1, (t)[4]	**37,825**	**57,818**	**6351**	**20,865**	**2161**	**306**	**1681**	**181**	**929**	**6220**	**135,523**
Approx. volumes export official, (t) (assumingly 60%)	8,544	13,060	1434	4,713	488	69	380	41	210	1,405	**30,611**
Smuggling rate (40%), (t)[5]	5,696	8,706	956	3,142	325	46	253	27	140	937	20,407
Total export volumes (100% equiv. to 86% of world mkt)[6]	14,239	21,766	2391	7,855	814	115	633	68	350	2341	51,018
Volumes ROW (14%), (t)	5,296	8,095	889	2,921	303	43	235	25	130	871	18,973
Total current market volumes 2, (t)[7]	**19,535**	**29,860**	**3280**	**10,776**	**1116**	**158**	**868**	**94**	**480**	**3212**	**69,992**

[1] Chen (2014).
[2] Assuming an increase of 11% similar to the increase in 1st batch production quota from 2014 to 2015 (Argus Media).
[3] Assuming similar distribution of REO as in the mining quota (see line 3).
[4] To be used in price model (available from Klossek) as current market volumes in the *total Chinese REE mining quota approach*.
[5] 40% of Chinese REEs being sold are illegally sourced (Argusmedia, 2015).
[6] Assumed current market volumes for the price model—assuming that overall exported volumes stay the same (as per TMR estimate), a part of illegal REO will be sold via official channels.
[7] To be used in price model (available from Klossek) as current market volumes in the *export quota and illegal supply approach*

Table A.3
Base case, supply—mining quota and export quota & illegal, 3 year delay scenario.

	2015	2016	2017	2018	2019	2020
ROW current (t) (see Table A.2—line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (t) (see Table A.2—line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3			42	219	219	219
Tb_4O_7			7	51	51	51
Y_2O_3			61	968	968	968
Projects on the market			Lynas[1]—11,000 t	Lynas—22,000 Frontier	Lynas Frontier Matamec[2]	Lynas Frontier RES[2] Avalon[2]
Total world production (t) (supply volumes + ROW current + China)						
Eu_2O_3	306	306	348	525	525	525
Tb_4O_7	181	181	188	232	232	232
Y_2O_3	6,220	6,220	6,281	7,188	7,188	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**275**	**275**	**313**	**472**	**472**	**472**
Tb_4O_7	**163**	**163**	**169**	**209**	**209**	**209**
Y_2O_3	**5,598**	**5,598**	**5,653**	**6,469**	**6,469**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3			42	101	101	101
Tb_4O_7			7	17	17	17
Y_2O_3			61	144	144	144
Projects on the market			Lynas[1]—11,000 t	Lynas—22,000 Frontier[2]	Lynas Matamec[2]	Lynas RES[2] Avalon[2]
Total world production (t)						
Eu_2O_3	306	306	348	407	407	407
Tb_4O_7	181	181	188	198	198	198
Y_2O_3	6,220	6,220	6,281	6,364	6,364	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**275**	**275**	**313**	**366**	**366**	**366**
Tb_4O_7	**163**	**163**	**169**	**178**	**178**	**178**
Y_2O_3	**5,598**	**5,598**	**5,653**	**5,728**	**5,728**	**5,728**

[1] This project is not profitable with current production rate but producing (planning production rate increase).
[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.
[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.
The results presented in this table are illustrated in Fig. 4 for approach (2) and in Fig. A.1 for approach (1).

The figure compares secondary supply to demand and primary supply. Potential secondary supply distribution for Y_2O_3, Eu_2O_3 and Tb_4O_7 based on our three EoL-RR as compared to demand (bars) and 3 year delay base case primary supply forecast (grey shading) from 2015 to 2020. This figure is based on approach 1 of the primary supply forecast which uses the total REE mining quota in China. Please note different *y*-axis scales. *Source:* authors.

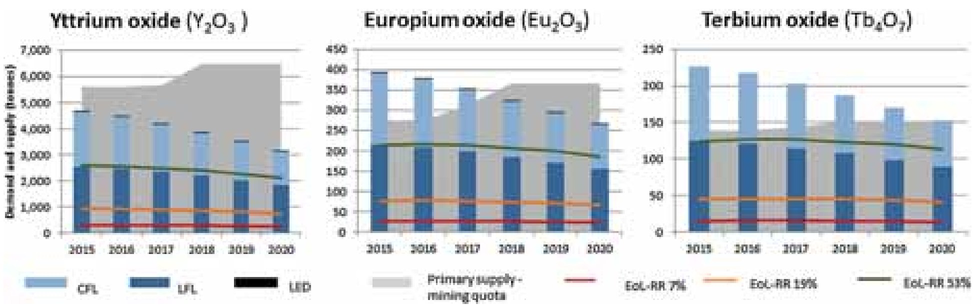

Fig. A.1. Base case, total Chinese REE mining quota approach, 3 year delay scenario.

Input data for primary supply.

Prices (USD/kg)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3
Base case (3 yr delay of production start) for export quota & illegal										
2015	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2016	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2017	8.199	3.726	95.937	55.533	4.256	473.153	44.532	756.914	374.416	12.268
2018	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962
2019	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962
2020	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962
Prices (USD/kg)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3
Base case (3 yr delay of production start) for mining quota										
2015	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2016	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2017	8.568	3.941	101.415	58.909	4.586	527.030	46.586	783.930	381.793	12.379
2018	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816
2019	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816
2020	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816

Best case, supply—mining quota and export quota & illegal, 1 yr delay.

	2,015	2,016	2,017	2,018	2,019	2,020
ROW current (t) (see Table A.2—line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (t) (see Table A.2—line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5,349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3	42	219	219	219	219	219
Tb_4O_7	7	51	51	51	51	51
Y_2O_3	61	968	968	968	968	968
Projects on the market	Lynas[1]—11,000 t	Lynas—22,000 Frontier	Lynas Frontier Matamec[2]	Lynas Frontier RES[2] Avalon[2]	Lynas Frontier Tasman[2]	Lynas Frontier Arafura[2]
Total world production (t) (supply volumes + ROW current + China)						
Eu_2O_3	348	525	525	525	525	525
Tb_4O_7	188	232	232	232	232	232
Y_2O_3	6,281	7,188	7,188	7,188	7,188	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**313**	**472**	**472**	**472**	**472**	**472**
Tb_4O_7	**169**	**209**	**209**	**209**	**209**	**209**
Y_2O_3	**5,653**	**6,469**	**6,469**	**6,469**	**6,469**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3	42	101	101	101	101	101
Tb_4O_7	7	17	17	17	17	17
Y_2O_3	61	144	144	144	144	144
Projects on the market	Lynas[1]—11,000 t	Lynas—22,000 Frontier[2]	Lynas Matamec[2]	Lynas RES[2] Avalon[2]	Lynas Tasman[2]	Lynas Arafura[2]
Total world production (t)						
Eu_2O_3	348	407	407	407	407	407
Tb_4O_7,	188	198	198	198	198	198
Y_2O_3	6,281	6,364	6,364	6,364	6,364	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**313**	**366**	**366**	**366**	**366**	**366**
Tb_4O_7	**169**	**178**	**178**	**178**	**178**	**178**
Y_2O_3	**5,653**	**5,728**	**5,728**	**5,728**	**5,728**	**5,728**

This table is presented for evidence of the 1 year delay scenario for approach (1) and (2).

[1] This project is not profitable with current production rate but producing (planning production rate increase)

[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.

[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.

Worst case, supply—mining quota and export quota & illegal, 5 yr delay.

	2,015	2,016	2,017	2,018	2,019	2,020
ROW current (t) (see Table A.2—line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (t) (see Table A.2—line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5,349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3					42	219
Tb_4O_7					7	51
Y_2O_3					61	968
Projects on the market					Lynas[1]—11,000 t	Lynas—22,000 tFrontier
Total world production (t) (Supply volumes + ROW current + China)						
Eu_2O_3	306	306	306	306	348	525
Tb_4O_7	181	181	181	181	188	232
Y_2O_3	6,220	6,220	6,220	6,220	6,281	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**275**	**275**	**275**	**275**	**313**	**472**
Tb_4O_7	**163**	**163**	**163**	**163**	**169**	**209**
Y_2O_3	**5,598**	**5,598**	**5,598**	**5,598**	**5,653**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (t)						
Eu_2O_3					42	101
Tb_4O_7					7	17
Y_2O_3					61	144
Projects on the market					Lynas[1]—11,000 t	Lynas—22,000Frontier[2]
Total world production (t)						
Eu_2O_3	306	306	306	306	348	407
Tb_4O_7	181	181	181	181	188	198
Y_2O_3	6,220	6,220	6,220	6,220	6,281	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (t)						
Eu_2O_3	**275**	**275**	**275**	**275**	**313**	**366**
Tb_4O_7	**163**	**163**	**163**	**163**	**169**	**178**
Y_2O_3	**5,598**	**5,598**	**5,598**	**5,598**	**5,653**	**5,728**

This table is presented for evidence of the 5 year delay scenario.

[1] This project is not profitable with current production rate but producing (planning production rate increase).

[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.

[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.

Appendix B. Input data for demand and secondary supply

Tables B.1–B.5

EU member states show some of the highest rates in the world along with other countries with compulsory collection legislation like Taiwan, which collects and recycles over 75% of lamps (EPA Taiwan, 2014), however Table B.1 demonstrates further potential for improvement in collection rates. Outside the EU there is less available data, but it is estimated that 95% of fluorescent lamps in Australia are landfilled (FluoroCycle, 2014), while Canada, Japan, Mexico, and South Africa all recycle less than 10% (EU Commission, 2014a,b) The United States has some, mainly state level, laws for management of waste lamps, requiring recycling by business users; however, enforcement is low and the recycling rate in these states is estimated around 23% (Silveira and Chang, 2011).

Table B.1
Demand input data (1/2)—Lamp market and Y_2O_3, Eu_2O_3 and Tb_4O_7 content in lamps.

New installations (million)[1]						
	2015	2016	2017	2018	2019	2020
Others	1073	935	831	749	698	610
LFL	659	630	594	562	521	489
CFL	704	653	616	564	509	436
LED	1365	1780	2163	2508	2818	3125
Lamp replacement (million)						
	2015	2016	2017	2018	2019	2020
Others	3469	2654	1975	1467	1150	903
LFL	1560	1512	1447	1346	1229	1106
CFL	2121	2039	1842	1644	1491	1322
LED	560	658	733	848	977	1078
Total lamps on market (million)						
	2015	2016	2017	2018	2019	2020
Others	4542	3589	2806	2216	1848	1513
LFL	2219	2142	2041	1908	1750	1595
CFL	2825	2692	2458	2208	2000	1758
LED	1925	2438	2896	3356	3795	4203
Rare earth in lamps[2]						
	Phosphor (g)	TREO (g)				
LFL	2.34	1.665				
CFL	1.5	1.069				
LED	0.01	0.006				
Composition as per standard tricolor phosphor (%)[3]						
	Y_2O_3 (Range 46.9–51.2)	Eu_2O_3 (3.9–4.4)	Tb_4O_7 (2.2–2.6)			
LFL	Averaged to 49.05	4.15	2.4			
CFL	49.05	4.15	2.4			
LED	49.05	4.15	0			
REO content (calculated from phosphor(g) × averaged REO content (%) above)						
	Y_2O_3 (g)	Eu_2O_3(g)	Tb_4O_7 (g)	Total RE (g)		
LFL	1.14777	0.09711	0.05616	1.301		
CFL	0.73575	0.06225	0.036	0.834		
LED	0.004905	0.000415	0	0.005		

[1] McKinsey & Company (2012). The data summarizes general lighting applications (residential, office, industrial, shop, hospitality, outdoor and architectural, yet excluding automotive and backlighting) for all world regions.
[2] Castilloux (2014b).
[3] Averaged from Wu et al. (2014), Table 3.

Table B.2
Demand input data (2/2)—Y_2O_3, Eu_2O_3 and Tb_4O_7 demand per LFL, CFL and LED.

Y_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL	2546.90	2458.52	2342.60	2189.95	2008.60	1830.69
CFL	2078.49	1980.64	1808.47	1624.54	1471.50	1293.45
LED	9.44	11.96	14.20	16.46	18.61	20.62
Total (rounded)	4635	4451	4165	3831	3499	3145
Eu_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL	215.49	208.01	198.20	185.29	169.94	154.89
CFL	175.86	167.58	153.01	137.45	124.5	109.44
LED	0.79	1.01	1.20	1.39	1.57	1.74
Total (rounded)	392	377	352	324	296	266
Tb_4O_7 (t)						
	2015	2016	2017	2018	2019	2020
LFL	124.62	120.29	114.62	107.15	98.28	89.58
CFL	101.7	96.91	88.49	79.49	72	63.29
LED	0	0	0	0	0	0
Total (rounded)	226	217	203	187	170	153
Total demand (t)						
	2015	2016	2017	2018	2019	2020
LFL	2887.01	2786.83	2655.42	2482.38	2276.82	2075.16
CFL	2356.05	2245.13	2049.97	1841.47	1668.00	1466.17
LED	10.24	12.97	15.41	17.85	20.19	22.36
Total (rounded)	5253	5045	4721	4342	3965	3564

Table B.3
Secondary supply—Availability of Y_2O_3, Eu_2O_3 and Tb_4O_7 as per different EoL-RR.

Y_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	2688.08	2667.42	2616.92	2546.90	2458.52	2342.60
CFL-EoL	2166.05	2161.63	2078.49	1980.64	1808.47	1624.54
LED-EoL						
EoL-RR 7%	320.37	318.72	309.90	298.82	281.62	261.83
EoL-RR 19%	931.99	927.18	901.52	869.29	819.26	761.69
EoL-RR 53%	2582.39	2569.06	2497.96	2408.65	2270.04	2110.52
Eu_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	227.43	225.68	221.41	215.49	208.01	198.20
CFL-EoL	176.54	183.26	182.89	175.86	167.58	153.01
LED-EoL						
EoL-RR 7%	26.66	26.99	26.68	25.83	24.79	23.18
EoL-RR 19%	77.56	78.52	77.63	75.14	72.11	67.43
EoL-RR 53%	214.91	217.56	215.09	208.19	199.81	186.84
Tb_4O_7 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	130.80	131.98	131.53	130.52	128.04	124.62
CFL-EoL	102.10	105.98	105.77	101.70	96.91	88.49
LED-EoL						
EoL-RR 7%	15.37	15.71	15.66	15.33	14.85	14.07
EoL-RR 19%	44.72	45.69	45.56	44.59	43.19	40.92
EoL-RR 53%	123.90	126.59	126.24	123.54	119.68	113.37

Table B.4
Sensitivity analysis (SA) for lifetimes of lamps.

	Lifetime original (yrs)	SA (yrs)				
CFL	3	5				
LFL	3	5				
LED	11	15				
Y_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	2673.16	2697.26	2688.08	2667.42	2616.92	2546.90
CFL-EoL	1815.83	1953.42	2086.59	2166.05	2161.63	2078.49
LED-EoL	–	–	–	–	–	–
EoL-RR 7%	296.27	306.94	315.13	319.01	315.38	305.28
EoL-RR 19%	861.89	892.93	916.74	928.03	917.48	888.08
EoL-RR 53%	2388.14	2474.16	2540.12	2571.40	2542.19	2460.71
Eu_2O_3 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	226.17	228.21	227.43	225.68	221.41	215.49
CFL-EoL	153.63	165.27	176.54	183.26	182.89	175.86
LED-EoL	–	–	–	–	–	–
EoL-RR 7%	25.07	25.97	26.66	26.99	26.68	25.83
EoL-RR 19%	72.92	75.55	77.56	78.52	77.63	75.14
EoL-RR 53%	202.05	209.33	214.91	217.56	215.09	208.19
Tb_4O_7 (t)						
	2015	2016	2017	2018	2019	2020
LFL-EoL	130.80	131.98	131.53	130.52	128.04	124.62
CFL-EoL	88.85	95.58	102.10	105.98	105.77	101.7
LED-EoL	–	–	–	–	–	–
EoL-RR 7%	14.50	15.02	15.42	15.61	15.43	14.94
EoL-RR 19%	42.17	43.69	44.86	45.41	44.89	43.45
EoL-RR 53%	116.85	121.06	124.29	125.82	124.39	120.40

Table B.5
Put on market, collection, and recycling of fluorescent lamps in selected EU countries.

	Put on Market (t) avg 2007–2009	Waste collected (t) 2010	% of put on market collected 2010	% of put on market recycled 2010
Belgium	3,100	1247	40.2	37.5
Denmark	1,606	694	43.2	41.1
France	13,070	3839	29.4	27
Germany	28,204	11,092	39.3	34.4
Greece	1,757	124	7.1	6.6
Sweden	3,141	1973	62.8	62.3

Source: Eurostat (2014).

Appendix C.

Table C.1

Table C.1
Cost estimates of different REE products for comparison of REE phosphor from primary and secondary (EoL) supply.

Input	Ore ~0.42 USD/kg (In-situ TREO)[1]		REE concentrate ~27.6 USD/kg (In-situ TREO)[1]	Collected EoL lamps			Phosphor powders	EoL REE phosphor concentrate	EoL REE phosphor concentrate
Process	Mine & beneficiation	Cracking & leaching (impurity removal)	Chemical separation	Sorting	Material from EoL lamps	EoL lamp recycling			
							Remaining glass & mercury/phosphor separation	Halophosphates removal	REE phosphors cracking
Output	By gravitational beneficiation concentrated ore (15,000 g/t REO[6] or 0.2–15% grade in deposit)	REE concentrate	Phosphor powders: Y_2O_3 (99.999%) 14 USD/kg[2] Eu_2O_3 (99.9%) 25USD/kg Tb_2O_3 620 USD/kg	Sorted EoL lamps	Sorted glass/metal/plastic	Phosphor powder	Concentrated phosphors (230,000 g/t REO[6] or 10–20 wt% REO[7]) or 15% (CMI, 2014) or 30% tricolour phosphor powder content in recycled phosphor[8]	REE phosphor concentrate	REE concentrate
Cost of treatment				btw. 0.15 and 2 EUR/kg for collection & recycling (WEEE forum)					
					Glass = net cost[*] Metals = very small positive return[~] Plastics = small cost for incinerating	Selling the powder to Solvay is slightly less the cost of landfilling with Solvay paying transport costs[5]	Price reductions for mercury and glass content in phosphor powder. Separating Hg out is very expensive[5]		REE extraction from mercury phosphor ~6 USD/kg[3]
(Avoided) environ-mental cost	63,000 m^3 waste gas; 200 m^3 acidic water; 1.4 t of radioactive waste (all per t of REO)[4] Note: 'Impurity removal' refers to the removal of radioactive elements (if present in the REE-bearing mineral host rock)					~1–2 USD/kg (or SEK 7–15/kg) to landfill phosphor powder[5]	~2500–1.1 million USD/kg Hg isolated from biosphere[9]		

Notes: Current hydrometallurgical processes applied recover 15 wt. pct. of rare-earth metals as oxides contained in phosphor dust (CMI Aug 2014 presentation).

[*] Ad glass: not clean enough for high-end uses—generally NOT used in new lamps.

[~] Ad metals: must be pre-treated and separated by magnets and flotation.

[1] As of TMR database, average of data from TMR for 7 junior REE projects (as per Table A.1., excluding Lynas and China), whereby the listing of two projects by one company has been summed up and averaged.

[2] Prices accessible from price charts to non-subscribed users of metal-pages, Oct 2014.

[3] Cardarelli (2014) in Chemical Engineering (2014) who originally states in the context of 98–99% recovery that 'REEs can be extracted for as low as USD 7/kg of mercury phosphor dust', presumably since it is a Canadian based firm, the price is indicated in CAD.

[4] Navarro and Zhao (2014), Weng et al. (2013).

[5] Interviewee D (2014)

[6] MLR (2002); Noble, 2013 in Tan et al. (2014)

[7] Otto and Wojtalewicz-Kasprzak (2012).

[8] Khetriwal et al. (2011).

[9] Hylander and Goodsite (2006).

The recycling process is cheaper the better and more homogenous the powder quality is. The sorting and collection can influence the efficiency and cost so that enabling a sourcing of the same quality and type of lamp phosphors could make the REE powder recycling process more efficient and cheaper, as pointed to in Binnemans and Jones (2014) with the three recycling routes, yet requires either smaller loops from companies taking back their own product or better separation of lamp types.

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Paper III

The complexity of value: considerations for WEEE, experience from lighting products, and implications for policy

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Abstract

This paper presents a general overview of WEEE and value considerations (both real and potential) as well as the specific results of a research project analysing the performance of EPR systems for lighting products, with particular focus on closing material loops. The research is based on a literature review, case studies, and interviews with key stakeholders. The case of recovery of rare earths elements (REE) from fluorescent lamps is an illustrative example of how EPR systems can create opportunities to recover valuable materials from WEEE. The rapid development of light emitting diode (LED) technology also raises questions of how to anticipate and manage value under uncertainties. The paper reflects on these findings within the general context of valuable waste and the specific implications for EPR policy in a transition to a circular economy.

1 Introduction

An extended producer responsibility (EPR) programme entails the establishment of collection schemes designated for targeted products like waste electrical and electronic products (WEEE). Some WEEE contains critical and valuable materials that represent an opportunity for many different actors to recycle, close material and product loops, and further promote a circular economy strategy [1]. This has also raised certain challenges for EPR programmes under the WEEE Directive 2012/19/EU that have been designed generally assuming waste with little or no value because this is no longer the case for many WEEE waste streams [2]–[5]. The aim of this paper is to contribute to a discussion of value in terms of WEEE and EPR; identifying key factors, actors, and contexts that can inform an agenda for research in the future.

This paper presents a review of the topic of valuable WEEE and EPR, with an interdisciplinary perspective drawing upon academic literature from diverse disciplines. It also presents a new case of lighting products in which EPR and other policies can be a significant enabler of value recovery. The case research is based on literature, EPR performance data in Eurostat and semi-structured interviews with key actors including producer responsibility organisations (PROs), recyclers, retailers, and municipal waste management organisations. A review of WEEE and EPR academic and grey literature reveals many of the observed conditions in which value has arisen in WEEE. The case of lighting products reveals additional conditions in which value can arise and the complex and dynamic nature of value that is influenced by individual and company level value considerations, policies on different levels, global market conditions and technological developments.

2 Valuable WEEE and EPR

There is little debate about the environmental benefits of recycling rather than landfilling of WEEE [6]. Sometimes recycling can recover material of value that exceeds the cost of the collection and recycling processes and this is what is most often meant by valuable WEEE; for example, this is true for many types of mobile phones and laptops.

Potential value can also be considered for different WEEE streams. For example, in 2014 a report for the EU Commission reviewed the suitability of imposing individual targets for WEEE categories [7]. The study primarily focussed on a status quo (overall WEEE targets rising to 85% of waste generated in 2019) versus an individual target (85% waste generated) scenario for each waste stream. Costs of additional collection and recycling (2008 estimates) were weighed against the potential material value of the embodied raw materials (e.g. based on metal prices). For three waste streams (small electronic equipment, small ICT, and PV panels), the report showed material value of the products exceeding costs of collection and recycling and found these categories to therefore be the most suitable for increased collection efforts[1].

[1] The study concluded that for these product groups the relevance of individual targets is high, though in the end it advised individual targets in general to be too administratively cumbersome to implement and that this should be left to the individual member states. France has individual targets for all WEEE categories with a margin of tolerance except for lamps [8].

However, the study had several significant assumptions in its approach that illustrate consideration of the potential value of WEEE is much more complex. First, treatment costs in the report included the costs of collection, transport, recycling, recovery and revenue from recycled fractions. However, the study acknowledged that treatment cost figures were old and that recyclers indicated costs had decreased as much as 50% for some waste categories. Factoring in this decrease would result in all WEEE categories having a higher value of materials than net treatment costs by the study methods. It also demonstrated potential of maturing recycling technology to influence the potential value of WEEE.

Further, in considering the value of materials the report uses a more theoretical approach, with estimates of the material composition of different product categories (in grams), the recoverability of these materials (in %) and the prices for these materials (e.g. based on metalprices.com). The study assumes some metals like aluminium to be 100% recoverable while others like rare earth elements (REE) to only be 30% recoverable. In reality the recovery can vary significantly depending on the type of product, product design, and recovery process. The value of materials is meant to represent the potential value lost to society, but the fact remains that many of the metals are not recovered (either at all or at the assumed rate) by the recycling processes currently used [9], necessitating development or use of different recycling processes. It is often assumed that the concentration of critical or precious materials being high in waste products, for example the concentration of gold in a mobile phone is significantly richer than that in an ore, makes e-waste an economical source for these elements [2], prompting researchers and policymakers alike to call for higher collection and recycling of WEEE to address supply of critical metals [9]–[12]. But most do not fully acknowledge barriers and the policies, technologies, and actions needed to drive this change. Though the concentrations of precious and critical materials in WEEE is indeed often much higher than an ore, it has a unique "minerology" that must be considered along with special techniques for these new urban mining activities [13], [14]. The cost effectiveness of different recovery techniques can also be context specific, e.g. dependent on labour costs for manual disassembly.

On the other hand, materials of value that can be easily recovered can make some WEEE attractive for informal and scrap recyclers outside of the established EPR system. WEEE that has value as reuse often ends up outside of official channels and often outside the EU – contributing to acknowledged problem of illegally transported e-waste [15]. This means that the treatment is not conducted by EPR system standards and the value recovery is not realised by EPR system actors. This has also led stakeholders to perceive that EPR systems are not effective for WEEE with value [5] (though it is hard to find clear differences in available Eurostat collection data indicating this). These challenges to meet higher collection rates of WEEE should not be underestimated [7], [16].

2.1 Smaller loops = greater value?

Moving up the waste hierarchy from recycling to reusing or refurbishment (i.e. following smaller product or material return loops as illustrated in Figure 1) is also often assumed to be an environmental gain because of the resource depletion and energy use avoided compared to manufacturing new (i.e. from a thermodynamic perspective) [3], [17], [18]. In a circular economy model, we would expect to see the value of closing loops increase the higher up the waste hierarchy (i.e. the smaller the loop to return products/material), but this is most often not the case [18].

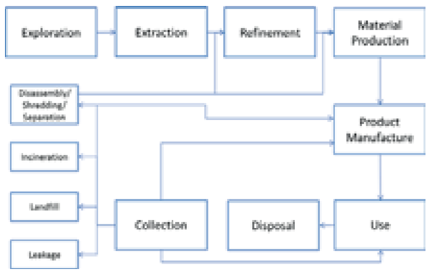

Figure 1 Generic Product Value Chain

The reality is more complicated and there are some cases where technological obsolescence results in only component reuse or recycling being preferable to whole product reuse; for example, if newer models of the product are significantly more resource and energy efficient to a standard beyond what remanufactured used products can achieve [19]. This is why the EU Waste Directive 2008/98/EC prescribes a lifecycle approach to considering the optimal management for waste (e.g. see Art. 4). There are other cases where repurposing (using the product for a different purpose) or remanufacturing (bringing the product back to at least its original performance with equivalent warranties) are preferable to direct reuse or reconditioning either for increased environmental gain or to meet consumer demands [18], [20]. Fashion obsolescence also represents a significant barrier for creating demand from consumers for used products [18], [19]. Reuse value can also be context specific, for example products are used for varying amounts of time and arrive at a reuse stage at different times in different EU member states [21].

2.2 Value for whom?

Also warranting consideration is how value is perceived by different actors. The importance of so-called "shared value" was argued by Porter and Kramer [22] and built upon in a subsequent "value mapping tool" [23] that considers value between and amongst different stakeholders, including: network actors (e.g. firms, suppliers, etc.), customers, society and the environment. The value of WEEE can also be dependent on stakeholders. For example, Esenduran, Atasu and Van Wassenhove [2] consider the value of waste products from the point of view of producers and unofficial collectors/recyclers. The value to producers is perceived mainly to be for meeting recycling targets under legislation, but also from sold recycled fractions. The authors also (less explicitly) consider the viewpoint of retailers and consumers who are enticed by better pricing of scrappers or other entities not within the official EPR compliance system. Despite their obligations to return end-of-use products to this system and the environmental benefits offered by the standards of the official system, it is clear that these actors are only considering the most immediate or highest monetary return value for the material [19].

It is not just unofficial entities that can impede producers from collecting, but also consumers. For example, many consumers who still perceive value to their old mobile phones will store them and this presents a major barrier to increased collection by either formal or informal channels [24], [25]. While these phones have value to their owners (or perhaps value in not being used by others if there is fear of access to personal data [19], [26]), these phones are rapidly decreasing in value for other potential users in the second-hand market [24]. Better understanding of how consumers value different WEEE is also key to understanding how to increase their use of EPR systems.

There is also a reuse value and value of the materials for society in general, particularly for strategic materials deemed critical for the economy and technological development [7], [9], [11], [19], [27]. Value to society may encompass more than the traditional valuable WEEE; and fully exploring this wider value means examining waste streams typically not seen as valuable waste. Lastly, the environment could be considered in many ways to be the primary stakeholder in EPR legislation through avoiding adverse effects from disposal of WEEE in nature, an externality with contested value (i.e. multiple valuation methods can be used) in traditional economic analysis.

3 The case of lighting products

Lighting products comprise their own category within the WEEE Directive, which covers all modern energy efficient lamps including fluorescent lamps and light emitting diodes (LEDs). Fluorescent, or gas discharge, lamps are also currently addressed as a sub-category and given special mention (e.g. Art. 5) due to the mercury they contain. For example, there are specific stipulations in the WEEE Directive to remove this mercury (Annex VII), which also warrants specialized processes to do so and adds another cost factor to ensure environmentally sound treatment.

As shown in Table 1, the recycling process yields mostly glass fractions, the value of which are highly dependent on contextual and geographic factors such as distance to lamp or glass manufacturers and competition from other recycled glass sources [28]. The requirement to treat at least 80% of fluorescent lamps and to remove mercury from lamps, means the recycling processes for lamps is tuned to remove a high level of the mercury-containing phosphor powder. It is this same powder that also contains the critical REE.

Fractions	*Approx. % (cfl – tube)*	*End use / disposal* **[28]**
Al/other metals	18-30%	Reused or recycled
Plastic /metal mix	20%	Recycling; energy recovery; landfill
Glass	45%-80%	Reused tubes; new lamps; construction material; landfill cover
Phosphors-REE, Hg, glass particles	2-3%	Separated into REO for new phosphors; separated to mixed REE in other applications (e.g. automotive); REE + Hg hazardous landfill

Table 1 Fractions from recycled fluorescent lamps

Despite the small amounts of REE in the lamp, the EPR system for collection and the advanced recycling processes has made these waste products a promising source for the first attempts at large-scale recycling of REE. Along with magnets and batteries, it is one of the few REE recycling processes considered to be mature and operational on a commercial scale [10], [29], [30]. The high 2011 REE prices as well as identification of their criticality for EU industries led to increased interest and funding for more research into recycling of REE from lamps, further developing techniques and efficiency (see e.g. [10], [31], [32]). However, technically promising recycling initiatives now face challenges to be economically viable since the high REE prices have since fallen.

Further scaling up recycling of REE, as well as other materials, from waste lighting products is also con-

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strained by collection rates and volumes [7], [10], [13]. Even with the WEEE Directive, the average collection rates in the EU are currently below 30% [7], [28]. It should be noted that this low collection rate is far from uniform throughout the EU as shown in Figure 2, with some countries such as Sweden collecting waste lighting products at very high rates.

Figure 2 Collection rate 2013 / 2010-2012 average put on market (source: Eurostat and www.lwf.no)

While data reliability for collection rates is still an issue [28], the variance in collection rates indicates variation to the EPR systems in place in different member states. There is evidence that a well-designed EPR system can enhance collection rates. In a study of the Nordic countries' EPR systems for lamps, Richter and Koppejan identify several key success factors to EPR system design. These specific system factors for increased collection from households of small electronics to other factors identified by prior research, including history, motivation, opportunity, and capacity [28], [33], to outline important variables for operational performance of EPR systems (Figure 3).

Figure 3 Factors for best practice in EPR for lamps (adapted from [26])

Lamps represent a classic product group for EPR policy as it was originally designed, i.e. they represent a net cost for treatment and recycling the waste products clearly avoids environmental harm. While some research estimates that implementing individual collection targets for lamps will incur increased costs [7], this is not true for all member states as some are already achieving high collection rates in this waste category. The lack of transparent data on WEEE collection and treatment costs makes it difficult to compare cost effectiveness more thoroughly [34]. However, it can be argued that the increased cost needed for higher collection in lower performing countries is the actual cost of running an effective EPR system and that these are the true costs that should be internalised as per the principle of EPR. For some EPR systems this might mean an increase in costs, but evaluation of current systems reveal that some systems are already effective at their current operational costs.

Gradual improvement of overall WEEE collection rates is an aim of the new targets (rising to 65% of put on market or 85% of waste generated in 2019), but there is already doubt about the ability of many member states to meet new targets [7], and even less certainty that these targets will increase individual categories like lamps. Meanwhile opportunities to collect (and retain the REE material) in waste lamps is a short term opportunity reliant on rapid, rather than gradual, improvement of collection rates. In the coming 10 years the waste from fluorescent lamps in the EU is expected to double [7]. However, after this, the amount of waste fluorescent lamps and the amount of REE available for recycling from this stream will decrease significantly. This is due to the rapid market penetration of LEDs to replace fluorescent lighting. This technology shift also means that there is less demand forecasted for REE in phosphors and that recycling could potentially meet a significant amount of demand if a closed loop system developed [30], [35].

The rapid shift to LED and solid state lighting technologies also means a shift in the value considerations for lighting products in their end-of-use stage. Compared to CFLs, LEDs have a higher initial price to the consumer, but also lower lifecycle costs, much longer projected lifespan (50000 hours), increased functionality, and lower overall environmental impact, particularly in the use and end-of-life stages [36]. LEDs, while containing critical metals including Indium, Gallium, and REE, also have much smaller amounts of REE compared to fluorescent lighting, which means recycling these materials from lamps in the future does not have a positive outlook [28].

The change in lamp product characteristics necessitates rethinking the end-of-use strategy for these products. While high recovery of REE could be less

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viable than with fluorescent lamps, the longer life and higher functional value of LEDs enable additional opportunities. These include reuse of LEDs and development of a second-hand market. The rapid development of the technology may also cause LEDs to reach fashion obsolescence before their end-of-life. An opportunity could develop for LED components to be repurposed or used in remanufacturing. The latter is more likely if lighting products move from a product ownership model to a functional ownership model, as some lighting producers like Philips already suggest as the preferred business model for value creation in a circular economy [37].

However, the development of product service models, modular design, and second-hand markets is not a given as there are barriers to reuse already mentioned in Section 2. There is also evidence of increasing integrated LED product design (i.e. integrated luminaires) rather than modularity, which can complicate reuse of components or recycling [28]. The value of used and end-of-life LEDs is likely highly influenced by design considerations taking place now. Smart design features, long life, standard fitting, and durability could result in valuable used or waste products. This raises questions about how policy should address issues such as competition for valuable used products and waste, the dynamic nature of value, and how it can best anticipate and manage value.

4 Implications of value for policy

4.1 Dynamic value and competition for waste

Waste streams with the highest potential value to cost of treatment ratios could well be the product categories best suited to individual targets in order to retain and recover valuable materials [7]. However, this value can also be problematic in achieving higher collection targets due to competition for waste from outside the official EPR schemes. Indeed, recognition of this issue has resulted in producers like Hewlett Packard suggesting that EPR policy should deal with value by only requiring "producers pay for waste where there is a cost" [4]. Esenduran, et al. [2], model the case of valuable waste and strong competition between producers and unofficial recyclers for waste, finding that higher targets for waste with value could potentially result in decreased landfill diversion overall as unofficial recyclers are pushed out of the market. The authors suggest one of two options: 1) tracking, registering and enforcement of standards for unofficial recyclers or 2) reducing collection and recycling targets imposed on producers. The authors argue several advantages to the latter approach, arguing that ambitious but not sufficiently high targets (as those in the current WEEE Directive) result in producers paying a higher recovery price to compete to recyclers, which in turn forces out recyclers and reduces the total welfare. In addition, it is argued that option 1 is made more difficult by leakage of valuable waste out of the EU [4].

There are several assumptions in these suggestions that need to be addressed. There is first the assumption that the environmental benefit simplified to only consider landfill diversion makes no differentiation between the environmental quality of treatment by official and unofficial recyclers [2]. In reality there is evidence that unofficial recyclers are more likely to only recover the materials with highest economic value while discarding the rest [19], [21], [38], [39]. Thus the environmental benefit of landfill diversion with unofficial recyclers is likely overestimated in the model. Standards for recycling like WEEELABEX are a welcome development and further assurance of environmentally sound treatment of WEEE is needed to confidently ensure the environmental objectives of EPR policy are being met. Lastly, the issue of leakage is a challenge that is widely acknowledged as needing to be addressed through better tracking and reporting [7], [15], [40].

The argument for scaled-back EPR for valuable waste is also contingent upon the fact that collection targets alone are not sufficiently high enough to result in the greatest overall welfare. This could be addressed more directly through more ambitious targets. While this may not be currently feasible at the EU level given the recent recast (with an aim to do just that), there is still room at the member state level for policies to go beyond the WEEE Directive in their requirements, for example as France has done with its individual product category targets. Best practices and success factors already identified can be further enhanced at the member state level to improve EPR systems [28].

There is also an assumption that the valuable WEEE will continue to hold its value. The fall of REE and other metal prices demonstrates that value can be dynamic, with boom-bust cycles. It is possible that the EPR policy can be designed flexibly enough to accommodate this with a mechanism for triggering responsibility, but this would raise issues of regulatory uncertainty. This in itself can be a cost for producers who would have to react to changing regulation. There is also a value to regulatory certainty that should not be underestimated.

4.2 Incentivising reuse and secondary supply of materials

There could be a role for policy in creating more certainty about value, particularly with regard to used products and recycled materials. Ideally EPR legislation would also include reuse targets. It is argued that this currently infeasible, with lack of data being the largest barrier [21]. Arguably this is an extension of existing challenges with information and tracking of WEEE. Better implementation and enforcement of data provision (for example, from reuse centres) and reporting requirements for both recycling and reuse (separately) should be a necessary starting point. Making a requirement that EPR schemes allow reuse organisations access to EEE and WEEE is also a way to increase reuse [19], [21] as well as documenting flows and ensuring quality of reused products [18].

Addressing demand for recycled materials is remains a challenge. As demonstrated by the case of fluorescent lighting, even with mature recycling technology and increased collection rates, recovery of critical materials is still dependent on market prices for the recycled materials. At the peak prices, spurred by Chinese control of the market, it was attractive to find alternatives to REE from China either by substitution to decrease the demand, opening (or reopening) mines like Lynas' Mount Weld in Australia and Molycorp's Mountain Pass in California to increase primary supply, or by recycling to provide a secondary supply [35]. The drop in REE prices saw interest in these initiatives wane too, resulting in closing mines like Molycorp's in California and the announcement by Solvay that it will discontinue its recycling from lamps [41]. While Lynas and Molycorp still struggle with low prices, there were some companies (e.g Siemens and companies in Japan) willing to sign longer term contracts with these companies (at presumably higher prices than those from Chinese suppliers) in order to have more certainty and control of their supply chains [30].

Managing supply chains to be more resilient, e.g. though alternative primary supply, has been advocated as a responsible way of addressing material criticality [42]. However, this will only be a mainstream practice if it is more widely acknowledged that this certainty of supply is of real value, i.e. an additional cost that companies are willing to pay. By the same argument, secondary supply from recycling can also help with certainty of supply for critical materials. However, there some concerns about volume, timing and quality, mainly because secondary supply chains remain less developed compared to more established primary supply chains [43]. Secondary supply of REE from waste products has another benefit in that it avoids the negative environmental and social impacts of extraction, which can be substantial given the considerable amount and nature of illegal mining practices in China [44], [45]. Further developing recycling and secondary supply of REE also contributes towards waste reduction and resource efficiency goals - all part of the circular economy agenda [35].

While retrieval of valuable secondary materials is part of the stated purpose of the WEEE Directive, this could be strengthened. For example, inclusion of recycling of targeted materials and products in the WEEE Directive (i.e. requiring recycling of critical materials where technology is mature, e.g. in fluorescent lamps) has been suggested [43] and would this would certainly help in incentivising the recycling of critical materials. An added emphasis on this aspect of the rationale for EPR could also be effective in realising higher collection rates (i.e. consumers return products not just to avoid environmental harm of landfilling but to actively conserve material resources [46]). However, this still does not necessarily assure that the recycling efforts match the market demand for the recycled materials. There also needs to be consideration in the critical materials strategy of how to best use or store critical materials if supply risks are anticipated but not immediate and the value for society of doing so.

To a certain extent, the characteristics of products initiate their value for reuse and/or recycling. As demonstrated by the case of lighting, design decisions made now will influence the feasibility of closing loops decades in the future. It is necessary to look at how policy can then further incentivise design changes that will make reuse, repair and recycling more likely to occur. While this is an aim of the WEEE legislation, this has also been a challenge due to the way EPR schemes are run (collectively) in practice [47]. Better understanding is needed of how to incentive producers to be more involved in the entire lifecycle of their products, e.g. through different business models. There is a role for the Ecodesign Directive and the WEEE Directive to both be enhanced in their design to further incentivise a transition to a circular economy, with producers not only thinking about the recyclability of their products, but also how recycled fractions or components of old products could be preferred for use in new products. Fundamental shifts in both producer and consumer perceptions of value are necessary if all waste is to become a resource.

The exploration of waste with value has demonstrated that the value of WEEE is dynamic and complex. Considerations of value depend on actor perspectives and objectives, networks, policies and market dynamics. Value also depends on consideration of the externalities, for example the negative environmental and social impacts of primary production and the wider benefits of recycling. It should not be understated that this is, and will continue to be, challenging for policy to address. However, transitioning to a more sustainable and circular economy will require more creative, ambitious and holistic policies encompassing the complexity of value in WEEE.

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The transition to a low-carbon economy requires enabling technologies including energy-efficient lighting products. Previous research has highlighted the need for increased collection and recycling of lamps to reduce mercury emissions, to avoid unnecessary negative environmental impacts, and to recover the critical materials they contain. Extended Producer Responsibility (EPR) policies aim to address these issues by promoting collection and recycling of waste products, closing material loops, and providing ecodesign incentives. This licentiate thesis contributed to EPR research with detailed knowledge about the performance of EPR policies for energy-efficient lamps in Europe. Using a theory-based evaluation approach, both the performance in relation to EPR goals as well as challenges perceived by key stakeholders were analyzed. Factors contributing to high operational performance and best practices in the Nordic countries were identified, as well as areas for further improvement. The research also examined opportunities and barriers for closing critical material loops from waste lamps, with considerations of value discussed in the context of prior and future EPR research.

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