Circle Economy

Universiteit Utrecht

Circular business models: An opportunity to generate new value, recover value and mitigate risk associated with pressure on raw material availability and price volatility

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Master thesis
May 2014

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Circular business models:
An opportunity to generate new value, recover value and mitigate risk associated with pressure on raw material availability and price volatility

"What is the effect of rising prices of critical raw materials from a company perspective and how can this effect be mitigated by using the circular economy approach?"

Colophon

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ECTS: 45
Time period: October 2013 – May 2014

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Version: Public

Abstract

The demand for resources has shown a sharp increase over the last decade. As resources become scarcer due to limitations of their physical supply resource prices rise and have become more volatile. Adding to this volatility are increasing tensions in the geopolitical-economic context stemming from the increasing resource scarcity. For LED lamps, the product analyzed in this thesis, it was found that more than half of the materials used in the production of LED lamps have shown an annual resource price increase exceeding 10% and an annual price volatility above 36% between 2007 and 2012. The increasing difficulty of companies to secure resources at a reasonable price threatens the continuity of production, their potential to grow, and because of the geopolitical implication also their competitive advantage. As an alternative to the current resource intensive production system where the influence over resources is lost, in this thesis we explore the introduction of circular business models as a strategy to reduce overall resource demand by closing the resource loops throughout the production cycle. Such business models have the potential to reduce the dependency to purchase resources from the market thereby potentially mitigating the risks associated with volatile and generally rising resource prices.

In a case study circular business models were applied to the production of lamps. In particular focusing on different end-of-life scenarios to recover value throughout the production cycle. Currently a transition in the lighting industry is materializing from one dominated by incandescent lamps and CFLs to a market that will be dominated by LED lamps. Therefore demand for specific resources for the production of LED lamps are required while at the same time valuable resources used in CFLs are being disposed. This gives an opportunity to re-use components from CFL lamps for the production of LED lamps. Our findings suggest that the value recovered through component harvesting is four times higher than material recycling because the production costs embodied in the product - for energy and labor input costs – can be recovered. Sensitivity analysis showed that key determinants in the end-of-life scenario were the labor wages and resource prices: higher resource costs have a positive effect on all three scenarios and higher wages have a negative effect on the component harvesting scenario.

The profitability of circular business models focusing on end-of-life strategies depend on many uncertain variables such as resource price developments, product demand, and technological development. To analyze and monetize the effects associated with these uncertainties the real option valuation method was applied which is better equipped to incorporate uncertainty and determine the profitability of circular business model than traditional investment decisions metrics such as the net present valuation (NPV) method. Results suggest that the NPV can significantly underestimate the value of circular business models; for example, the profitability for the recycling scenario was underestimated by a factor five using the NPV method. Furthermore, the risk premium was calculated as a means to quantify the implicit costs for companies associated with the vulnerability stemming from increasing and volatile resource prices. The risk premium corresponds to the value by which circular end-of-life strategies mitigate the potential impact of rising and volatile resource prices. The avoided risk premium increases the margin of recycling, component harvesting, and component & recycling by respectively 24%, 18% and 30%.

Outcomes suggest that applying circular business models in the form of smarter end-of-life scenarios for the production and refurbishment of lamps may recover value over the production lifecycle. When this is combined with higher shares of products and resources that are maintained within a manufacturer's production cycle it may increase operational stability by mitigating effects related to raw material scarcity and price volatility.

Acknowledgements

I am particularly grateful for the assistance, feedback and contributions given by my supervisors from the university, Prof Dr. Ernst Worrell and Dr. Mark Sanders. My deepest thanks go to the Circle Economy (team) for giving me the opportunity to write my master's thesis. Their continued energy, support and especially passion for a circular economy has been a true help and inspiration. Special thanks should be given to dr. Marc de Wit for his continued support, advice and time during this research project. Last, but not least, many thanks to all of my friends and family for their continued support.

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List of abbreviations

BOM:	Bill of Materials
BOL:	Beginning of Life
CAPM::	Capital Asset Pricing Model
CE:	Circular Economy
C2C:	Cradle to Cradle
CFL:	Compact Fluorescent Lamp
CPI	Consumer Price Index
EEE:	Electronic and Electrical equipment
EU:	European Union
EMF:	Ellen Macarthur Foundation
EOL:	End-of-life
DfD:	Design for Disassembly
GDP:	Gross Domestic Product
LED:	Light Emitting Diode
MOL:	Middle Of Life
NPV:	Net Present Value
PGM	Platinum Group Metals
WEEE:	Waste of electronic and electrical equipment
R&D:	Research and Development
REE:	Rare Earth Elements
RO:	Real Option
ROV:	Real Option Value
RSC:	Reverse Supply Chain
SCM	Supply Chain Management

1. Introduction

For most of the 20th century, the prices for critical natural resources such as food, water, and materials have been declining (McKinsey, 2011), but since the beginning of this century resource prices are on the rise again. In fact, they have increased with 147% since the beginning of this century (McKinsey, 2011). Over the last decades, the demand for resources has grown rapidly along with the steep economic growth (Bringezu, Schütz, Steger, & Baudisch, 2004). At the moment 50 billion tons of materials are extracted every year (T. Graedel et al., 2011). When the accelerating extraction of resources is continued at its current pace, the amount of used resources will grow by 180% in 2030 compared to 1980 (SERI, 2009). The acceleration in global resource use is particularly fuelled by the rapid economic growth in emerging countries, such as China and India. It is projected that over three billion middle-class consumers will emerge over the next 20 years (McKinsey, 2011). At the same time resource supplies are getting more scarce, mines are depleted and the rate of discovery of new supplies for many resources is stalling. (British Geological Survey, 2012). And because natural resources are distributed heterogeneously across the planet, geopolitical tensions rise (European Commission, 2010). Securing resources is becoming more challenging, especially for countries or regions that are dependent on imported resources. The European union is mostly dependent on external supplies of resources (Ecorys, 2012). This makes the EU incredibly sensitive to external factors, such as shortages or higher resource prices, and can potentially disrupt the continuity of the economy (World foresight forum, 2011).

In the current economy, growth is very much dependent on the use of natural resources (Bringezu et al., 2004). However in a closed system such as our planet, the amount of resources that are available are finite and the resources that are extracted end up as waste, or otherwise, in the system (Pearce & Turner, 1990). This implies that economic growth is inevitably limited by the boundaries of this planet, and leads to an accumulation of waste. In this current resource intensive economy, significant amounts of resources are wasted throughout the production process, from extraction to disposal (SERI, 2009). Leading to both an economic loss because of wasted valuable resources through inefficient processes, and damages to the natural ecosystem through resource extraction and disposal of waste. The contradiction is that large volumes of resources are needed for the production of products; consequently an increasing amount of valuable resource embodied in products are being disposed. From an environmental and an economic perspective, resources should circulate as much as possible throughout the economic systems, thus increasing economic value while decreasing the environmental impact (Pearce & Turner, 1990).

The Circular Economy (CE) has been proposed as an alternative to our linear economy. The CE uses a systems approach where ideally all waste should be used as a resource for another part of the system. These principles should not be applied at a product of company level, but instead should be viewed from a holistic perspective. It is argued that by using the CE approach, resource dependency, waste and the environmental impact is reduced (The Ellen MacArthur Foundation, 2013). The potential gains are substantial cost savings: for the EU these range up to 500 billion euros (The Ellen MacArthur Foundation, 2013). Furthermore the CE can not only be a solution to our current resource problem, but can also be a source of innovation and profit (PBL, 2013).

1.1. Problem definition

Concepts such as Industrial Ecology, Cradle to Cradle, Bio-mimicry and Blue Economy, have been developed to formulate an alternative to the current resource intensive economy (Braungart, McDonough, & Bollinger, 2007; Garner & Keoleian, 1995). The CE builds upon these frameworks. As mentioned before, the CE has the potential to drastically change the way resources are being used in the economic system. However it is still largely unknown what a shift towards a CE will mean for companies, and the way resources circulate through the production cycle. It is expected that it will create higher profits, reduced material costs, greater resilience and increased competitive advantage (The Ellen MacArthur Foundation, 2012).

1.1.1. Material scarcity and resource prices

Resource prices are the largest cost-determining factor for the production of goods (Angerer et al., 2009a, p. 6). Increasing and volatile resources affects the costs structure for companies (Angerer et al., 2009a, p. 6). Up to 50% of the total production costs for over a quarter of the companies in the EU consists of material costs (The Gallup Organization, 2011). Manufacturing companies material costs account on average for over 40% of production costs (Angerer et al., 2009b). When observing the importance of resources for production companies it is worrying that over 80% of companies in the European Union have experienced increasing material costs over the last decade (INVERTO, 2011). In the German manufacturing industry raw material costs have increases 160% during 1995-2006, whereas the Gross Domestic Product only increased with 20%. Increasing prices have had a negative impact on the performance of companies, consequently it was found that a 10% increase in resource costs resulted in a 6% decrease in earnings (Truecost, 2011).

Companies foresee that problems concerning material scarcity will only increase in the near future (The Gallup Organization, 2011). Higher prices, supply problems for metals, and material scarcity are expected to be an increasing problem (KPMG, 2012). There are numerous ways to mitigate these potential negative effects. These strategies commonly focus on diversification of supplier networks or financial hedging of resources (KPMG, 2012). However, only ten percent of the firms have implemented comprehensive strategies to address supply risks while 59% have no strategic response developed at all (KPMG, 2012).

The problem with traditional methods to diminish the effect of rising resource prices is that they still use the linear economy as a starting point, and thereby limit their focus on the production and selling of goods (The Ellen MacArthur Foundation, 2012). However, in a closed system all necessary resources are for a large share available in the production cycle itself. By expanding the sphere of influence of companies by including resource use and waste management, new opportunities that reduce resource dependency can be created. For example: resources from production residues or disposed products can be used as an input for the production of new goods. This essentially means that the flow of resources throughout the production process is a closed loop, thereby not only making use of the product's end-of-life value but also reducing material dependency and costs for the production of new goods (Circular Economy Task Force, 2013). At the same time fewer resources are extracted from the earth, thus decreasing the environmental burden.

The optimal strategy in a CE is one that recovers the production costs embodied in the product. Therefore not only the material value should be recovered, but the labor, energy, investment and/or other types of inputs should be recovered as well (The Ellen MacArthur Foundation, 2014). For example the material value of an smartphone recovers only 0,24% of the retail value, whereas 48% of the retail value can be recovered by reuse of the product (Circular Economy Task Force, 2013, p. 16). The most common end-of-life strategies, in order of value recovery, are: repair, reuse, remanufacturing, refurbishing, component harvesting, recycling and incineration (Parlikad, Mcfarlane, Fleisch, & Gross, 2003).

1.1.2. Technological feasibility of circular business models

Many high-tech and sustainable technologies - such as electric cars, solar panels and smartphones – use resources that are more rare and valuable, such as rare earth metals, than many other products (Angerer et al., 2009a). The accelerated transition towards a high-tech and sustainable society sharply increases the demand for materials used for the production of high-tech and sustainable products. (Angerer et al., 2009a). For example, it is expected that the demand for Gallium in 2030 will be six times the total world production in 2006 due to growing penetration rates for technologies such as Thin Layer Photovoltaic (Angerer et al., 2009a). Due to the complex nature of many technological advanced products it is unknown to what extent end-of-life strategies can be applied.

The case study used in this research will focus on the current transition from a Compact Fluorescent lamp (CFL) and incandescent lamp dominated market towards a Light Emitting Diode (LED) lamp dominated market (International Energy Agency, 2006; McKinsey, 2013). It is expected that the LED lighting market will account for 60% of the overall lighting market in 2020, resulting in over 2,6 billion sales (Mckinsey, 2012). The lighting transition is characterized by increasing material demand for the production of LED lamps, whereas an increasing amount of CFLs is being disposed of (Deubzer, Jordan, Marwede, & Chancerel, 2012). In this research two end-of-life strategies will be used in order to analyze to what extent material and components from disposed products can be used for the production of products. The first end-of-life strategy is material recycling, comprising the recovery of material value from products. The second end-of-life strategy is component harvesting, which is the recovery of reusable parts and modules from used products in order to be used in the production of a new/refurbished or remanufactured product (Parlikad et al., 2003, p. 6).

1.1.3. Investing in smart end-of-life scenario's

Substantial investments have to be made in order to create smart end-of-life systems that fully capture the value of a circular economy. The profitability of these investments depends on many variables such as resource prices, technological development and product demand. Especially for longer time periods it becomes increasingly difficult to accurately estimate the variables that are key in circular business models. For example the profitability of material recycling depends on the underlying value of resource prices, which have been extremely volatile over the last decade. This uncertainty can result in a slowdown or decrease in investments (Leahy & Whited, 1996).

Often the net present valuation (NPV) method is used to determine the profitability of a project. In environments characterized with high uncertainty, as in a transition towards a circular economy, the NPV method doesn't always appropriately determine the value of future investments (Dixit & Pindyck, 1994). The real options valuation (ROV) method is an alternative method to the NPV method, but better equipped to incorporate uncertainty and flexibility (Trigeorgis, 2002). Rather than using deterministic price forecasts, it uses dynamic modelling to determine the value for end-of-life strategies at each point in time. Furthermore it recognizes that new business ventures need flexibility in order to adapt to changing market circumstances. If for example resource prices were extremely high, resource recycling would become a lot more profitable, thereby creating an incentive to increase recycling capacity. The ROV will be used as an alternative to the NPV in this research.

1.2. Research objective and research Question

The main objective of this thesis is to evaluate opportunities to apply circular business models aimed at developing smart end-of-life scenarios such as component harvesting and closing material cycles to recover value, generate new value and increase operational stability by mitigating effects related to raw material scarcity and price volatility.

The problem definition is paraphrased into the central research question:
" What is the effect of rising prices of critical raw materials from a company perspective and how can this effect be mitigated by using the circular economy approach?"
In order to answer the main central research question four sub-research questions have been formulated:

1. What are the characteristics of business models used in a circular economy?
2. What are the effects of rising resources prices on companies, regarding their financial performance and the strategies they develop to cope with rising resource prices?
3. To what extent can the effect of rising raw materials prices, volatility and disruptions of critical raw materials be mitigated by using a circular economy business model?
4. What is the value of end-of-life strategies used in a circular economy?

1.3. Societal and scientific Relevance

For the past century the steady increase in economic growth has been accompanied by an increase in the use of resources and an increasing negative impact on the environment (FIscher-Kowalski et al., 2011). The extraction of construction materials has grown by a factor of 34 and for fossil fuels by factor of 12 (FIscher-Kowalski et al., 2011). This not only gives considerable negative environmental externalities (such as pollution), it also causes political unrest. UNEP (2011) reports that the majority of international conflicts and 40% of the intrastate conflicts ultimately have an issue pertaining resources at heart. It is essential that different systems are being developed that disconnect economic growth from resource use. Smart business models that reduce resource dependency have the potential to make the economy and society more resilient.

The European Union and especially the Netherlands are very dependent on the import of resources (PBL, 2011). Policy makers are becoming more and more aware of the profound effect that resource scarcity can have on the economy. The European commission has identified 14 critical raw materials that are subject to a higher risk of supply interruption (European Commission, 2010). Strategic policies have been implemented that should improve the security of raw materials destined for Europe. An increase in attention for resource security has taken place in The Netherlands as well. CE has been advocated as a solution for the current resource problem and can in term be a catalyst of innovation(PBL, 2013).

1.4. Research structure and reading guide

The theory used in this research will be discussed in Chapter 2. First the dimensions of resource scarcity and the role of resources in the economy systems will be described. This is followed by a detailed description of the circular economy, the various end-of-life strategies, and enablers for circular business models. An analysis of net present value and real option valuation method as ways to estimate the value of circular business models will conclude this chapter.

In order to quantify the value of circular business models a conceptual model was developed and is presented in Chapter 3. First a detailed analysis on resource prices will be done, followed by a description on the role of the product life cycle in end-of-life strategies. In order to estimate the value of circular business models, derivations by the use of the NPV method for the various end-of-life strategies will be given. Lastly the ROV method will be used for valuation circular business models.

The case study will be followed by a discussion in chapter 4 and the conclusion in chapter 6. The research structure is graphically depicted in figure 1.1.

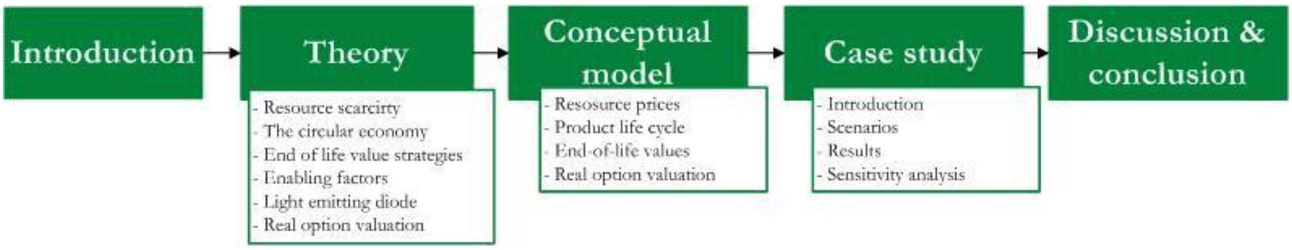

Figure 1.1: Research structure.

2. Theory

40 years ago The Club of Rome has shaken up our understating about how (economic) growth is limited by the limits of our planet (Meadows, 1972). Economic growth is very much dependent on the use of natural resources (Bringezu et al., 2004). Natural resources are needed to build roads, create factories, for our basic needs such as water and food and it incorporated in every product we use. With more and more people on this planet and an increasing standard of living the demand for resources is expected to increase (The Ellen MacArthur Foundation, 2012). The amount of resource the planet can supply is finite, by physical limitations. And in an economy that is fundamentally depended on natural resources it is impossible to have infinite growth because natural resources, the fuel of our economy, are limited. To put it differently:
"anyone who believes in infinite growth in a finite world is either mad or an economist" –Kenneth Boulding.

The discussion on the criticality of natural resources was first dominated by the geological constraints of resource extractions, showing that the reserves that we have left in the earth will be quickly depleted. Nowadays the discussions shifted towards more the geopolitical and economical dimensions of resource scarcity.

The dimensions of scarcity will be discussed in 2.1. The fundamentals of a circular economy will be discussed in section 2.2. There are varies end-of-life strategies that can be applied to products and will be given in section 2.3.

In order to stimulate a transition towards a circular economy, new business models and other enablers are needed, this will be discussed in 2.4.. In section 2.5 the net present value and real options valuation methodology will be discussed. The Light Emitting Diode technology will be discussed in more detail in section 2.6.

2.1. Dimensions of resource scarcity

In the past resource scarcity was mainly focused on the psychical dimension of resource depletion. Today, the focus shifted towards securing access to resources. Political and economic dimensions have become more important as a driver of resource scarcity, see Figure 2.1. Section 0 deals with the psychical dimensions of scarcity, section 2.1.2 with the geopolitical-economic dimension of scarcity, and section 2.1.3 elaborates on the relation to material demand from emerging technologies.

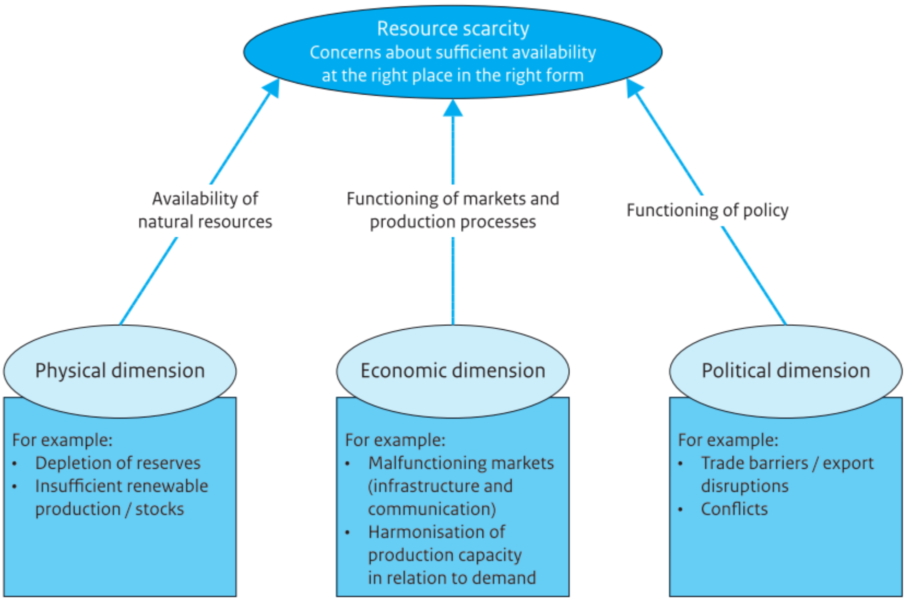

Figure 2.1: Dimensions of resource scarcity. Source: (PBL, 2013, p. 21)

2.1.1. Psychical dimension of scarcity

The physical dimensions of resource scarcity refer to the amount of resources that are available in the earth. Two types of resources can be distinguished: Renewable resources, such as biomass, which are renewed on a yearly basis. And non-renewable resources, such as minerals, that are available up to a certain amount in the earth's crust, but do not renew themselves in a relevant time-scale.

Geologically, different classes of reserves can be distinguished. The McKelvey diagram, see Figure 2.2, is often used to show the availably of resources, which is a function of the economic feasibility and geological probability (McKelvey, 1972). Economic feasibility refers to the degree resource are affordable to mine. For example, lower ore grades or unconventional mines, such as deep-sea mining, are more expensive to mine. The geological probability, refers to the degree it is likely that resources are available in the earth. When resources become economically feasibility they will increase the amount of reserves that are available. Higher market prices for resource will therefor increase the amount of reserves.

According to the economic feasibility and the geological probability, the following reserve classes can be distinguished: *Mineral reserves* are the resources that have been fully geologically evaluated and are economically and legally mineable (European Commission, 2010). The *Reserve base* includes mineral reserves plus the resources that have a reasonable potential to become economically available. The *mineral resource* are all identified resources.

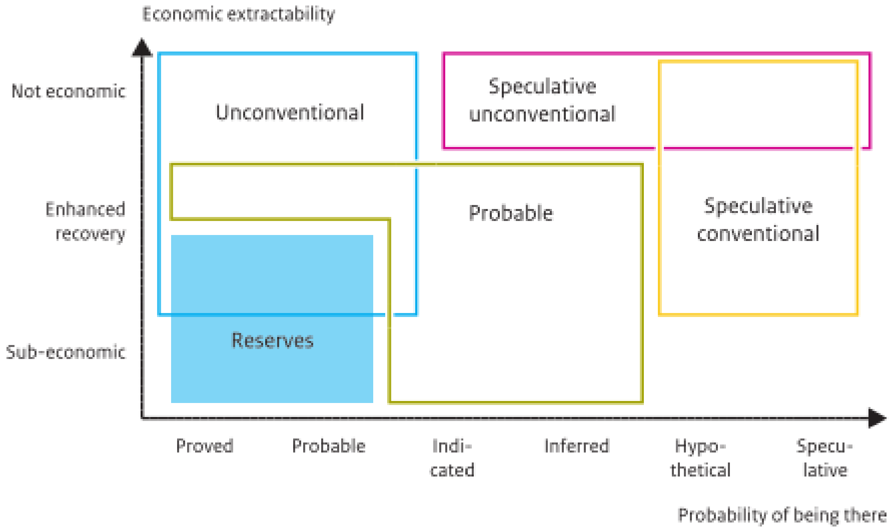

Figure 2.2: McKelvey Diagram. Source: (PBL, 2011, p. 20) Based on (McKelvey, 1972).

New reserves are discovered continuously due to research and innovation (R&D). Over the last 50 years the mining industry has succeeded in matching the demand for reserves, and has continually extended the calculated time of reserves left (European Commission, 2010). The reason that the amount of reserves left remains relatively steady, is that mining companies do not have the incentive to discover the full range of resources, as they are only interested in the investment decision in the medium term. From their perspective it is not necessarily to explore all the reserves in the earth for the coming 100 years, but only what might impact their profit for the coming 30 years.

Technological progress has been a key driver for increasing the amount of supplied resources (European Commission, 2010). Mining and processing technologies increases the amount of reserves that are discovered and that are economically feasible to mine. Innovation in mining technologies increases the mining efficiency through which previously uneconomic mines or low-grade ores become economically viable to mine. Secondly, technological innovation enables us to access previous inaccessible resources, such as resource at seafloors or extreme depts. However there is no clean answer whether technological change is effective enough to keep up with demand for resources (Bretschger, 2005, p. 18).

At some point newly discovered resource are not economically viable to mine. This is referred to as the mineralogical barrier, which is the point where easily processed minerals are so rare that mineral extraction techniques cannot be applied economically (Diederen, 2009, p. 4). The question is when this will happen in the near future. For example, copper mining already closes the technical limits of mining (Circular Economy Task Force, 2013, p. 13). More concerning is that the concentration of copper ore dropped from 8 percent to 0,7 percent over the last 150 years (Circular Economy Task Force, 2013, p. 13). With lower ore grades, more energy and water is needed to extract the copper. Especially the latter is becoming a more scarce material in mining areas, and also directly competes with human consumption.

A complicating factor in resource extraction is that some elements are derived as by-products from major "carrier' elements or are coupled together with other elements. Figure 2.3 illustrates that a few basic metals such as aluminum and copper are at base for the production of many other metals. This is especially the case for metals used in the production technological advanced products (Resnick Institute, 2011, p. 18). Examples of coupled metals are Germanium and Indium that are typically mined together with zinc. By-product elements are groups without a real carrier metal. These groups include the platinum group metals (PGMs) and rare earth elements (REE), which have to be mined and processed together.

Supply of coupled and by-products minerals could be at risk if the demand of the "carrier" metal is not enough to satisfy the demand for the coupled- or by-product minerals (European Commission, 2010). If demand for copper would be extremely low it would also mean that elements with no or limited production infrastructure, such as Iridium (Ir) or Bismuth (Bi), would have a low supply, even though demand might be high. This is complicated by the fact that these metals are usually produced in such as small amount that even exceptionally high prices for the by-product would not provide a strong financial incentive for mining companies (Resnick Institute, 2011, p. 18). Secondly, the demand for many technology metals is much more uncertain and harder to predict in the long-term than the demand for copper. Copper demand has been relatively stable over the past years, whereas demand for "technology elements" is a recent phenomenon. The demand for these elements depends on technology adaptation and market penetration rates and are more difficult to model.

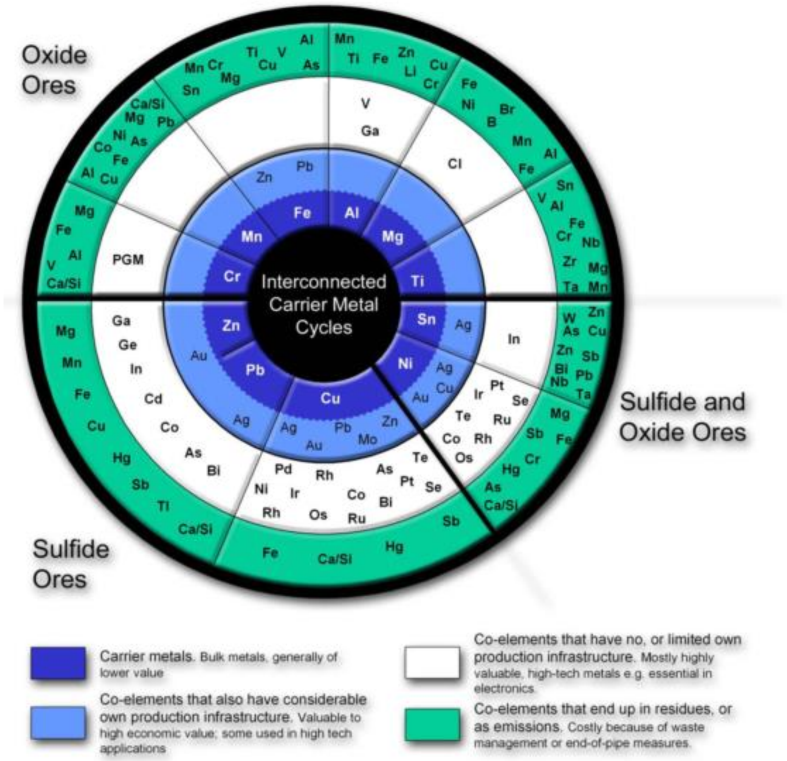

Figure 2.3: The metal wheel, illustrating the material supply dependency for various metals . Source: (European Commission, 2010, p. 18).

Although non-renewable in nature, many minerals and metals are not "lost" after its being utilized in the economic system. They are relocated above surface and are still available for future use. In fact there has been an substantial shift in metals stocks from below the ground to above the ground in applications in society (T. E. Graedel, 2010, p. 2). Recycling these materials is essentially extracting the resource from above ground; often referred to as "urban mining". There is little information about stock volumes that currently exists in industrial stockpiles, landfills and government repositories.

2.1.2. Geopolitical-economic dimension of scarcity

Natural resources are distributed heterogeneously across the planet, meaning that resources are concentrated in a limited number of countries, varying per resource. I.e. high concentrations of rare earth elements can be found in China whereas large oil reserves are found in Arabic countries. This means that countries with fever reserves are more depended on international trade. This can create political tensions for important-dependent countries. Especially when resources are becoming more scarce, countries might not be willing to share their resources on the global market.

A complicating factor is that many countries are using export taxes, quotes, subsidies and other means to secure their resources. Protectionism has been evolving over the last decade as an strategy for resource scarcity (European Commission, 2010). For example china is setting export quotas on the export of rare earth elements. And with a dominance on rare earth elements market it directly affects the global supply and prices of these elements. Another disruptive development is the increase of market speculation on resources. Which often causes price spikes or inefficiently high resource prices, as is the case with coffee (Bos & Molen, 2011, p. 2).

The above-mentioned, are all factors that disturb the efficient working of the global market economy. Securing of resources already is and will probably become more problematic in the future. Especially with the decreasing resources, and increasing demand, resources stress will increase.

2.1.3. Material demand for emerging technologies

In a world that has become increasingly depend on technological solutions the demand for materials used in the production of those product has gained a sudden shift. Many elements that are used in the production of smartphones, flat-screen televisions or computers are more precious and less to be found in the earth. Rare earth elements are an example of frequently used elements that are being used for its chemical characteristics. The demand for these elements, hereafter named technological materials, is likely to increase due to the continued economic growth of emerging economies, increased competition among technology sectors, increasing resource consumption due to decreasing life spans and the lack of recycling infrastructure (Köhler, Bakker, & Peck, 2013, p. 443). Sales for energy efficient products such as LED lights and Electric cars are increasing rapidly (European Commission, 2010, p. 11). Renewable energy producing technologies such as solar, wind and nuclear power require many precious metals (Moss, Tzimas, Kara, Willis, & Kooroshy, 2011). A shift towards a society that uses more renewable energy technologies increases the demand for many precious elements (WWF, 2014).

The demand for materials used in the production of emerging technologies is highly dependent on product adaptation and market penetration rates. The Fraunhofer Institute (2009b) analyzed the increase in demand for metals in 2030 compared to 2006 due to increasing demand for various emerging technologies. For Gallium the demand is 6,09 times the global production in 2006 due to Thin Layer photovoltaic and WLED production. For many of the materials analyzed in the study the demand is higher than the current supply, see Figure 2.4..

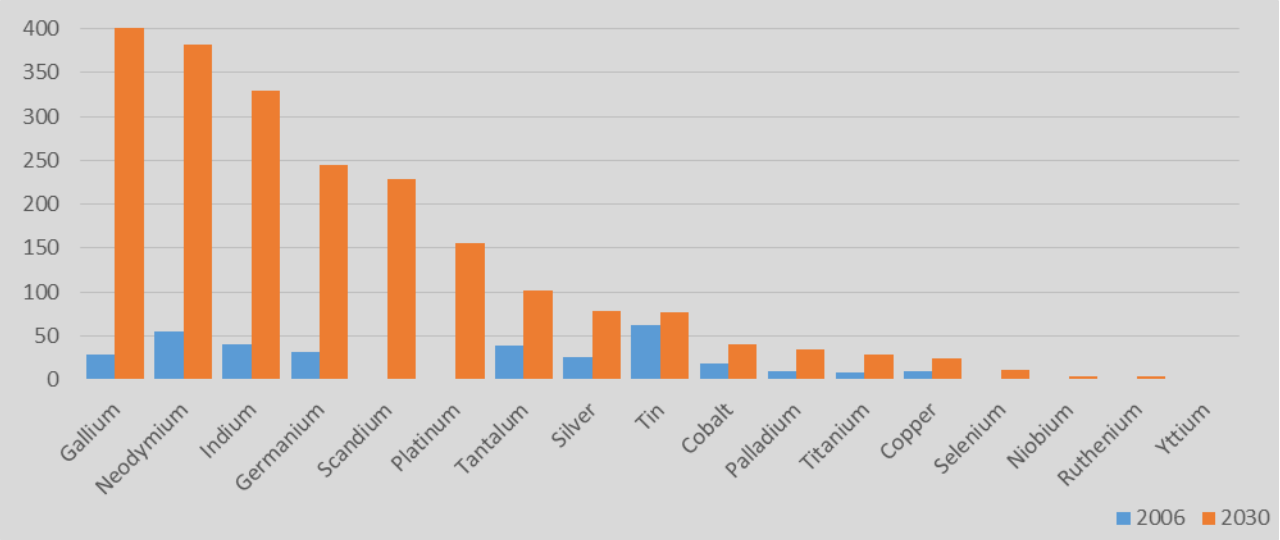

Figure 2.4: Global material demand for emerging technologies for 2006 and 2030 compared to today's total world production. Source: (Angerer et al., 2009a).

The European commission identified 14 critical materials[1], which were defined according to their economic importance and its supply risk, see Table 2.1. Materials are labeled critical when supply risk and their impact on the economy is higher than other raw materials.

Antimony	Indium	Beryllium	Magnesium
Cobat	Niobium	Fluorspar	Platinum Group Metals[2]
Gallium	Rare Earths[3]	Germanium	Tantalum
Graphite	Tungsten		

Table 2.1:Critical raw materials in the EU. Source: (European Commission, 2010).

The economic importance of raw materials can be seen from the input analysis of the manufacturing industry in Germany, see Table 2.2. Over 43% of the input costs come from material inputs and the material costs have increased 58% in 2006 compared to 1995.

Type of costs	Share in 2006	Increase in costs from 1995
Material costs	43%	58%
Energy costs	1,8%	-
Personal costs	22,7%	1%
Other costs	32,5%	-
Gross production value without turnover tax	100%	26%

Table 2.2: Development of production costs in the manufacturing industry of Germany in constant prices. Source: (Angerer et al., 2009a, p. 5).

2.2. The Circular economy

No direct publication or author can be linked to the concept circular economy but one of the early foundations is done by Pearce and Turner (1990), whom describe the environment from economics/resource perspective. This perspective will be discussed in more detail in section 2.2.1. Building on the concept of a resource based view industrial ecology emerged. Which looks at the interrelationships between our industrial activities and nature (Socolow, Andrews, Berkhout, & Thomas, 1994). Hereafter other concepts such as cradle-to-cradle, Biomimicry and blue economy emerged and will be shortly discussed in section in section 2.2.2.

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[1] For a detailed list of material risk indications by other report see (Department for environment food and Rural Affairs, 2012, p. 11)

[2] The Platinum Group Metals (PGMs) regroups platinum, palladium, iridium, rhodium, ruthenium and osmium

[3] Rare earths include yttrium, scandium, and the so-called lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium)

2.2.1. From a linear to a circular economy

The circular economy is an alternative to the current linear economy. The resource based view can be insightful to see how our current linear economy works and why it should be changed towards a circular economy. Pearce and Turner (1990) saw resources as the primary input for any utility we derive through our economy. Resources *(R)* are used to produce[4] *(P)* products which are consumed *(C)* to derive utility from. This process is illustrated in Figure 2.5. At every step in this process waste is produced: processing resources creates waste (W_r); production creates waste in the form industrial effluent and air and water pollution and solid waste (W_p); final consumer creates waste by generating litter, sewage and municipal refuse (W_c) (Pearce & Turner, 1990).

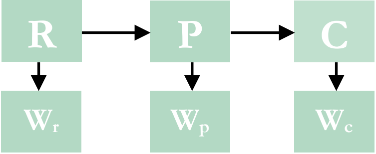

Figure 2.5: Resource based view for Resources (R), Production (P) and consumption (C), and the residual waste (w_x). Based upon (Pearce & Turner, 1990, p. 7).

The interesting insight from this model is that the amount of waste produced is equal to the amount of natural resources used[5]. The reason for this is due to the first law of thermodynamics. Which states that total amount of energy and matter remain constant in a closed systems. Thus we cannot destroy nor create energy[6] or matter. This implies that in whatever way we use resources they end up somewhere in the environment. Therefor the amount of waste produced must be equal to the amount of resources used. The consequence of this notion is that every time we produce a product and derive utility from it, we create waste. This is the inevitable consequence of consumption.

The limiting factor in this system is that the environment has only a certain capacity to take up waste. This is the environments assimilative capacity. As long as waste is disposed at a rate lower than the assimilative capacity the circular systems will just function as a natural systems. If the amount of waste produced is larger than the assimilative capacity it will damage the capacity of the environment to absorb waste. This will impair the economic functions of the environment. Furthermore it damages any amenities we derive from nature, such as purifying the air or filtering water, thereby reducing the resources we can derive from it. Thus the environment has only a certain capacity to take waste and transform it into harmless or ecologically useful products.

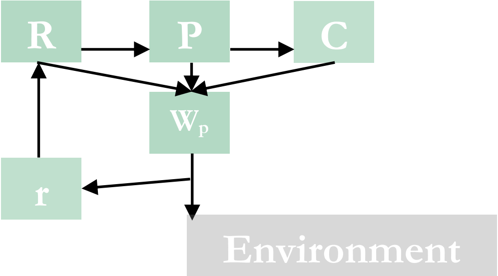

Figure 2.6: Resource based view for resources (R), Production (P) and consumption (C), waste (W) produced and recycling (r). Based upon (Pearce & Turner, 1990, p. 7).

In order to minimize the amount of waste, the residual waste production has to be reduced at every step to the point where the environment can absorb the amount of residual waste. Furthermore the flow of waste to the environment can be reduced by recycling *(r)* the waste and converting them back to resources, see Figure 2.6.

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[4] Additionally resources are used to produce capital goods which are then used to produce goods

[5] If timing of production to create capital stock is ignored

[6] Excluding the potential of nuclear reactions, where matter is transformed into energy. However the net result is that the sum of energy and matter remain the same.

However this option is not unlimited, due to the second law of thermodynamics. The second law of thermodynamics, which deals with entropy, states that the entropy in a closed system will never decrease. When resources are extracted and are being used in the economy its entropy increases. Thereby decreasing its economic quality. For example, when coal is burned in order to create energy, its residue is largely carbon dioxide. Thereby the high quality fuel is transformed into a low quality residue. Inevitability the degree of entropy is bound to increase in an closed economic system where humans extract more and more matter and energy. Therefor circulating matter and energy would lower the increasing entropy and would reduce the need for resource inputs (Andersen, 2006, p. 135).

By looking at the environment from the perspective of resource economics, four basic economics welfare functions can be derived from the environment: (1) amenity values; (2) a resource base for the economy; (3) a sink for residual flows; (4) a life-support system (Andersen, 2006, p. 3). Amenity value refers to the pleasures the environment gives; for example the beauty from a landscape. The resource base is the input for our economy, both in terms of renewable- and non-renewable resources. The environment functions as a waste bin for residual waste. The life support systems refers to life-support functions such as cleaning the air, and ecosystem services.

Ideally the price of resources should include any negative externalities to the environment. The price of raw materials should than be high enough to offset costs that are associated with recycling and reducing material inputs. Currently the prices of raw materials reflects only the costs associated with mining and short term values but it does not incorporate environment costs (externalities) (Andersen, 2006, p. 134). The inclusion of externalities in form of taxes, such as Carbon emission trading, or charges, can reveal the real price of materials. Creating an incentive to optimize towards a circular economy.

2.2.2. Fundamentals of a circular economy

The following principles are incorporates or show resemblance to the circular economy. Many elements of the circular economy are based on earlier concepts.

Industrial ecology is a systems view on the interactions between industrial and ecological systems (Garner & Keoleian, 1995). One goal of industrial ecology to change the nature of our current industrial system where byproducts and waste is generated, to one where waste in the form of energy or materials is reused. Fundamental for industrial ecology is identifying flows of energy and materials through various systems. In industrial ecology the mass-flow analysis is the dominant guide. Whereas the economic value of mass-flows is more important in the CE (Andersen, 2006, p. 3). Meaning that decisions should not be leaded by the mass-flow but more by its economic value it represents.

Cradle-to-Cradle (C2C) is focused on product design where the goal is not to minimize waste but to generate cyclical metabolisms (Braungart et al., 2007). The argument is that eco-efficiency is primarily focused on reducing impact through efficiency and recycling, which reduces its environmental impact but doesn't make the product "good". The eco-effective approach on the other hand deals with maintaining the resource quality through many cycles of use. This approach should both benefit the economy by its value creation and the environment with restorative nature. It is however questionable to what extent this approach is practicable and applicable on a larger scale. The approach is different from the CE because it is much more focused on a product level, rather than using a holistic approach.

Biomimicry is the imitation of models from nature for the purpose of solving complex problems. Ideas from nature are studied and are applied to human problems. For example one of the early examples is the study of birds to enable humans to flight.

Blue economy, an ideology presented by Gunter Pauli, aims at a shift towards a society from scarcity to abundance. It has a strong focus on open-source scientific solutions to overcome environmental problems. Furthermore the role of entrepreneurs and new business models is emphasized.

2.2.3. Principles of a circular economy

The above mentioned concepts laid down the fundamentals for the circular economy, but the concept gained an increase in attention with the reports from the Ellen Macarthur foundation (The Ellen MacArthur Foundation, 2012, 2013, 2014). The Ellen MacArthur foundation defined the following five principles:

1. Design out waste: Product should be designed to recovered and upgraded. Thereby minimizing energy and material inputs, which would be beneficial for the economy and environment
2. Build resilience through diversity: A diverse systems with many nodes is more resilient against shocks. Production systems should flexible and should not be solely focused on (economic) efficiency.
3. Work towards using energy from renewable sources: the end goal is to run solely run on renewable energy. Stimulating taxes on resources could fasten this shift as it would shift production to labor
4. Think in systems: Nodes are interconnected in a system, optimizing one node doesn't necessarily increase the effectiveness of the system.
5. Think in cascades: Value should be retrieved in different stages where it is optimized to generate the most value after end-of-life.

Although circular economy is based on system-thinking, for its practical implications it's necessary to separate three scopes of implementation: micro-level, meso-level and macro-level (Taylor, 2010, p. 4; Yuan, Bi, & Moriguichi, 2006, p. 6). It should however be kept in mind that circular economy is a holistic approach, that aims to incorporate all three levels. The micro level is at the corporate level, which includes waste minimization, remanufacturing and energy efficiency. The meso-level is at the inter-firm level, which focuses on eco-industrial parks and industrial symbioses to capitalize firm waste products. The macro-level is at the societal level, focusing on cities, provinces or nations

2.3. End-of-life value strategies

Throughout the product life cycle different strategies can be applied in order to recover value from products at the end-of-life. The life cycle can be separated into three stages; Beginning of life (BOL), middle of life (MOL) and end-of-life (EOL) (Jun, Kiritsis, & Xirouchakis, 2007, p. 1). BOL includes design and production. MOL includes logistics, distribution, service, repair and maintenance. End-of-life includes reverse logistics, remanufacturing, refurbishment, reuse, recycle and disposal. Furthermore EOL is defined as the point in time when the product no longer satisfies the initial purchaser or first user (Rose, Ishii, & Stevels, 2002, p. 84). Definitions for the most common life cycle strategies are given in Table 2.3.

Table 2.3: Definitions of repair, refurbished, remanufacture, component harvesting and recycling. Source: (Parlikad et al., 2003).

	Definition
Reuse	Reuse is the second hand trading of product for use originally designed (Parlikad et al., 2003)
Repair	'the purpose of which is to return used products in working orders. The quality of the repaired products could be less than that of the new products" (Parlikad et al., 2003, p. 6).
Refurbishment	"The purpose of which is to bring the quality of used products up to a specified level by disassembly to the module level[7], inspection and replacement of broken modules. Refurbishing could also involve technology upgrading by replacing outdated modules or components with technologically superior ones" (Parlikad et al., 2003, p. 6).
Remanufacturing	"The purpose of which is to bring used products up to quality standards that are as rigorous as those for new products by complete disassembly down to the component level and extensive inspection and replacement of broken/outdated parts" (Parlikad et al., 2003, p. 6).
Component harvesting / cannibalization	"The purpose of which is to recover a relatively small number of reusable parts and modules from the used products, to be used in any of the three operations mentioned above." (Parlikad et al., 2003, p. 6)
Recycling	"the purpose of which is to reuse materials from used products and parts by various separation processes and reusing them in the production of the original or other products. "(Parlikad et al., 2003, p. 6)

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[7] A module is defined as a group of individual components connected together physically and logically to perform

In each part of the product life cycle value is added. This means that the value of a completed product is higher than value of parts which is respectively higher than the material value. For example the value of a recycled iPhone is only 0,24% of the product value (Circular Economy Task Force, 2013, p. 19). Whereas a re-used smartphone retains 48% of its original value, see

Table 2.4 The optimal end-of-life strategy in a circular economy is respectively: re-use, refurbish, remanufacture, and recycling, and will be discussed in the coming paragraphs.

Table 2.4: The value across supply-chain in pounds, versus its end-of-life value. Source: (Circular Economy Task Force, 2013, p. 19).

	Material	Parts	Product	Reuse	Parts	Recycling
Car	1300	5900	8940	475	421	134
Smartphone	1,50	188	599	290	170	0,72
T-shirt	1000	3000	27000	2600	410	121

2.3.1. Reuse

Reuse is the most optimal EOL strategy in a circular economy since it can reduce the demand for new goods and optimizes the recovered value of products (Circular Economy Task Force, 2013). Generally reuse is second-hand trading of products for the use it was originally designed for (Rose et al., 2002, p. 84). The second-hand market is especially efficient with low transactions costs and a long product lifetime (Thomas, 2003). For products with a low lifetime it relatively expensive to transfer the good, since the transaction costs will be relatively high compared to the recovered value. Both the informal and the formal channels are important for the circulation of second-hand goods (Lane, Horne, & Bicknell, 2009). Informal channels can refer to second-hand markets. Formal channels can be the re-use of product through the manufacturer, i.e. Patagonia which gives customers the opportunity to resell its product through their website ("Patagonia," 2014). Furthermore there is an increasing amount of goods going from developed to developing countries. Especially for Electronic and electrical equipment (EEE), such as TV's and smartphones(Yoshida & Terazono, 2010).

2.3.2. Refurbishment

Refurbishment is the purpose of bringing used products up to quality standards that are as rigorous as those for new products by completely disassembling it down to the component level with extensive inspection and replacement of broken/outdated parts. (Parlikad et al., 2003, p. 6). Refurbished products have a lower quality and are sold a lower price level than remanufactured products. They often do not come with the same warranty as with new manufactured products. The price-quality differentiation makes that the refurbished market and remanufactured market are independent of each other (Mitra, 2007, p. 557). Producers can therefore both increase profit margins and sales by taking back and reselling refurbished products. Interestingly it can also provide the producers with a first movers advantage, since it can give advantages in terms of lower productions costs, and can defer competitors from following this strategy (Heese, Cattani, Ferrer, Gilland, & Roth, 2005).

2.3.3. Remanufacturing

Remanufacturing is the process of restoring the quality level of a used product to that of a new product. Currently the remanufacturing business in the US alone is worth over $53 Billion, and more than 73.000 companies are engaged in remanufacturing (Giuntini & Gaudette, 2003). Common examples are: Xerox with its Green line, which saves over $20 million per year in manufacturing costs; and Caterpillar whom handles more than 70.000 tons of remanufactured products in 2010 and is growing at annual rate of up to 10% (The Ellen MacArthur Foundation, 2012, p. 28).

The main advantage of remanufacturing is that the embodied energy and resources of the working parts are saved. Only the broken parts are replaced, which requires minimal energy in order to restore the product to its original quality. The costs of remanufacturing is typically 40 to 60% of the costs of a newly manufactured product (Mitra, 2007). It is estimated that over 126 Billion joules of energy are saved globally from remanufacturing and annual materials savings amount up to 14 million tons per year worldwide (Giuntini & Gaudette, 2003).

A major obstacle for remanufacturing is the reverse logistics scheme; the reverse flow of goods. Getting products returned, ensuring the quality and have a proper inventory management can be challenging task (Mitra, 2007). The uncertainty in quality of goods does not necessarily have to be barrier, if reliable inspection mechanism (and technologies) are in place. Inspection of remanufacturing often occurs at two points; preliminary inspection before transportation to the remanufacturing facility and a detailed inspection at the remanufacturing facility (Robotis, Boyaci, & Verter, 2012, p. 386). Preliminary inspection reduces transportation costs of goods because nonworking products are not being transported.

Another challenge is that remanufacturing can potentially cannibalize the existing market. Ideally, products would be perfect substitutes and can therefor address new markets, like the Kodak single-use cameras. However, even if products are identical to the original products, consumers can be skeptical about the quality of products. In that case different pricing strategies have to be developed in order to market the remanufactured product (Ferrer & Swaminathan, 2010). This might imply that the lower priced goods can compete with its original product (Mitra, 2007).

Remanufacturing can be a very beneficial strategy for the producers while at the same time it optimizes for a circular economy. There are however some major challenges, regarding the reverse logistics scheme, quality control and potential cannibalizing of existing market.

2.3.4. Recycling

Recycling of non-renewable resources is often considered as the solution for potential supply shortages or rising resource prices. There is already an existing recycling market for many resources such as plastics, paper, and cloths. For metals, the recycling rates have been relatively low, due to low efficiencies in collection. Only for 30% of the metals the recycling rates are above 50%, see Figure 2.7 (T. Graedel et al., 2011).

The volume of Waste of Electronic and Electrical Equipment (WEEE) is growing exponentially over the past decade and is becoming an interesting group of products due to the high volumes and low collection rates. Especially since many WEEE products contain precious metals such as gold. In Europe about 8,3 million tons of electronic and electrical equipment were produced and only 2,2 million tons were collection and treated. Due to the fact that WEEE is not separated during collection and inappropriate treatment, the recovery of precious metals is currently not efficient (Chancerel, Meskers, Hageluken, & Rotter, 2009).

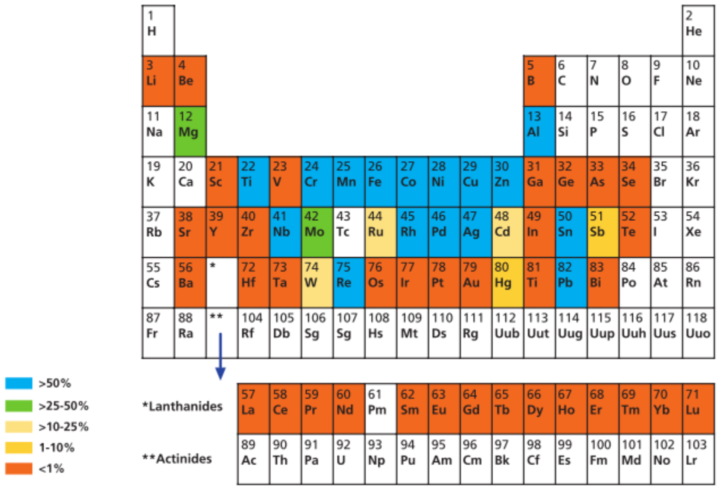

Figure 2.7: Recycling rates of various elements. Source: (UNEP, 2011).

2.4. Enabling factors

Regarding the earlier discussed end-of-life strategies, there are various factors that increases end-of-life values and stimulate the transition towards a circular economy. Optimizing for high end-of-life values begins at the design stage. Designing products in such a way that they can be easily taken apart increases the value that can be retrieved.

Design for disassembly and modular design will be discussed in section 2.4.1. Design for disassembly can be stimulated under ownership-to-usage business models. In this business model the manufacturer remains owner of the product and sells a service rather than a product. Since the manufacturer is also responsible for end-of-life treatment, it has an incentive to optimize for higher end-of-life values. The shift from product to service systems will be discussed in section 2.4.2.

Reverse logistics are an important part of any EOL strategy, and will therefore be discussed in section 2.4.3. Furthermore the role of technological development and product life cycles on remanufacturing and refurbishing will be assessed in section 2.4.4

2.4.1. Design for disassembly and modular design

The effort to reduce the total life cycle costs for a product through design is generally referred to as Design for X (DfX) (Huang, 2001). Related to the concept of DfX is modular design; which is an approach to subdivide a system into smaller parts, which can be independently produced and used in different systems (Zwolinski, Lopez-Ontiveros, & Brissaud, 2006). The main advantage is that the individual components can be upgraded to include inferior modules. This makes the product not only cost-effective to upgrade but it can also be beneficial for the environment (Tseng, Chang, & Li, 2008).

Design for disassembly (DfD) is the process of designing products in such a way that they can easily be taken apart at the end of the product's lifetime (Ecodesign, 2014). This increases the ratio between the value of components and materials reclaimed and the labor and energy needed to extract it. Although this can lead to higher design costs, the gained EOL value is higher thereby lowering the total life cycle costs (Zwolinski et al., 2006). For example, with integrated design the remanufacturing costs of low-costs phones could be reduces by 50% (The Ellen MacArthur Foundation, 2012, p. 41). Additionally it reduces material costs for remanufacturing with 50%. Furthermore DfD allows easier repair, inspection, handling and cleaning (Wu, 2012, p. 1).

The potential downside of a modular design is that competitors could also use modular products to remanufacture products. For example; printers are designed in such a way that cartridges can easily be replaced (instead of replacing the printer). Competition can also use the modular design to sell their cartridges, often at lower prices. It was estimated that the printer industry lost $13 billion of revenues (in 2010) because of low-costs competitors (Wu, 2012). The modular design gave competitors an opportunity to compete for the remanufactured product, thereby cannibalizing their market. Although, from a circular economy perspective, it does not matter who makes the product, producers might be les incentivized to move towards modular design if they know their future profits might be threatened.

To prevent competition, the manufacturer has an incentive to decrease the degree of modular design, making it harder for competition to remanufacture products. One way to prevent this is by selling a service rather than a product. See section 2.4.2. This would incentivize producers to optimize for disassembly or remanufacturing (Sundin, Bjorkman, & Jacobsson, 2000). Another way would be to give consumers a (monetary) incentive to return the product to the, originally, intended producer.

2.4.2. Product service systems (ownership to usage)

An important characteristic of a circular economy is the focus on services rather than products. This idea is also referred to as a functional service economy, performance economy, or service based economy. Product service systems can be classified into three types. Firstly, product-oriented services (POS): traditional sales of product (Barquet, de Oliveira, Amigo, Cunha, & Rozenfeld, 2013, p. 695). Secondly, use-oriented services (UOS): the product is owned by its manufacturer, and only sells product use or function by leasing, sharing or renting. And lastly, result-oriented services (ROS): when the manufactured sells a result or competence rather than the product. (Barquet et al., 2013).

As mentioned, changing the ownership from the consumer to the producer can greatly reduce the environmental impact and resource stress due to design improvements. Furthermore it can provide improved longer-term relationships with customers thereby making it possible to increase interactions between the customers and companies during the lifetime of a product (The Ellen MacArthur Foundation, 2013, p. 85). This can be used to improve products, improve loyalty and increase retentions rates.

2.4.3. Closing the loop; Reverse logistics

Supply chain management (SCM) is the management of flow of goods. Traditionally, companies were focusing on the forward supply chain (manufacturer-wholesaler-retailer). However with increasing environmental concerns and regulations, reverse logistics have become more important. Reverse logistics are all operations related to reuse of products and materials (Kocabasoglu, Prahinski, & Klassen, 2007, p. 1142).

Closing the loop can be done in an open or a closed form. A closed loop is when an individual company controls a suitable product or material system, and focusses on reuse and remanufacturing (Circular Economy Task Force, 2013, p. 19). This enables the company to mitigate potential price volatility that affect production and can be done in private control or public control. Private control means the company is responsible for production, collection and returning the products, while maintaining ownership over the product. With public control the manufacturer is. responsible for end-of-life disposal, but the product changes ownership and therefor needs a fee to incentivize customers to bring back the product. According to Green Alliance (Circular Economy Task Force, 2013, p. 22), closed circles are profitable when:

1. Materials or product are sufficiently valuable.
2. There is control over the whole product or material chain.
3. Materials product are relatively easy to reuse, remanufacture or recycle.
4. The pace of product and material change is not too fast, so demand for future products can be predicted.
5. Materials and products are kept concentrated and uncontaminated.

An open loop is when products are returned to the bulk and benefits accrue to all users of the material stream, and can be done in private or public control. Private control is when recycling occurs through self-organizing systems, with a variety of companies, including collecting, sorting and processing of materials. An example of this is in japan, where flat panel display manufactures collect indium from the production process and send it to a recycling facility when supplies are low or prices are high (Circular Economy Task Force, 2013, p. 17). This is a direct contract between manufacturer and recyclers, meaning that the recycler cannot sell the indium to anyone else. An example of public control is the WEEE directive in the European Union. Under the WEEE directive companies have an extended producers responsibility for collection of products. Producers (or consumer) pay a fee for this collection.

2.4.4. Product life cycle

The product life cycle[8] describes the evolution of a product, measured by its sales over time. (Östlin, Sundin, Björkman, & Strategies, 2009). The following stages can be separated throughout the life cycle: development, introduction, growth, maturity and decline, see Figure 2.8. For example; the VCR was developed to provide video access to consumers. It was, however, one of the many products providing that service, and experienced heavy competition during its introduction. Once a dominant product arises, VCR in this scenario, it experiences considerable growth in sales. Within the product class (VCR) different product forms were developed (such as 2-head) with increasing technological benefits. Within the product form, new product models were developed. However at some point a superior product, such as the DVD, was developed. Consumers shifted from the inferior to the superior product, resulting in decline for VCR demand.

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[8] The terminology product life cycle is conflicting with the earlier used product life cycle, which describes the life throughout production, use and end-of-life, instead of the development of the product.

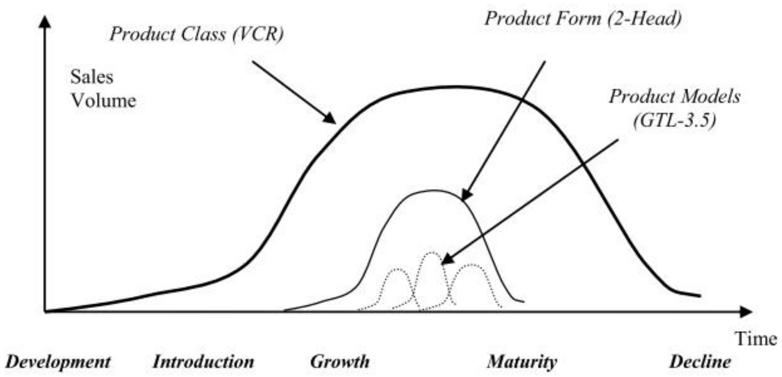

Figure 2.8: Product life cycle of a product- class, form and model, measured by sales over time. Source: (Östlin et al., 2009, p. 3).

The product life cycle has certain implication for remanufacturing and refurbishing. The supply of disposed products that could be used for remanufacturing and refurbishing only occurs after its average usage time. The demand for remanufactured products decreases over time along with the demand for the original product due to technological development. For example, demand for VCR's would be less if there were already affordable DVD players on the market. The balance between supply and demand is illustrated in Figure 2.9, where the demand for remanufactured and disposed products plotted. The grey area represents the area where the demand and supply overlap, which accounts for a small area of the total demand. In case the remanufactured product can be upgraded there can be additional product demand.

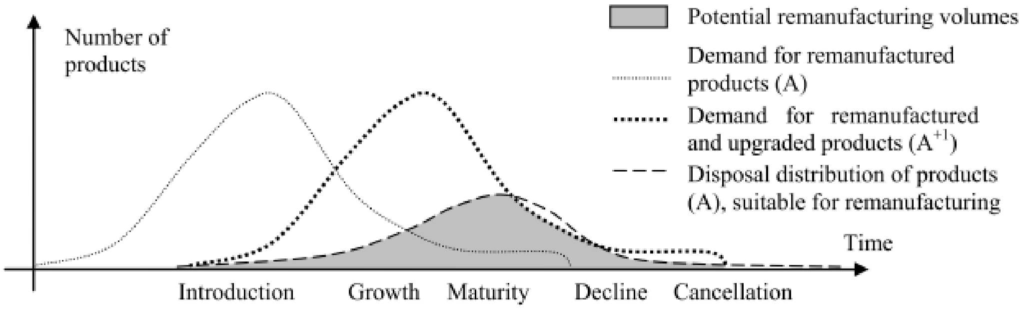

Figure 2.9: Demand and supply dynamics of remanufactured product. Source (Östlin et al., 2009, p. 10).

Determining the future demand for remanufactured products and the supply of disposed products can be a challenging task. Determining factors are the rate of technological innovation and expected product life (Östlin et al., 2009).

2.5. Real option valuation

The transition towards a circular economy depends on a lot of variables such as consumer preferences, resource prices, energy prices and technological development. The uncertainty of these variables creates uncertainty for the profitability of future investments. Managing this uncertainty in this highly dynamic market environment and to successfully take advantage of favorable future investment requires flexibility. Traditional investment decision rules such as net present valuation (NPV), are limited in incorporating flexibility and uncertainty (Dixit & Pindyck, 1994). Therefor the real options approach is introduced. This method includes uncertainty in investment decisions, and emphasizes the role of flexibility and staged investment.

Section 2.5.1 will discuss the shortcoming of the NPV method and why ROV can be the better alternative. The fundamentals of real options will be explained in section 2.5.2. The various ways to value real option will be presented in section 2.5.3. And lastly, relevant literature on real option application will be discussed in section 2.5.4

2.5.1. Current practice and shortcomings

Currently, the net present value (NPV) is the most commonly used decision rule for investment decisions. NPV is calculated by using the discounted cash flow analysis, given in equation (2.1). This approach involves making a forecast of all future cash flows relevant to the project, incorporating costs and expected revenues. A positive cash flow indicates that there is a cash inflow; a negative cash flow indicates a cash outflow. The cash flows are than discounted back to its present value, to adjust for time and risk. If the present value of the discounted cash flow (DCF) is larger than the investment needed the NPV for a project is positive.

$$NPV = \sum_{t=1}^{T} \frac{C(P)_t}{(1+r)^t} - I_0 \qquad (2.1)$$

NPV calculations are often based on strongly simplified assumptions that may not be appropriate for many investments. First of all the cash flow structure of the whole project needs to be known from the beginning of the project. And secondly the discount factor is assumed constant over the lifetime of the project and is equal for all variables. This approach is well suited for mature companies in a stable market, with reliable estimates of cash flow, costs and discount rates. But many project that invest into the CE do not meet these criteria. Especially in an unstable and dynamic market it is difficult to be certain about future prices, revenues, or other uncertainties.

Furthermore the deterministic approach of the NPV method does not appropriately account for flexibility that that is often required to adjust to changing market circumstances (Mun, 2006, p. 16). Today's markets are becoming ever more volatile and future costs and benefits are becoming more uncertain. Flexibility is becoming essential in order to adapt to changing market conditions, technological changes, market prices or other movements on the market (Trigeorgis, 2002, p. 1). Future information can make investment worthwhile again or can make the made investment unprofitable.

When assessing risk, DCF analysis is often focused on the negative effects of risks, thereby neglecting the upside potential of risk. Project flexibility, which is strongly incorporated in RO, can more effectively capture the upside potential of investment. I.e. production can be increased when product demand is high and lowered when demand is low. Resulting in an increase in revenues when demand is low, and a decrease in operating costs when demand is low. And unlike DCF, ROV incorporates the effect of investment timing (Yang & Blyth, 2007, p. 3). Waiting to invest may yield additional information that is useful in making the decision to invest. According to (Schulmerich, 2010), real options analysis is needed in the following situations:

1. When there is a contingent investment decision. No other approach can correctly value this type of opportunity.
2. When uncertainty is large enough that it is sensible to wait for more information, avoiding regret for irreversible investment.
3. When the value seems to be captured in possibilities for future growth options rather than current cash flow.
4. When uncertainty is large enough to make flexibility a consideration. Only the real options approach can correctly value investments in flexibility.
5. When there will be project updates and mid-course strategy corrections.

2.5.2. What are real options

To understand the basics of real options theory an example using the decision tree tool will be given. In this example, illustrated in Figure 2.10, there are equal probabilities of up and down movements (Damodaran, 2007). The potential loss is larger than the benefits and thus the expected value for this investment is negative and is calculated as follows:

$$\text{Expected value} = \frac{1}{2}(\$100) + \frac{1}{2}(-\$120) = -\$10.$$

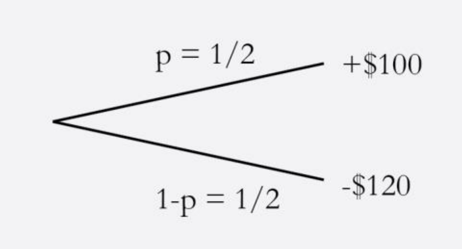

Figure 2.10: Payoff decision tree for one period with equal probabilities of moving up or down.

Now consider the two-phase decision tree in Figure 2.11. The potential losses and profits over the two phases are exactly the same as the loss and profits from Figure 2.10. The total gain is $100 in the upward movement and -$120 in the downward movement. However the expected value of this tree is :

Expected value= $\frac{2}{3}(-\$10)+\frac{1}{3}[10+\frac{2}{3}(\$90)+\frac{1}{3}(-\$110)] = \$4,44$

Thus the investment that first had a negative potential is now turned into a positive investment. The change in expected value is due to two factors. Firstly, by allowing a relatively small investment in the first period we allow for learning. If the outcome of the first phase is bad, it is an indicator that the overall investment will be losing money rather than making money. Secondly, learning allows for adaptive behavior. If the outcome in the first phase is bad, you will be more likely to abandon the investment since there is a high chance it will lose money. The value of real options comes from the fact that we can adapt on observation made in the real world, thereby increasing potential upsides form the investments and decreasing the possible downsides.

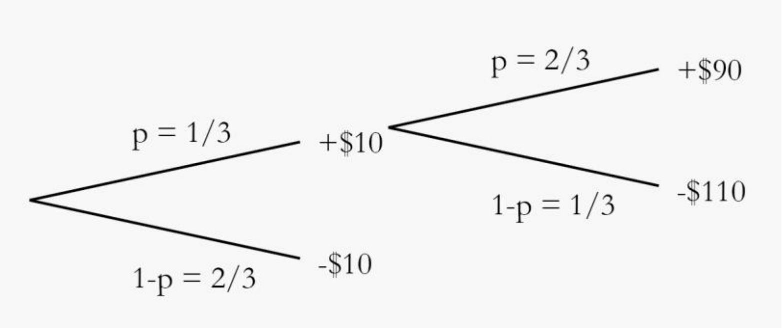

Figure 2.11: Payoff decision tree for two periods.

Real options valuation is based on financial options. A financial option is the right but not the obligation to purchase a stock at a pre-specified price in the future (Ross, Thompson, Christensen, Westerfield, & Jordan, 2007). The date by which the stock must be sold or bought is called the exercise date. The time between now and the exercise date is the time to maturity. The predetermined price to buy or sell a stock is the strike price. The payoff of a call option is the price of a stock minus the strike price. Thus when the strike price is lower than the stock price at maturity the owner will exercise the call option. For a put option, the right to sell, an option will be exercised if the strike price is higher than then stock price.

Option valuation techniques present a valuable method in situations with high uncertainty. An option protects the owner against negative outcomes, because the investor can choose to not exercise the option when it would result in a loss, whereas he benefits from upside stock prices. This is illustrated in Figure 2.12, where a high stock price gives a positive payoff, but a low stock price doesn't yield a negative payoff. The value of a call option depends on the time to maturity, risk free rate, the volatility of the underlying stock price, the strike price and the exercise price (Luehrman, 1998).

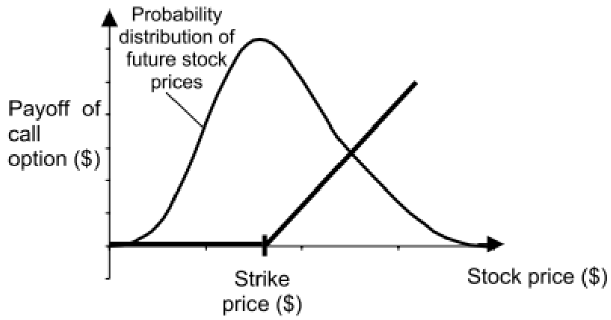

Figure 2.12: Payoff for a call option, from (Greden, 2005, p. 38).

The analogy between financial options and real options is given in Table 2.5 (Schulmerich, 2010). For example the strike price is equal to the costs to acquire the assets needed for the project, and the stock price is equal to the present value of future cash flows from the asset.

Table 2.5: The analogy between financial options and investment opportunities (Luehrman, 1998, p. 4).

Variable	Financial option	Project investment
K (I)	Strike price (exercise price)	The costs to acquire the asset
S (V)	Stock price	The present value of future cash flows from the asset
t	Time to maturity	Length of time the option is viable
σ	Variance of returns of stock	Riskiness of project assets
r	Risk-free rate of return	Time value of money

In Table 2.6 various real option strategies are described. For example the option to defer, gives the investor the option to postpone the investment until the exercise date. The value of the investment depends on the expected cash flows of the project. For example the profitability of resource efficiency project depends resource prices. If the price of resources is high the investment becomes more profitable, whereas at low prices it become less profitable. With time, information becomes available that resolves uncertainty, and thus may affect the optimal timing of the investment (Dixit & Pindyck, 1994, p. 6).

Table 2.6: Five types of real options within investment decisions. From (Busch & Hoffmann, 2009, p. 301).

Type of option	Management flexibility	Description
Option to defer	Deferring the exercise data into the future	An option to defer allows the management to postpone the start of an investment. This applies to investments that are not profitable under current conditions but might become profitable at a later stage
Option to Grow	Flexible adjustment of project's scope	Growth options can be adequate in situations where an initial investment turns out to be profitable. While building on this investment, further investments generate additional revenues at a later stage
Option to extent	Broadening the utilization of gained knowledge	Considering options to extend, firms are able to utilize an initial investment in related areas afterward if the conditions are favorable. Management is able to transfer technologies or knowledge gained to other projects
Option to switch	Flexible choice of path	Within a project's lifetime, management may have the option to move back and forth between different possibilities to utilize the initial investment, depending on each possibility's profitability An
Option to abandon	Stop project	An option to abandon describes the possibility to stop a project at a later stage while retaining the ability to capture a remaining value of the initial investment. A reason for stopping a project could be a change in market conditions

Applying the principles of real options can create insight in how (resource) price uncertainty affects a transition towards a circular economy. Early strategic investment (Such as R&D) may enable future opportunities that can result in lower production costs or other forms of competitive advantage. For example investments needed to change towards the ownership-to-usage model enables companies to retrieve materials from products in the future. If resources prices are indeed high in the future we can retrieve components or materials at end-of-life. This can be used to mitigate the effect of increasing and volatile resource prices in the supply chain. If, however, resource prices are lower than expected, resources can be bought on the market thereby mitigating potential loss. Using real options valuation techniques can give new insight into the optimal timing of investments and the price of uncertainty.

2.5.3. Real option valuation methodologies

Since the introduction of option theory pricing in 1972 by Black and Scholes, option theory has made vast strides (Black & Scholes, 1973). In general three methods to value real options can be distinguished: the Black-Scholes formula, binomial option valuation and the simulation approach. Black-Scholes uses a "replicating portfolio" to value an option. Their method is mathematically complicated and less intuitive to use. The binomial model draws on the same logic but is more intuitive to use. More complex decisions may be solved with simulation approach. In the simulation approach Monte Carlo simulations are used to generate a large amount of possible values that create a payoff matrix. Not all approaches will be used in this thesis but especially the binomial tree and the Black-Scholes method are useful for the fundamental understanding of the mechanics in valuing an option. The binomial tree option will be discussed first because it is more intuitive to use.

Valuing of an option begins with the assumption that future prices follow a stochastic process. Stochastic prices are often modeled by a Geometric Brownian Motion (Dixit & Pindyck, 1994). This is a process that describes price movements as being party deterministic and partly random. Equation (2.2) represents the Geometric Brownian Motion. The first part of the equation is the deterministic price growth *(μ)* of the stock *(S)*. The second part of the equation is the randomly distributed price *(ε)*, using the volatility of the stock *(σ)* among the stock price. Historical prices are used to determine the volatility and annual growth rate.

$$\Delta S = \mu S \Delta T + \sigma S \varepsilon \sqrt{\Delta t} \tag{2.2}$$

The binomial tree method is based on the concept of replicating portfolios. The argument is that because the two different strategies yield the same payoff, the value must be the same or otherwise there would be an arbitrage opportunity[9]. The model assumes that the value of a stock follows a discrete time random walk in which values either move up or down. The probabilities whether they move up or down are unknown. Furthermore the probabilities are not the stocks actual probability but risk neutral probabilities which remain constant during the analyzed period.

Consider the example[10] in Figure 2.13: a stock currently sells for \$10, and the share price one year from now will be either \$11 if the stock moves down *(Sd)* or \$13 if the stock moves up *(Su)*. The exercise price is \$10,50 and the risk free rate is 12 percent. Since the exercise price is \$10,50, the payoff will be either \$0,50 if the stock moves down or \$2,50 if the stock moves up.

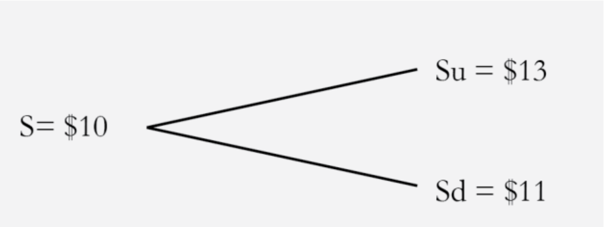

Figure 2.13: Payoff matrix for a stock price starting with \$10 and equal probabilities of moving up or down.

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[9] An arbitrage opportunity is the opportunity to buy an asset at a low price then immediately selling it on a different market for a higher price.

[10] Example from (Ross et al., 2007, p. 731).

The crucial observation is that the payoff can be duplicated using a combination of the option and the risk-free asset, by investing \$9,375 in a risk free asset and buying one call option. A risk free asset will earn 12 percent, so it will be worth \$10,50 is on year time, and the option will be worth \$0,50 or \$2,50. The total value will be \$11 if the stock moves up and \$13 moves down.

Table 2.7: Option payoff matrix.

Share value	Risk free asset value +	Call value =	Total value
\$11	\$10,50	\$0,50	\$11
\$13	\$10,50	\$2,50	\$13

The payoff for the two strategies, buy a share versus buy a call and invest in a risk free asset, are the same, see Table 2.7. Since the two strategies have the same future payoffs, they must have the same value today, or else there would be an arbitrage opportunity. Thus the value of the call option is: \$10 = \$9,375 + C, C = \$0,625.Where \$9,375 is the present value of the exercise price today: \$10,50/1,12.

With more time-steps the binomial tree method becomes more complex, but the logic remains the same. The binomial tree is solved backwards to generate the option value all the generated prices at every price step.

Whereas the binomial model is a discrete-time model for price movements, the Black and Scholes model price process is continuous. As the time interval shortens the Black-Scholes formula approximate the binomial tree method. The black-Scholes option pricing formula was derived for a European-style[11] call option. Meaning that an option can only be exercised on expiration date.

The inputs, named in

Table 2.5, are used in equation (2.4) and (2.5) to estimate d_1 and d_2. And are accordingly used in the normal distribution functions of $N(d_1)$ and $N(d_2)$ (Ross et al., 2007, p. 737). The value of the call options is the stock price times $N(d_1)$ minus the present value times $N(d_2)$, see equation (2.3). Which effectively tells us that the value of an option is the price of the share price times the probability that the share price is relevant minus the present value of the exercise price times the probability the exercise price is paid.

$$C_0 = S_0 N(d_1) - Ke^{-rt}\, N(d_2) \tag{2.3}$$

$$d_1 = \frac{\ln\left(\frac{S_o}{E}\right) + R_f + \frac{1}{2} + \sigma^2}{\sigma + \sqrt{t}} \tag{2.4}$$

$$d_2 = d_1 - \sigma\sqrt{t} \tag{2.5}$$

The principle of replicating portfolios in binomial tree valuation is also embedded in the Black-Scholes formula. SN(D_1) is equal to the number of share bought, and $-Ke^{-rt}N(d_2)$ equals the amount that needs to be borrowed (Damodaran, 2007).

Two limitations exist with the Black-Scholes formula: the model does not take into account early exercise of the investment and the payment of dividends. Dividends are an important factor in the value of an option since it decreases the value of an option. The Black-Scholes formula can be adjusted to incorporate dividends, denoted by y, and will reduce the value of a call option. The Black-Scholes formula will be as follows:

$$C_0 = S_0 e^{-yt} N(d_1) - Ke^{-rt}\, N(d_2) \tag{2.6}$$

Dividends can be used to include the decline in project revenues. For example if a company has a patent for only 15 years, a delay in investment of one year means that one year of revenues will be missed. Thus dividends are 1/15 of the stock price.

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[11] With an European call option the holder is only allowed to exercise the option on expiration date. In contrary to an American call option, which can be exercised at any time during the life of an option

2.5.4. Literature review

Since the introduction of real options, the method has been applied to various case studies. In the field of sustainability, research has primarily been done on energy investments. Resource related investments, such as recycling, have not been researched so far. Main insights from relevant studies will shortly be discussed in the following section.

Johansson (2010) conducted research on real options for a gas fired turbine investment. A gas fired turbine is a flexible energy supply that can easily be turned off and on, and is often used during energy peaks. With lower gas prices, or higher fuel (other than gas) prices it can be turned on, while with low energy or high gas prices it can be turned off. Because the net present value is incapable of including switching flexibilities, the real option valuation method was used. From the study it was concluded that the binomial tree method can very accurately value investments if switching can be done without costs. The introduction of switching costs significantly lowers the real option value.

A study by Busch and Hoffman (2009) looked into how corporate investment decisions should be made in the face of uncertainties relating to the natural environment. For example climate change is becoming an important risks factor, in fact it is seen as the number one risk factor for insurance companies (Ernst & Young, 2008). Secondly institutional actions aimed at reducing the environmental impact can create another source of uncertainties. For example the European Union Emission Trading Scheme is experiencing a high price volatility and is a critical source of uncertainty for many investments. The same uncertainties, natural and institutional, can be found for investments in a circular economy. From the study is was found that real option thinking might create the environment for low-carbon and low-energy technologies to thrive, even if they appear not to be profitable under current market conditions.

A study by Menassa (2011) looked into the uncertainties for sustainable retrofits in existing buildings (2011). The profitability of energy savings technologies are highly dependent on the underlying electricity prices. Using option pricing, and the capital asset pricing model (CAPM), a single-stage investment and multi-stage investment were analyzed. In the single-stage investment; postponing the investment until uncertainty is resolved will result in a higher NPV. Multi-Staged investment increases the NPV (compared to single-stage) because it gives opportunity for more learning.

Ashuri et al. (2011) conducted research on energy retrofitting in existing building and focused on the flexibility that is required in the option to delay an investment until energy efficient technologies become available at a lower price. The model includes uncertainties in the price of energy, photovoltaic technology efficiency and price volatility in photovoltaic technology. High flexibility increases the NPV because it adjust and adapt to changing market circumstances. Greden (2005) also looked into flexible building design. Currently systems are designed as though they will remain static, despite the uncertain environment. In this research it is shown that the option value of flexibility increases with increasing time horizon and increasing uncertainty. Furthermore the Black-Scholes formula approximates the value of flexibility (compared to the binominal tree).

Yang et al. (2008) used the Real options approach for analyzing the effect of government climate policy on decision making in the power sector. Furthermore they attempted to quantify the implicit risk premium of carbon price uncertainty to investors in new capacity. The risk premium was defined the difference between the NPV and ROV. The NPV was defined as the certain scenario, since its uses deterministic values for future prices. The ROV was defined as the uncertain scenario because it better incorporates uncertainty.

In a transition towards a circular economy there are many uncertainties regarding institutional or the natural environment. In such environments the ROV method may lead to better decision making because it incorporates uncertainty better than the NPV. High flexibility in project design can increase the project revenues because it allows to adapt to changing market circumstances. The value of flexibility is especially high with an increasing time horizon and uncertainty. The Black-Scholes approximates the value of flexibility in project design. Multi-stages investments yield a higher NPV than single-stage investments, because it allows for more learning. The ROV method can be used to determine the risk premium paid for volatility resource prices. This can be used to value the impact of reduced resource dependency from circular business models. From the literature it was clear that no real option valuation studies have been done recycling or otherwise end-of-life strategies

2.6. Light emitting diode (LED)

Light emitting diodes, one of the emerging technologies, will be discussed in more detail since it will be used in the case study. Fist the historical context of the transition in the lighting market will be discussed in section 2.6.1. The technology itself will be explained in section 2.6.2. And finally the use of critical raw materials will be discussed in section 2.6.3

2.6.1. Lighting transition

There has been an incredible development in lighting technologies over the past century. Going from candles, to whale oil, gas light, paraffin light and electric lights. Light consumption has grown incredibly over the last 300 years, see Figure 2.14. With each technology improvement lighting has become cheaper. The real price of light has fallen 6.300 times since 1600 in Britain (whereas GDP has only grown 19 times) (International Energy Agency, 2006).

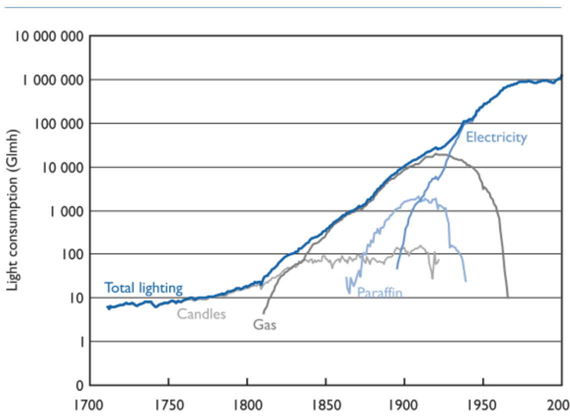

Figure 2.14: Light consumption over time. Source: (International Energy Agency, 2006, p. 65).

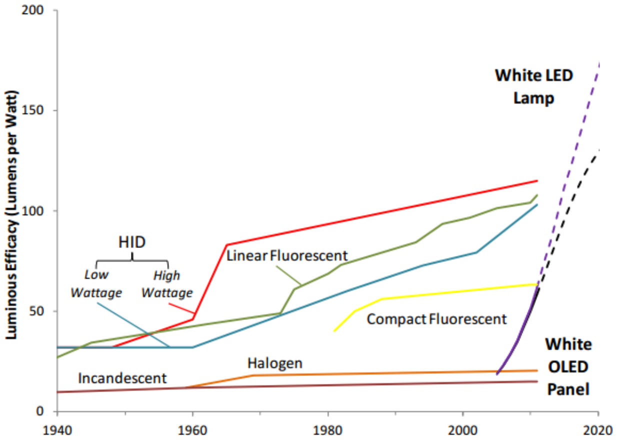

Figure 2.15: Historical and predicted luminous efficacy. Source: (US Department of Energy, 2012).

The efficacy, which is the amount of light produced by a lamp, measured in lumens as a ratio of the amount of power it consumes in watt, has increased considerably, see Figure 2.15. Current efficacies for incandescent lamps usually range between 10 to 20 lm/w, and research has demonstrated that this can be increased to potentially 45 lm/w (US Department of Energy, 2012, p. 40). However since its discovery in early 1800 and its commercialization early 1900 there have been relatively low improvements in efficacy. Furthermore incandescent lamps have a relatively low life span of 750 to 2000 hours. Compact fluorescent lamps were the next major improvement in efficacy, which ranged from 25 lm/w up to 118 lm/w and a longer life of up to 8000 hours. A major downside of CFLs is the use of mercury, which is highly toxic.

The next range of technology improvements came from solid-state lighting. This technology uses solid-state electroluminescence as opposed to thermal radiation. Two technologies can be distinguished; Semiconductor light-emitting diodes (LED) and organic Light-emitting diodes (OLED). Their efficacies are considerably higher than of the previous mentioned light sources. Furthermore they have a longer life span, up to 50000 hours, and they don't contain high concentration of mercury. Current prototypes have a efficacy of 150 lm/w but is expected to increase due to intensive research and development (US Department of Energy, 2012). Currently, LED lamps are still more expensive than CFL- and incandescent lamps. But, as can be seen in Figure 2.16, prices are declining fast and expected to cross the CFL price point soon.

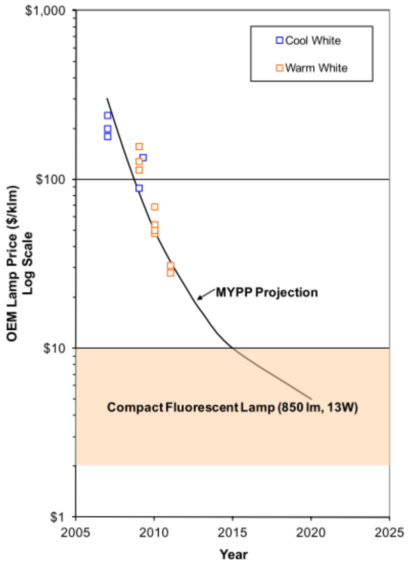

Figure 2.16: Price projection for white light LED lamps. Source: (US Department of Energy, 2012, p. 46).

Because LED can be retrofitted into existing lamps they open up a huge market of replacing CFL- and incandescent lamps (McKinsey, 2013). With decreasing costs LED lamps are expected to quickly take over the lighting industry. And with over 25 billion of installed lamps, which all need to be replaced, this is an incredible transition. In Figure 2.17 the expected annual sales are illustrated, showing an exponential increase in LED sales.

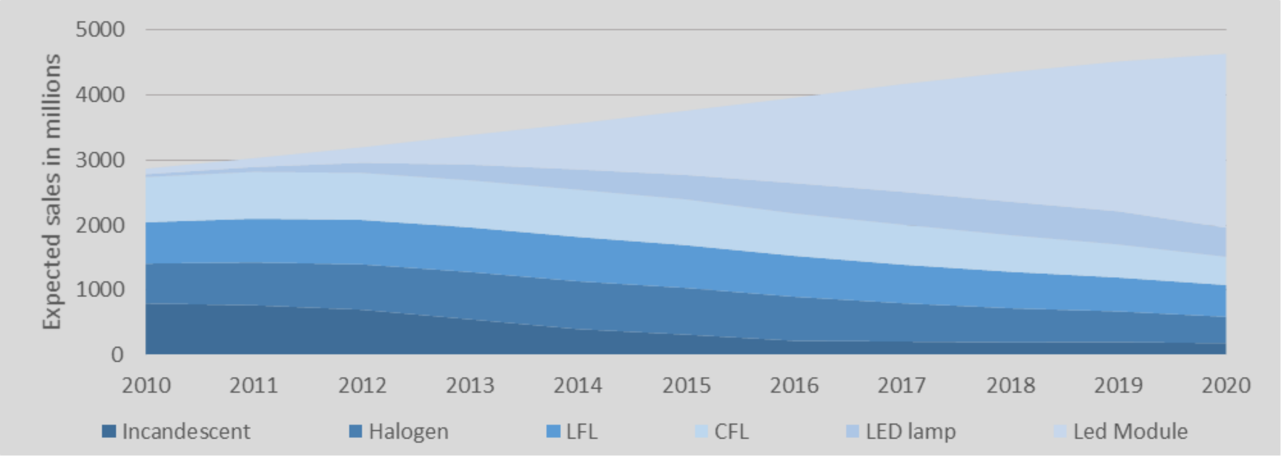

Figure 2.17: Expected sales per type of lamp. Data based on (Mckinsey, 2012).

2.6.2. LED technology

LED lamps emit light due to the generation and recombination process of photons (Deubzer et al., 2012). The color of the emitted photons is correlated to the band gap between valance and conduction band. This is done by a combination of two semiconductors. To change the color of a LED lamp a different mix of materials is needed, this is shown in Figure 2.18. Substitution of Gallium with Aluminum shifts the wavelength to short values, such as green and blue, which require more energy. Substituting Gallium with Indium shifts the wavelength to longer values, such as red.

In order to generate white light, multiple colors must be mixed. There are three methods to mix multiple colors: 1) phosphor-conversion; 2) discrete color-mixed; 3) hybrid approach which combines phosphor conversion and color mixed approached (US Department of Energy, 2012, p. 32). The phosphor-converted is currently the most used approach. The phosphor materials is a coating that is applied to the LED die during the packaging process (Wilburn, 2012, p. 10). The phosphors used in LED production can be separated into two groups. The first containing Yttrium (Y), Terbium (Tb) and Lutetium (Lu), and the second group so called Orth-sillicated using Europium (Eu) and Cerium (Ce).

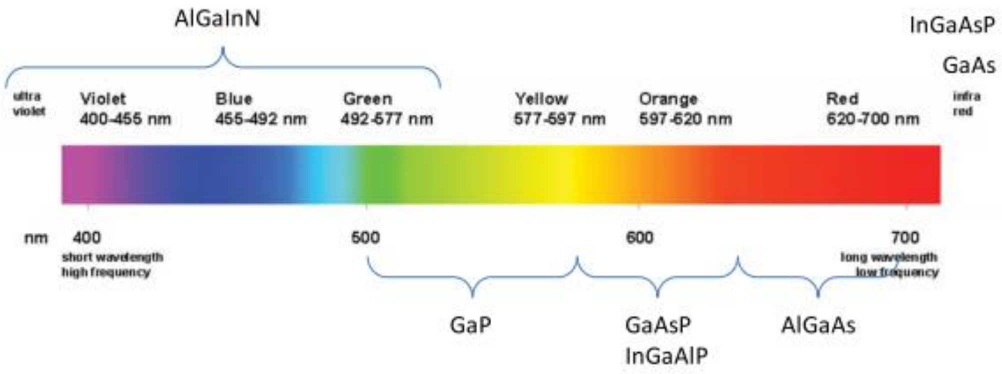

Figure 2.18: LED-die materials composition dependency on wavelength. Source: (Angerer et al., 2009a).

The led package is the assembly of one or more LED dies together with phosphorus elements and interconnection technologies. Although the materials used in LED packaging are less rare than the materials used in LED dies, there are more materials needed. Interconnecting of the different components can be done in several ways, with each having its own benefits and effects on the potential of recycling. Gluing is most commonly used but is also the method that makes dismantling the hardest.

The different steps of LED production are shown in Figure 2.19. The definitions for the steps are shown in Table 2.8. The module (or lightengine[12]) makes together with LED driver, an ANSI standard base and optical, thermal, mechnical components, the LED lamp. Which can be used for retrofitting on a ANSI standard lamp-holder (Socket). A luminaire is the combination of a LED module, fixture and ballast and is a complete lighting unit that can be connected directly to the branch circuit.

Table 2.8: Definitions for various LED lamp components. Source: (Illuminating Engineering society, 2009).

Component	Description
LED	A pn junction semiconductor device that emits incoherent optical radiation when forward biased. The optical emission may be in the ultraviolet, visible, or infrared wavelength regions.
LED die	A small block of light-emitting semi- conducting material on which a functional LED circuit is fabricated.
LED package	An assembly of one or more LED dies that includes wire bond or other type of electrical connections, possibly with an optical element and thermal, mechanical, and electrical interfaces. Power source and ANSI standardized base are not incorporated into the device. The device cannot be connected directly to the branch circuit.
LED On PCB	assembly of led package or dies on printed circuit board. Possibly with other connections that are designed to connect to the load side of a LED driver
LED Driver (ballast)	A device comprised of a power source and LED control circuitry designed to operate a LED package (component), or an LED array (module) or an LED lamp
LED module (light engine)	An assembly of LED packages (components), or dies on a printed circuit board or substrate, possibly with optical elements and additional thermal, mechanical, and electrical inter- faces that are intended to connect to the load side of a LED driver. Power source and ANSI standard base are not incorporated into the device. The device can- not be connected directly to the branch circuit.
LED (Retrofit) lamp	An integrated assembly comprised of LED packages (components) or LED arrays (modules), LED driver, ANSI standard base and other optical, thermal, mechanical and electrical components. The device is intended to connect directly to the branch circuit through a corresponding ANSI standard lamp-holder (socket)
LED luminaire/fixture	A complete lighting unit consisting of LED-based light emitting elements and a matched driver together with parts to distribute light, to position and protect the light emitting elements, and to connect the unit to a branch circuit. The LED- based light emitting elements may take the form of LED packages (components), LED arrays (modules), LED Light Engine, or LED lamps. The LED luminaire is intended to connect directly to a branch circuit.
Lens	To focus or disburse light emissions.

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[12] Although light module and light engine is often used as synonyms, the difference is that a LED light engine is an integrated assembly designed to connect directly to the branch circuit (Illuminating Engineering society, 2009)

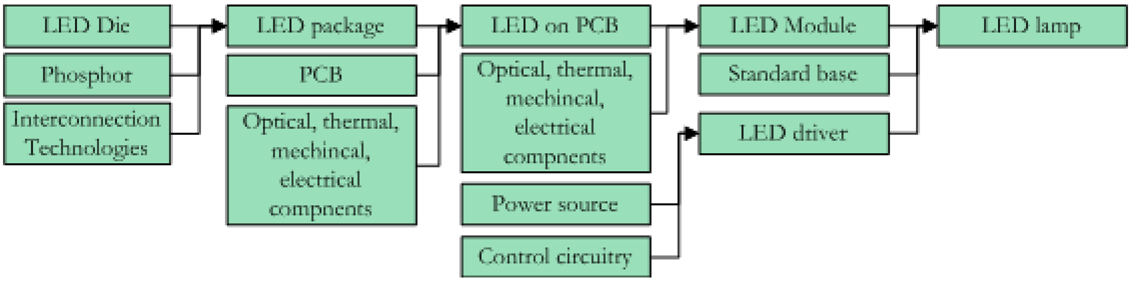
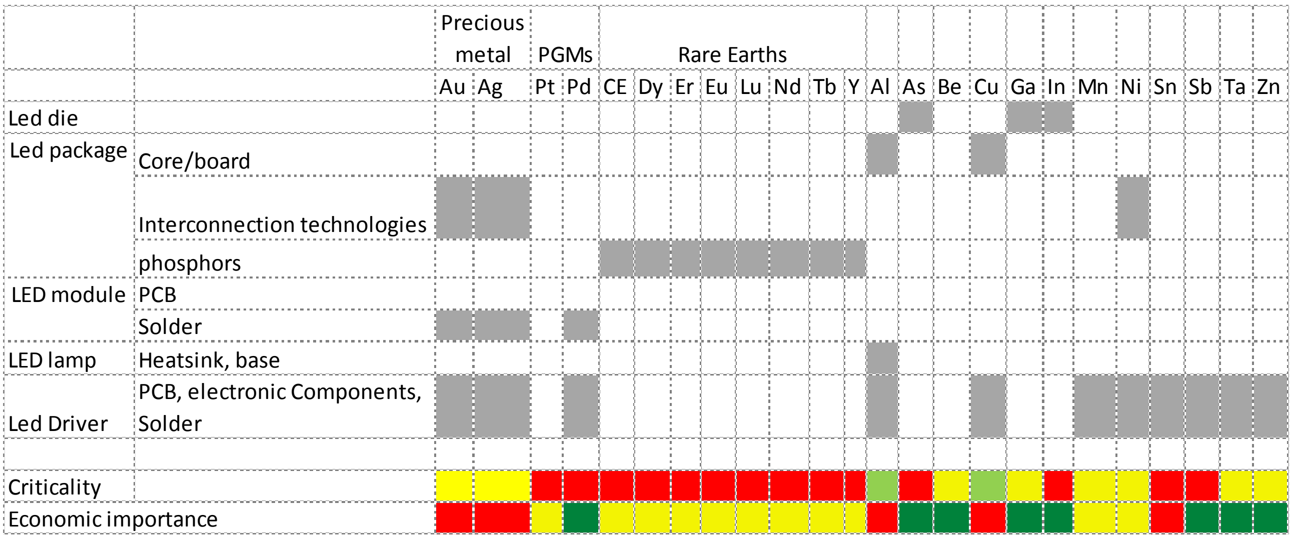


Figure 2.19: Steps in the production of a LED product. Based on (Deubzer et al., 2012, p. 5; McKinsey, 2013, p. 51; US Department of Energy, 2012, p. 59).

2.6.3. Critical materials in LED lamps

Material use for each of the LED production steps is presented in Table 2.9. All of the rare earth elements used in LED production are for the Phosphors in the LED package. For the production of the LED die, mainly Gallium (Ga), Indium (In) and Arsenic (As) are used. The Led driver contains precious metals such as Silver (Ag) and Gold (Au).

The Fraunhofer Institute (2012) conducted an meta-analysis on the critical elements from six criticality reports. The outcomes are given in the sixth row of Table 2.9, red represent a high criticality and green a low criticality. 13 out of the 22 materials used in the production of LED are categorized as highly critical. Furthermore most elements have a high economic importance. The economic importance is according to their total material costs in the electronic industry.



		Precious metal		PGMs		Rare Earths																			
		Au	Ag	Pt	Pd	CE	Dy	Er	Eu	Lu	Nd	Tb	Y	Al	As	Be	Cu	Ga	In	Mn	Ni	Sn	Sb	Ta	Zn
Led die															▨			▨	▨						
Led package	Core/board													▨			▨								
	Interconnection technologies	▨	▨																		▨				
	phosphors					▨	▨	▨	▨	▨	▨	▨	▨												
LED module	PCB																								
	Solder	▨	▨		▨																				
LED lamp	Heatsink, base													▨											
Led Driver	PCB, electronic Components, Solder	▨	▨		▨									▨			▨			▨	▨	▨	▨	▨	▨
Criticality		🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟨	🟩	🟨	🟥	🟨	🟨	🟥	🟥	🟨	🟨
Economic importance		🟥	🟥	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟩	🟩	🟥	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟩

Table 2.9: Component breakdown for a LED product, together with is criticality and economic importance(red 5 > billion $, yellow 1-5 billion $, green <1 billion $). Source (Deubzer et al., 2012, p. 42).

Some reports made forecasts of future material demand from LED production. One study, on metals and rare elements used in the production of LED, calculated a demand of 3,9 ton Yttrium (Y), 0,7 ton Cerium (Ce) and 0,6 ton Arsenic (As) and relatively smaller amounts of for other metals in 2012 for the estimated 59 billion LEDs consumed (Wilburn, 2012, p. 11). Which is considering the total demand for many REE, not a significant amount. However this was a minimal approximation, based on material concentration from toxicity reports and not the actual bill of materials. The U.S. department of energy expects that LED technology will not begin to significantly affect global REE demand until about 2017 (U.S. Department Of Energy, 2011). The most likely event of supply shortages is due to processing capacity limitations or changes in supply of raw materials from China as a result of export restrictions.

3. Conceptual model

The purpose of this chapter is to assess the value of circular business models focusing on end-of-life strategies, how they relate to increasing resource price (volatility) and the investment needed to creates circular business models. Resource and labor prices will be discussed in section 3.1. Section 3.2 describes the influence of the product life cycle on the expected flow of products that can be recycled and/or used for component harvesting. In section 3.3 the derivations for end-of-life valuations will be presented. And lastly, real option valuation and the risk premium will be discussed in section 3.4.

3.1. Historical resource prices and forecasting

For the collection of historical resource prices, three sources were used: The Worldbank (2014a), is used for basic metals prices, metal-pages.com (2014) for rare earth elements prices and U.S. Geological survey (2013) for other elements used in the production of lamp. The prices are adjusted for price inflation using the consumer price index from the World Bank (Worldbank, 2014b). The nominal prices are corrected to 2010 US dollars and indexed against 2010 prices.

In Figure 3.1 the historical indexed real prices from 2000 to 2013 are plotted for basic and precious metals. Basic metals (such as aluminum and copper) and precious metals (such as platinum and gold) show a slow price trend upwards, spiking in 2006 along with high economic growth, and dropping sharply in 2008 along with the financial crisis. In general a upward price trend can be observed.

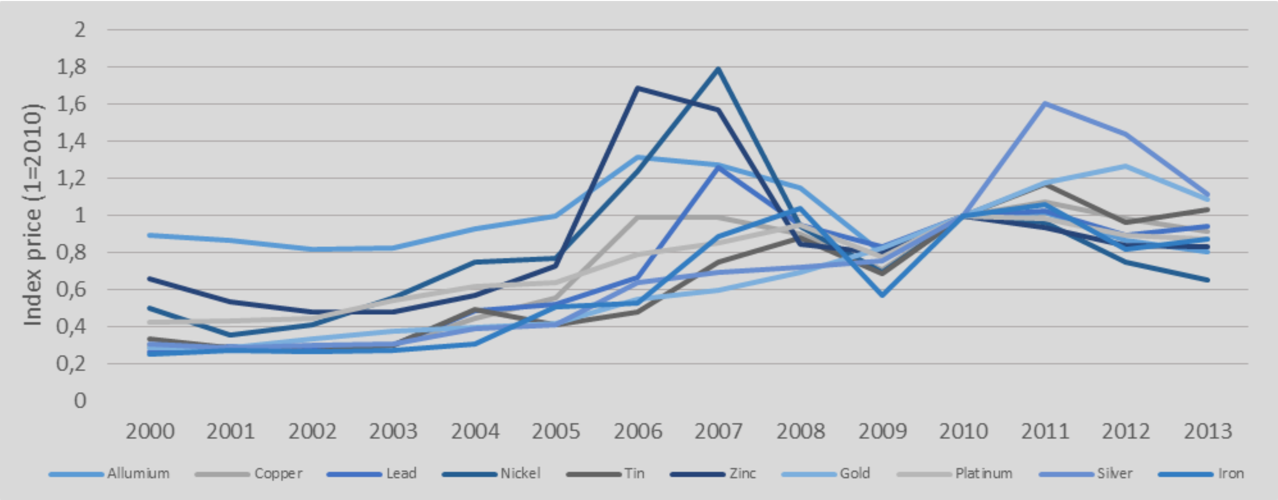


Figure 3.1: Indexed prices for basic metals, precious metals and iron ore. Prices are from The Worldbank (2014a) and are normalized for 2010, using Consumer Price Index (CPI) from the Worldbank (2014b).

The historical real indexed resources prices from 2007 to 2013 for rare earth elements are shown in Figure 3.3. Rare earth metals prices have increased six times in 2011 compared to 2011. After 2011, prices quickly declined but are still above the prices observed in 2007. For most prices of rare earth elements an upward moving trend along with high volatility can be observed

Historical price for other resources used in lamp production are shown in Figure 3.2. Although most materials increased in price and show a high volatility, there is no general trend for all of the materials.

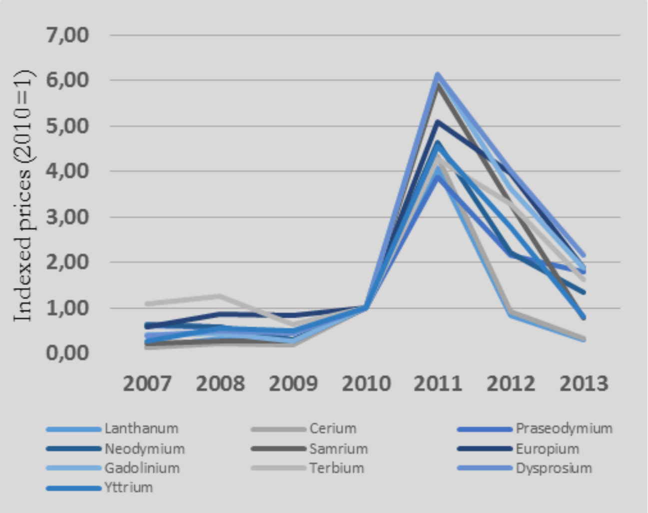


Figure 3.2: Indexed prices for Rare Earth elements. Prices are from Metal-pages.com (2014) and are normalized for 2010, using CPI (2014b).

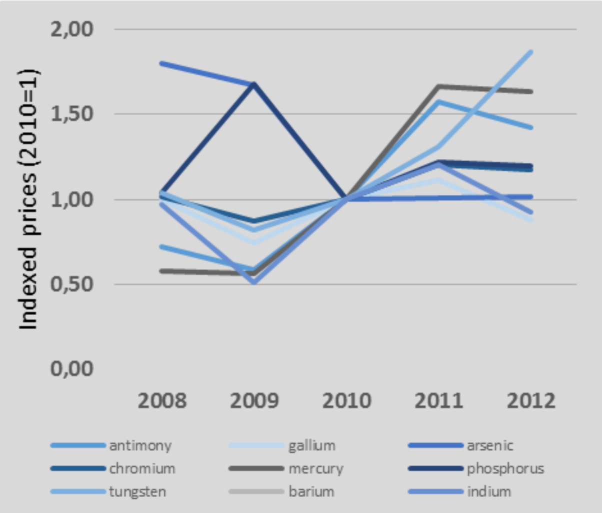


Figure 3.3: Indexed prices for various metals. Prices are from USGS (2013) and are normalized for 2010, using CPI from the Worldbank (2014b).

An important part in the process of component harvesting is the use of labor for screening and disassembly of components, this will be further discussed in section **Fout! Verwijzingsbron niet gevonden.**. Because the case study, which will be presented in chapter **Fout! Verwijzingsbron niet gevonden.**, is located in Indonesia, labor prices for Indonesia will be used in this conceptual model. Historical manufacturing wages for the period 1997-2012 are from the statistical agency Indonesia, and is depicted graphically in Figure 3.4 (BPS, 2013). The wage of production works was \$0,87 per hour[13] in 2012 (taxation in this bracket is 15%) and has been growing, on average, at 8% per year for the last five years.

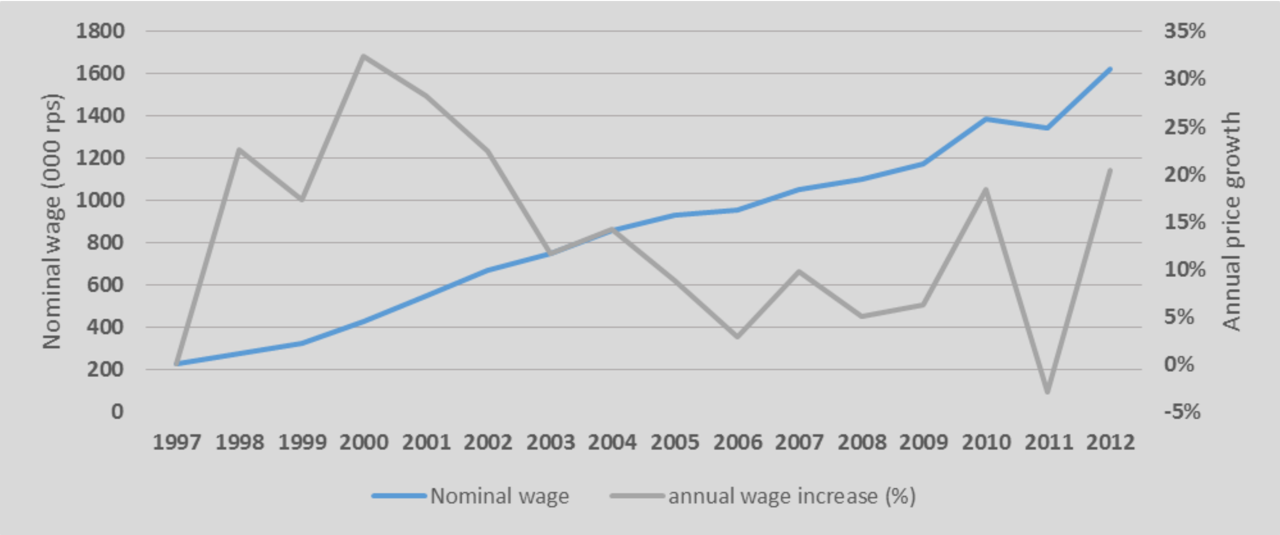


Figure 3.4: Monthly nominal wage in thousands of Indonesian Rupiah. Nominal wages are from BPS (2013).

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[13] Based on an exchange rate of 0,000086 dollar to one Indonesian Rupiah, with 160 hours per month.

3.1.1. Resource price volatility

The price volatility of a single resource can be calculated using the standard deviation, and is depicted in equation (3.1), where:

n is the number of data points,
p_i is the price in year i,
$\bar{p}$ is the mean price in the time series.

$$standard\ deviation\ (volatily) = \sqrt{\frac{\sum_{p=1}^{n}(p_i-\bar{p})^2}{n-1}} \qquad (3.1)$$

For a product that consists of multiple resources, the calculation of the price volatility is more complicated. Resource prices are often correlated with one another, meaning that to some extent the prices are moving up and down together. Since there is a potential correlation between resources prices, the volatility of a portfolio of resources is not just the sum of volatilities for every resource but also includes correlation between prices. A high correlation between resources would increase the portfolio volatility since they would move in the same direction and enforce each other. The variance of a portfolio consisting of two assets is calculated using equation (3.2), Where:

ρ describes the correlation between assets 1 and 2,
w the weights of the products in the portfolio.

$$\sigma p2 = w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + 2w_1w_2\,\rho_{1,2,}\,\sigma_1\sigma_2 \qquad (3.2)$$

The correlation between two resource prices is calculated by dividing the covariance of asset 1 and 2 by the standard deviation of asset 1 and 2:

$$Correlation_{1,2} = \frac{Cov\ (1,2)}{\sigma_1\sigma_2} \qquad (3.3)$$

The covariance coefficient can be calculated using equation (3.4), where:

P_1 and P_2 represent the prices for resource 1 and 2,
μ is the average growth for resource 1 and 2, during n periods.

$$Covariance_{1,2} = \sum_{i=1}^{n}\frac{(P_1-\mu_1)(P_1-\mu_2)}{n\ periods} \qquad (3.4)$$

With more than two resources, equation (3.2) becomes increasingly complex. It is therefore best to use matrix multiplications. The portfolio variance of multiple stocks is calculated with the following matrix multiplication:

$$= \begin{bmatrix} w_1\sigma_1 & \cdots & w_n\,\sigma_n \end{bmatrix} \text{ x } \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1n} \\ \rho_{21} & 1 & \cdots & \rho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{n1} & \cdots & \cdots & 1 \end{bmatrix} \text{ x } \begin{bmatrix} w_1\sigma_1 \\ \vdots \\ w_n\,\sigma_n \end{bmatrix} \qquad (3.5)$$

3.1.2. Resource price growth

Two methods will be used for resource price forecasting: deterministic prices will be used for the NPV method and stochastic prices will be used for the ROV method. The compounded annual growth rate is used to calculate the deterministic annual price growth rate from historic prices and is depicted in equation (3.6), where:
p is the resource price at time *t*

$$\mu(t_o t_n) = (\frac{p(t_n)}{p(t_o)}^{\frac{1}{t_n - t_o}} - 1) \qquad (3.6)$$

In order to calculate the price growth rate for a portfolio of resources, the growth rates must be weighted according to the value it represent in the product. This means that if for example aluminum represent a higher share in the total value, higher aluminum price will have a greater effect on the total material price growth. The weighted growth rate of a portfolio of resources is calculated with the equation (3.7), where:
w is the weight of the resource in the total weight of the product

$$\mu_{avg} = \sum_{i=1}^{n} \frac{w_i \, p_i \mu_i}{\sum_{i=1}^{n} w_i p_i} \qquad (3.7)$$

The deterministic price growth will use the portfolio's average growth rate from equation (3.7). The change in price in one year is the current price times the average price growth, μ. Stochastic price changes will use the geometric Brownian motion for potential price path. The change in price in one year is the annual growth rate times the stock price, plus a randomized variable. This is depicted in equation (3.8), where:
ε is the randomized variable,
ΔT *is* the times steps and
S is the current stock price.

$$\Delta S = \mu S \Delta T + \sigma S \varepsilon \sqrt{\Delta t} \qquad (3.8)$$

The difference between the two methods can be seen in Figure 3.5. The black represent the historic price of one kilo of iron, the red line represent deterministic forecast of iron prices and the blue lines represent 100 simulations of stochastic price paths. The stochastic model includes past volatility and recognizes that there is uncertainty in future prices. Whereas the deterministic approach uses past prices and assumes that there is no uncertainty.

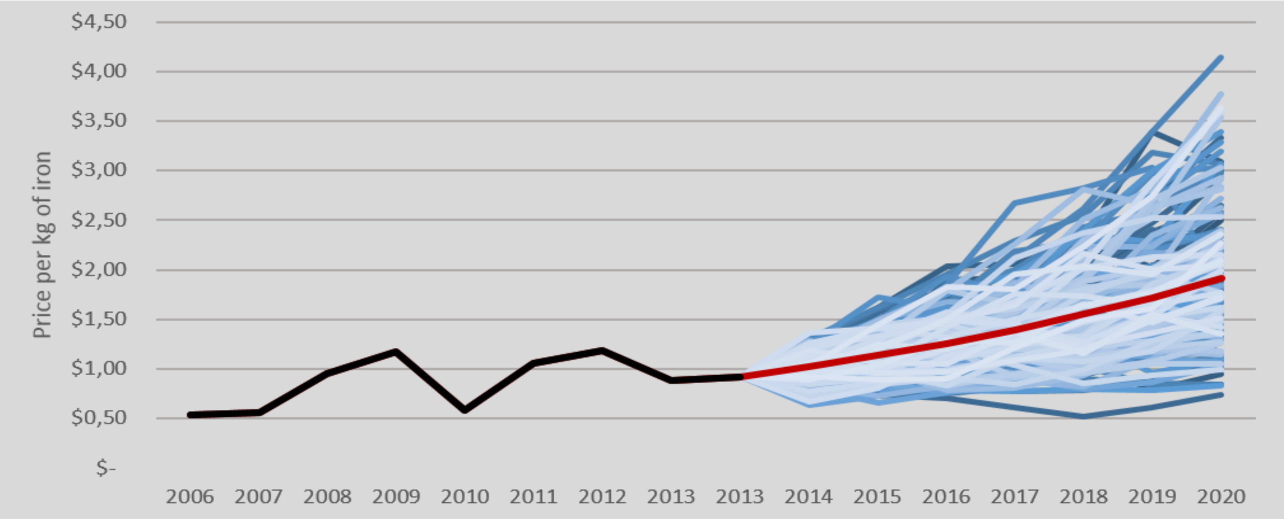

Figure 3.5: Historic and forecasted prices for one kilo of iron. The black represent the historic price of one kilo of iron, the red lines represent the deterministic forecast price and the blue lines represent the stochastic price paths

3.2. Product life-cycle supply and demand

The annual amount of disposed products is a function of amount of produced products and the average usage time of the product. The amount of lamps that reaches end-of-life and is disposed is denoted by Q, and is illustrated in Figure 3.6. From the annual amount of products that reaches end-of-life, only a fraction will be directly returned to the producer or recycling facility. This fraction, denoted by r, can be the amount of returned products within warranty, returned products from the retailer or other reverse logistic systems. The remaining lamps go to through existing disposal system, such as collective collection schemes, to landfills, or recycling and incineration facilities.

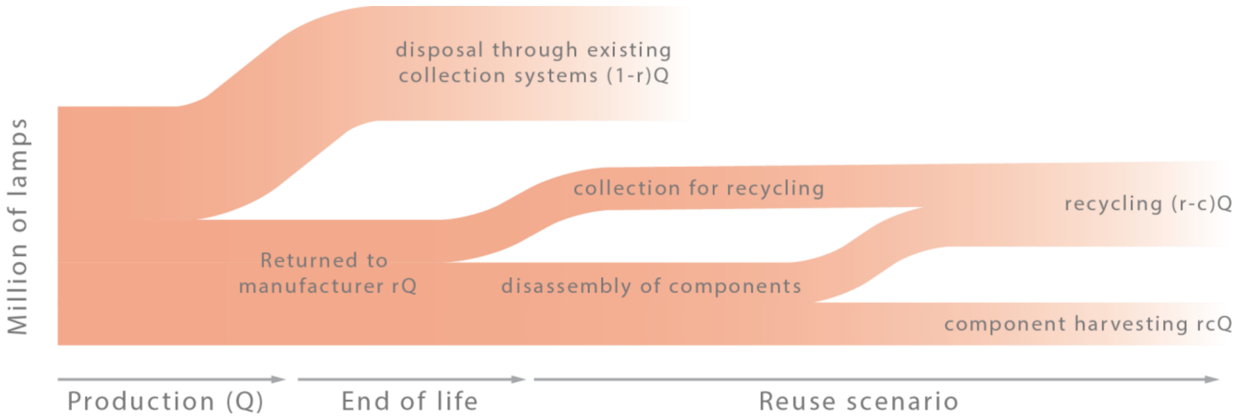

Figure 3.6: Product flow during production, end-of-life and reuse.

The amount of products that is returned to the factory is the amount of disposed products multiplied by the returned fraction, and is denoted by rQ. In this model it is assumed that there are two options for end-of-life treatment: recycling and component harvesting. Component harvesting is the purpose of recovering reusable component and parts from used products, to be used for the purpose of refurbishing and remanufacturing. Because the components need to suitable for reuse, screening is done to check whether the components are suitable for reuse in another product. The fraction of products that is suitable for component harvesting is denoted by c. The total amount of products that is suitable for component harvesting is the amount of lamps that is returned multiplied by the suitable reuse fraction, and is indicated by crQ. Because recycling applies to any component, whether they are broken or not, it is not limited by these constrains. The total amount of products that are suitable for recycling is denoted by rQ. In case both component harvesting and recycling are used, the amount of products for recycling is $(r\text{-}c)Q$ and for component harvesting this is crQ.

In order to assess whether the materials and components can be reused in production of another product the product life cycle analogy is being used, see section 2.4.4. Because of technological development new products will emerge, this process gradually emerges over time. Superior products, denoted by *product* z, replace the inferior product, denoted by *product* y. The consequence is that the amount of inferior *products* y that are disposed and demand for superior *product* z changes over time with the product life cycle. The amount of disposed products will slowly decrease, whereas the demand for the superior products will slowly increase.

For component reuse and material reuse, the demand for new products and the supply of disposed products needs to overlap. This is illustrated in Figure 3.7, where the blue area represents the amount of returned products that can be used for the production of *product* y. The green area represent the amount of products that can be recycled with component harvesting $(r\text{-}c)Q$ (products that are unfit for component harvesting can still be used for recycling). The blue area represents the amount of products that are suitable for component reuse of *product* y. With increasing time between demand and supply the amount of components that can be harvested will decrease. Thus if the lifetime of the used products increases or the demand for a new product increases, the time where in this is possible will decrease. Therefor the amount of reusable components and materials are conditioned by:

$$Q(t) > D(t) \tag{3.9}$$

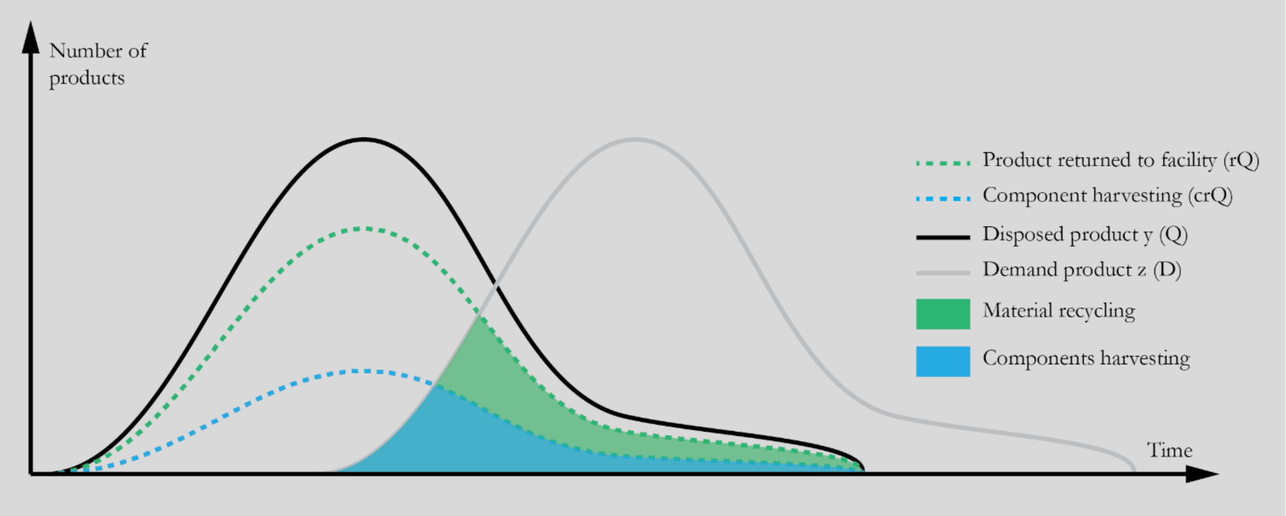

Figure 3.7: Illustration of the product life cycle for two products.

3.3. End-of-life values

The monetary benefits for end-of-life strategies are equal to the residual value that can be retrieved from the products that are returned. The NPV method will be compared to the ROV used for assessing the benefits of a circular business model. For both models the costs and benefits needs be known for the duration of the project. The NPV calculation is presented in equation (3.10). The benefits are in the numerator and the costs are in the denominator and determine the cash flow for each year. The investments costs are made in year zero.

$$NPV = \sum_{t=1}^{T} \frac{C(P)_t}{(1+r)^t} - I_0 \tag{3.10}$$

Three end-of-life strategies are used in this research. First is the recycling scenario where are all products are recycled for their material value. And will be discussed in section 3.3.1. The second scenario, component harvesting, in which all suitable product are harvested for components. And will be discussed in section 3.3.2. The third scenario is combined scenario of component harvesting and recycling. Components that are not suitable for component reuse will be recycled. This scenario will hereafter be referred to as *component & recycling* and is discussed in section 3.3.3. The three scenarios are illustrated in Figure 3.8. Beginning with the material, labor and energy inputs, components are produced. Each component embodied a labor, energy and material costs. The value that can be recovered through recycling is the material value. With component harvesting the material, energy and labor inputs are recovered. And the value lost represents the labor and energy inputs that were not recovered. The three scenario will be further elaborates in the following paragraph.

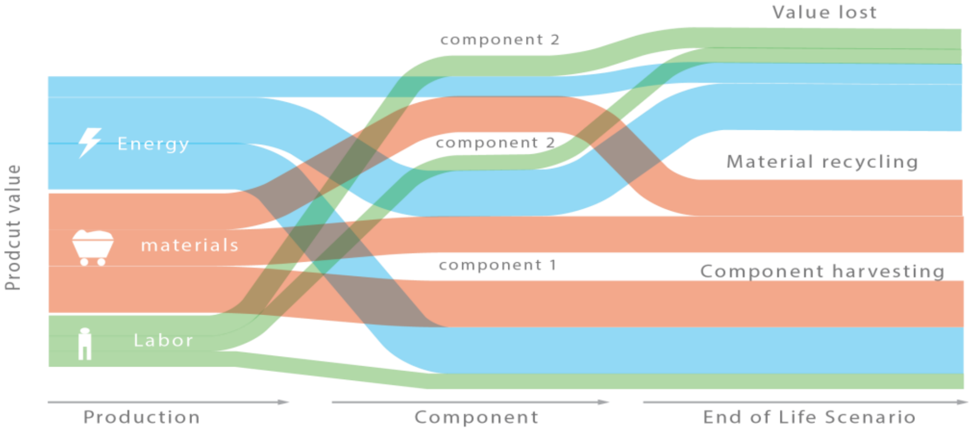

Figure 3.8: Material value flow, for recycling, component harvesting and Component harvesting and recycling.

3.3.1. Recycling

The recoverable value for recycling is directly represented by the material value of the product. The material value equals the weight of materials, denoted by w_x, times the price of the material, denoted by p_x. Due to limitations in the efficiency of recycling technologies, the recoverable value is lower that the material value of the product. The efficiency is denoted by $R_{ecycling}$. The technically recoverable value of materials is different per material due to characteristics of the metals or progress in recycling technologies (Denne, Irvine, Atreya, & Robinson, 2007). However metal efficiencies are often in the same range, and for the simplicity of the model we assume a single recycling efficiency for all metals. The equations for the recovered value is as follows:

$$v_{recycling} = E_{recycling} \sum_{j=1}^{n} w_j p_j \tag{3.11}$$

The costs for recycling are simplified to the processing costs and the investment costs. The processing costs are the costs needed to recycle lamps, and include shredding, sorting, dismantling, pre-treatment, the recovery process and other costs. The investment costs are equal to the costs needed to build recycling facility. The recovered value will grow each year with the price increase of the specific resource, calculated in equation (3.8). The net present value for recycling is given by the following equation:

$$NPV_{Recycling} = \sum_{t=1}^{T} \frac{\left(E_{recycling} \left(\sum_{i=j}^{n} w_j p_i\right)^{(1+\mu)^t} - C_{processing}\right) rQ}{(1+i)^t} - I \tag{3.12}$$

3.3.2. Component harvesting

The end-of-life value for the component harvesting scenario is equal to the recovered value from components. The value of components, denoted by $c_{omponent,}$ is higher than the material value in the recycling scenario because the energy and labor inputs embodied in production can be recovered. The residual value of component harvesting is the number of components that can be reused multiplied by the component value. The value of component harvesting is expressed in the following equation:

$$V_{component\ harvesting} = \sum_{i=1}^{n} V_{component,i} \tag{3.13}$$

Prior to the processing of the components there is a screening to check whether the returned products are suitable for component harvesting, this is done manually. In this model it is assumed that all screening costs are due to manual labor. The screening costs are therefore amount of labor times the wage of manufacturing workers and is denoted by $L_{screening}w$. The products that are suitable for component harvesting are then processed and the reusable components are extracted. This is a labor-intensive process. Similarly to the screening process, all costs are assumed to be from manual labor, and are denoted by $L_{component}w$. The margin of component harvesting for every returned product is the difference between the value of components and the labor costs involved with processing and screening, and is expressed in the following equation:

$$m_{Component} = c\left(\left(\sum_{i=1}^{n} V_{component,i}\right) - L_{component}w\right) - L_{screening}w \tag{3.14}$$

The material value of resource in the components will increase each year with the annual expected deterministic growth rate, calculated in equation (3.8). However the value of component is only partly from resources, and partly from energy and labor inputs. The material value divided by the total component value is the factor, denoted by *d,* by which the value of components will grow. The NPV for component harvesting is given by following equation:

$$NPV_{Component\ harvesting} = \sum_{t=1}^{T} \frac{\left(c\left(\left(\sum_{i=1}^{n} V_{component,i}{}^{(1+d\mu)^t}\right) - L_{component}w\right) - L_{screening}w\right) rQ}{(1+i)^t} - I \qquad (3.15)$$

3.3.3. Component & Recycling

The value of the component & recycling scenario is the combined value of component harvesting and recycling. The components that cannot be reused can be used for material recycling. The fraction of components that can be recycled is the material value of components divided by the total material value of the product, expressed in $\frac{\sum_0^n V_{component}}{\sum w_x p_x}$. Furthermore the share of products that cannot be harvested for components can be recycled, and is denoted by *r-c*. The margin for the extra costs and revenues for this recycling besides component harvesting is:

$$m_{recycling\ of\ unused\ components} = \left(r - c + c\frac{\sum_{i=1}^{n} V_{component,i}).}{\sum w_x p_x}\right)\left(E_{recycling} \sum w_j p_j - C_{processing}\right) \qquad (3.16)$$

The net present value for the component & recycling scenario is given by the following equation[14]:

$$NPV_{C\&r} = \sum_{t=1}^{T} \frac{(c\left(\left(\sum_{i=1}^{n} V_{comp,i}{}^{(1+n\mu)^t}\right) - L_{comp}w\right) - L_{scr}w + \left(1 - r + c\frac{\sum w_{comp}p_x}{\sum w_x p_x}\right)\left(E_{rec}(\sum_{i=j}^{n} w_j p_i)^{(1+\mu)^t} - C_{proc}\right))rQ}{(1+i)^t} - I \qquad (3.17)$$

3.4. Real option valuation

In order to value real options for the described end-of-life values the Black-Scholes formula, expressed in equation (2.3), will be used. Analogue tot financial options the following variables are used, see Table 3.1. The underlying stock price is the value of materials or components on the market. The strike price is the costs to acquire the resources through recycling or component harvesting, which are the marginal costs, or processing costs.

If the resource prices are high it become more profitable to recycle products because they can be bought at a specified price, namely the costs to harvest the resources. If resource prices become lower than the exercise price they can be bought on the market. Thereby taking advantage of the upside potential of risk.

The option value represents the maximum costs that such an option should cost, and are equal or larger than the investment costs of recycling and/or component harvesting facility. Thus the investment should be made if ROV is larger than the investment costs.

The option value will be calculated for every year during the project lifetime, and is calculated back to the present value. If the option value is larger than the investments costs, the project has a positive value.

Table 3.1: Real options approach for recycling or component harvesting.

Variable	Financial option	Project investment	Case study
K (I)	Strike price (exercise price)	PV of the costs to acquire the asset	Recycling or component harvesting costs
S (V)	Stock price	Future cash flows from project	Present value of Price to acquire materials or components
t	Time to expiration	Length of time the option may be differed	Length of project
σ	Variance of returns of stock	Riskiness of project assets	Volatility of resource prices
r	Risk-free rate of return	Time value of money	Discount rate

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[14] Abbreviations are used for denominators

3.4.1. Real Option valuation in relation to Net Present Valuation

The NPV often uses deterministic prices, thereby neglecting the uncertain nature of future resource price uncertainty. If producers indeed use the NPV value method to address their future material costs, any change in price is a form of risk because it exposes the company to increases production costs. Real option method uses stochastic prices and dynamic modeling in order to incorporate uncertainty, and is therefore more equipped to assess the effect of price changes on future material costs

Circular end-of-life scenarios can be seen as an option to be less dependent on the market for material supply. For companies that do not engage in recycling and/or component harvesting their material supply is to supply of market resources. The difference can be seen in Figure 3.9. Where the green line represents one stochastic simulation of a resource price, and the dotted green is the deterministic price growth path. The black lines represent the marginal costs of for example recycling. With the NPV the benefits of this project are negative, because the marginal costs are higher than the value of resource that can be recovered. However by using the ROV the blue area represent the profit that can be made from recycling. If market prices are lower than the material recycling costs, resources can be bought from the market, and if resource prices are higher than the material recycling costs, the material from the recycled products can be used.

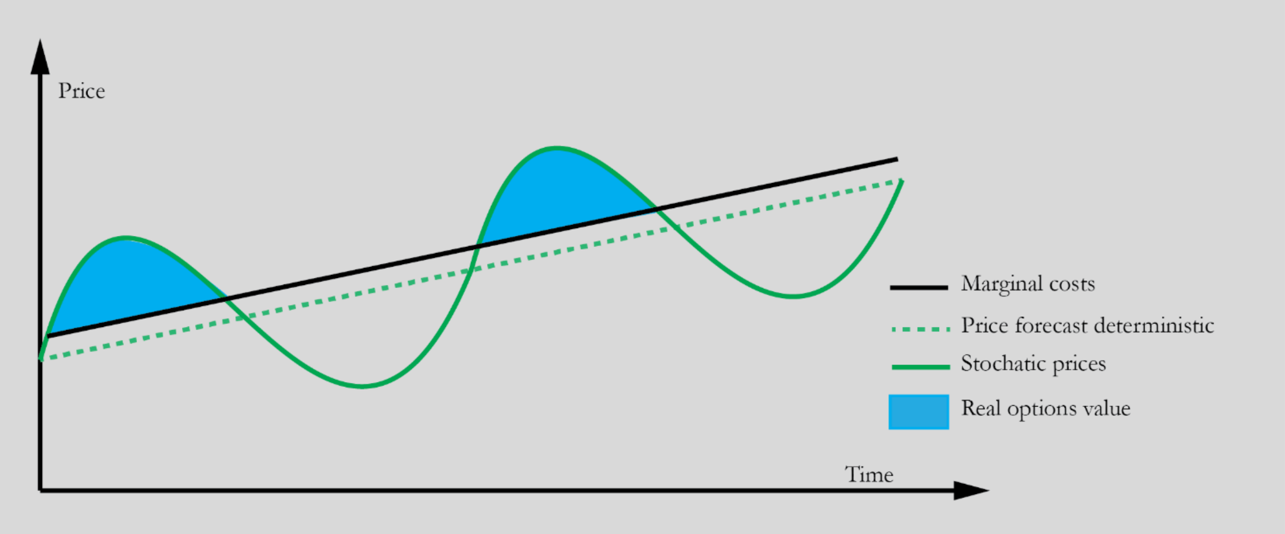

Figure 3.9: The option value compared to the net present value method.

As mentioned, the NPV assumes that there a certain degree of certainty over forecasted variables. Resources prices, product demand, processing costs were all taken as-stochastic, at their expected values using deterministic growth rates. With the ROV the resources prices are set to uncertain, by using stochastic price changes. The NPV scenario is defined as the certain scenario and the ROV as the uncertain scenario. By comparing the ROV and the NPV the risk premium can be calculated (Yang et al., 2008). The risk premium is calculated as follows:

$$Risk\ premium\ (US\$/product)\ = \frac{ROV_{uncertain} - NPV_{Certain}}{quantify\ of\ products} \qquad (3.18)$$

4. Discussion

The following section will put the outcomes in(to) context, discussing the robustness of the results in relation to input data availability and quality and assumptions made in constructing scenarios and other aspects that have bearing on the outcomes as presented. First the conceptual model will be covered, after which the case study and the practical limitations of this research will be discussed.

4.1. Conceptual Model

The conceptual model presents a simplified representation of the analyzed cases, providing insights into the structure and the relation of the analyzed supply chains. This section will address the robustness of the outcomes in relation to the model structure, data availability and quality and the assumptions that were made.

One key assumption that oversimplifies the actual practice is that in the harvesting of components only labor is required to screen and process components. Thereby other costs such as the energy inputs or machinery processes involved are neglected. In case wages would indeed have a significantly lower share in the production costs, it would, however, still influence the processing costs. Thereby the assumption only affects the *degree* to which labor and wages influence the component harvesting and the component harvesting & recycling scenario. Other factors may influence the costs curve, but the result that increasing labor costs would increase component harvesting costs is still valid.

The residual value of component harvesting is more difficult to model than the residual value of material recycling since it not only depends on material inputs but also on the input of energy and labor. In here it assumed that the component reused in the production of lamp accounts for 50% of the material value. This is consistent with data found on the input factors of production, given in Table 2.2. Other input factors include the use of labor and energy. This however neglects any investments that are done to produce and develop components and products. R&D investments for any product can be considerable, especially with newly addressed markets as in the case of LED lamps. Additionally, investments are needed for production facilities. Whether to account them for in the residual value or the beginning of life is as much an accounting questions as it is a definition problem. R&D and other investment are depreciated and accounted for in the retail value of a product.

Due to data limitations on historic prices of rare earth elements and other materials, the volatility and annual growth rates of resources are only calculated over a period of 5 years, 2008-2012. Especially during this period the volatility was high due to the turbulent world economy. This might give overestimated high numbers of the resource price volatility and annual growth rates.

4.2. Case study

For the case study the market forecast for the lighting industry is modeled based on existing data and assumptions. The first assumption is that the lighting market will grow along with the increase in GDP. The second assumption is that the lighting market will quickly change from a CFL and incandescent dominated market toward a LED lamp dominated market. The second assumption depends largely on the expectation that the price of LED lamps will decrease quickly and will match the price of a CFL in the coming decade. If this process will slow down in the future it would potentially affect the penetration rate of LED lamps. However this would imply that the CFLs will be produced for a longer period of time, resulting in an extended period in which components can be harvested. A different growth path of the lighting industry influences both the quantities of CFLs and LED lamps sold. This results in lower quantities of disposed lamps, thereby limiting the amount of lamps that can be used for component harvesting.

It can be expected that the CFL components that are being reused have a different lifetime than that of a newly produced LED component. Not only because it is already being used, but also because the CFL components are designed to operate for a shorter period due to the limited lifetime of a CFL. It is unknown how long the CFL component will actually remain functional. If the reused CFL components decrease the lifetime of a LED lamp it could reduce the benefits from components harvesting because additional LED lamps would have to be produced to account for the lost lifetime. This potentially decreases the environmental benefits, because in that case new resource and energy inputs have to be used.

An important characteristic of this case study is the low reverse logistic costs because customers return their product to the factory to claim their warranty. It may, however, be questionable if customers will return their product without a (financial) incentive, even if it is under warranty and consumer can receive a new lamp. Secondly, the production facility is likely to be of distance from the point where consumers return the product, creating extra reverse logistic costs. It is unknown what the additional costs are, but it can be expected that they are lower than the existing reverse logistic scheme in Europe.

The processing costs are derived from the WEEE directive, a European recycling platform. The European infrastructure and economy differs substantially from the case study area. The question is whether this would positively or negatively affect the business case. Since the recycling infrastructure is less developed in the case study area, it can be expected that higher investments are needed in order to develop the recycling infrastructure. However, labor costs are considerably lower than in Europe, which would reduce the processing costs. Whether this would offset the extra costs needed for the recycling infrastructure is unknown.

The investment costs in this model are assumed to be eight times the processing costs multiplied by the number of maximum returned products per year. This is done to make the case study adaptable to the amount of returned lamps. However, when operating on a small scale the model fails: the investment costs for one recycled product is just eight times the processing costs. A facility at such a small scale is not realistic since facilities are usually built to process large quantities of products to increase efficiency. However, as was found in the sensitivity analysis, the impact of the investment costs variable on the NPV variable is considerably lower than other input variables. No literature was found to more accurately estimate investment costs.

4.3. Practical limitations

For cost-effective material recycling, large volumes of products (and weight) are required. And although large quantities of lamps are collected in the case study, they may spatially be very scattered, thereby making the collection scheme more challenging and costly. Secondly, the material mass for many materials, such as rare earth elements, is very low for lamps. This makes it difficult to satisfy the minimal material mass that is often required in recycling facilities.

Due to the fact that many LED lamps are being produced in China, the trade restriction on for example rare earth elements do not apply because they are already embodied into the product. This implies that the production of LED lamps in China is less sensitive to the geopolitical-economic dimensions of resource scarcity.

From the case study it was observed that a component from a different product class can be reused. However with the transition towards a LED dominated market, the emphasis should shift from internal product class component reuse towards the reuse of components from different forms and models. LED technology is constantly evolving and increased efficiency and broader color ranges can be expected. With the long lifetime of LED lamp, there are considerable benefits to be made if components could be reused or upgraded.

One issue with the reuse of components is liability. As mentioned earlier in the discussion, the LED lamps that have been produced with reused components may breakdown earlier than the LED lamps that were not produced with reused components. Companies do not want to be affiliated with products that are of inferior quality since it could potentially damage the corporate image. One option to avoid these problems is to produce the LED lamps under a different entity by using a spinoff company that markets lower priced LED lamps, thereby protecting the corporate image of the mother company.

5. Conclusion

Outcomes suggest that applying circular business models to develop smarter end-of-life scenarios for the production and refurbishment of lamps may recover value over the production lifecycle. When this is combined with higher shares of products and resources that are maintained within a manufacturer's production cycle it may increase operational stability by mitigating effects related to raw material scarcity and price volatility.

These findings - and in fact the rationale for the analysis - are an immediate response to rising raw material prices and increasing price volatility. More than half of the resources used in the production of lamps have shown an annual resource price increase of 10% or higher and an annual price volatility exceeding 36%. Furthermore, 13 of the 22 materials used in lamp production were categorized as critical regarding recourse scarcity. The combination of resource price growth, volatility and the use of critical raw materials results that LED lamp production very vulnerable to external supply disruptions.

In order to mitigate the impact of raw material prices and increasing price volatility, three circular business models focusing on product end-of-life values were analyzed and applied onto the case study. Firstly, the material-recycling scenario represents the recovery of material value from products through recycling. The second scenario focuses on component harvesting, in which the recovery of components from an inferior product are to be used in the production of a superior product. The third scenario combines component harvesting and material recycling where components that cannot be reused will be recycled. Due to the fact that the embodied energy, material and labor inputs can be recovered through component harvesting, the recovered value from component harvesting is three times higher than material recycling. The component harvesting & recycling scenario gives the highest recovered value because it recovers materials in addition to components. The costs for recycling are relatively high compared to the recovered value, therefore the margin of the component harvesting scenario is higher than the component harvesting & recycling scenario The recovered value can directly be used to reduce Light Emitting Diode (LED) lamp production costs, thereby mitigating the potential of rising and volatile resource prices. Key determinants in the end-of-life scenario are the labor wages and resource prices: higher resource costs have a positive effect on all three scenarios and higher wages negatively affect the component and component harvesting & recycling scenario.

For smart circular end-of-life business models, large investments have to be made for a longer period of time. The net present value method is often used to determine the profitability of investments but in environments characterized with high uncertainty it may ineffectively incorporate uncertainty. This can under- or overestimate the profitability of these investments. The real option valuation method (ROV) is used as an alternative to the Net Present Valuation method (NPV) and is better equipped to incorporate uncertainty. Rather than using deterministic variables it uses stochastic prices and dynamic modeling. Hereby the flexibility that is required to adapt to changing market circumstances is incorporated. The results suggest that the NPV significantly underestimates the value of circular business models. The calculated ROV is five times higher than the NPV for the recycling scenario. For the component harvesting and component harvesting & recycling scenario the difference was smaller, but still the ROV valuation was 1,6 and 1,9 times higher. Because the end-of-life value directly represents the production costs for new products it also implies that future production costs may be significantly underestimated. The difference between the NPV and ROV was defined as the risk premium that companies implicitly pay for their dependency on rising and volatility resource prices. The risk premium is correspondingly the value by which circular end-of-life strategies mitigate the potential impact of rising and volatile resource prices. The avoided risk premium increases the margin of recycling, component harvesting and component harvesting & recycling by respectively 24%, 18% and 30%.

Furthermore the results suggest that in order to optimize component harvesting individual collective schemes are preferred over collective schemes. Extended manufacturer responsibility is often executed in a collective effort to minimize costs. Since all products end up in same product flow, it is more difficult to retrieve specific components or products desired by individual companies. Individual collective schemes may increase reverse logistics costs due to lower product flows but by making smart use of existing logistic product logistics, these costs are reduced.

6. References

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