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SUSTAINABILITY ISSUES FOR SSL

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ACCELERATE SSL INNOVATION FOR EUROPE

DELIVERABLE 2.8

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SUMMARY

This is the final SSL-erate project report on sustainability issues in Solid State Lighting (SSL) and methods for handling these, including Product Environmental Footprint, scarcity, recycling, eco-design and the principle agent problem. The report summarizes a number of explicit results from the comprehensive research on LED related matters conducted lately. The report relates to ambitions to develop a circular economy and an environmental Life Cycle Assessment (LCA) perspective. One concern is to develop a societal stock of product material that it is worthwhile to recycle. One advantage is the LED controllability enabling SSL solutions that provide the right light at the right place at the right time. However, quite a number of the luminaries have non-replaceable LEDs. Recycling challenges are the small amount of critical materials, the number of different electronic components and the plastic materials with flame-retardants used to manufacture SSL products.

There are two kinds of sustainability issues. One is that any new technology, such as SSL, may introduce new kinds of sustainability risks, and the other one that deployment of SSL systems is still limited. On the positive side SSL and, in particular, smart lighting systems enable significant energy savings and at the same time light environments that promote health, productivity and wellbeing. This is a significant advantage for sustainable social, environmental and economic development. The report summarizes risks and possibilities in the sustainability dimensions.

This report focuses on what can be done to increase the usefulness of SSL as a tool for sustainable development. The main sustainability advantage is that SSL systems can improve the working and living environments in preschools, schools, offices, hospitals, for the elderly and in the streets. It is becoming a Societal Social Responsibility (SSR) to make use of this improvement potential. Cities and municipalities should start to develop policies and specifications for and to demonstrate more advanced lighting solutions.

There are high quality LED products on the market but consumers have trouble to assess their qualities and to find the right products for different needs. Real life demonstrations are important to build awareness and customer trust in the new technology. Introduction of lighting as a service enables a change from transaction to relationship and is facilitating customer adapted solutions. The company retains responsibility for the performance of the lighting system, which means that they have more incentive to design for long-term appreciation, longevity, re-use and recycling. This report presents some new business models as well as drivers and barriers for adopting these models.

From environmental risk point of view SSL is comparable to electronics in general. SSL have high luminous efficacy. The Carbon Footprint and the Ecological Footprint of SSL are smaller than for conventional lighting technologies, but SSL demands some scarce materials. The limited availability of Rare Earth Elements (REE) is an uncertainty for SSL and electronics in general, but the content of REE in LED is relatively low and long-term supply risks are not anticipated. In the short term, supply shortages are possible due to geopolitical and commercial factors. In Europe, LEDs are regulated under the WEEE Directive, which gives the companies selling electronics the responsibility to provide collection points. In this way, the responsibility for management of residual materials is shifted to private industry. In the end it is the consumer who is responsible for the actual collection of the products, but cities can influence their actions. One precondition for meaningful recycling is to make the products from materials with recyclability value and then make such procurement choices of products that high quality materials enter the societal material stock.

Cities ought to enhance application of SSL in municipal properties, public spaces and street-lighting, support public procurement for innovation (PPI) and local and regional e-Waste reuse, and collection/recycling schemes. Public institutions can lead by example in procuring SSL and opening up markets for new lighting solutions, and business models. A green system solution with energy effective lighting tends to have higher procurement cost and lower life-cycle cost. One municipality obstacle to investment in renewal is that different departments with own budgets are responsible for procurement, energy and maintenance. Another barrier is short-sightedness, e.g. by considering the payback time to be too long.

The main sustainability issue is that the deployment of SSL is so slow. Cities and municipalities should take a lead role in building awareness about the significance of user adapted lighting, for productivity and image as well as safety, health and wellbeing. This can be promoted by social sustainability priorities and enabled by green SSL and ICT system solutions that also enable significant energy savings.

INTRODUCTION

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1 | INTRODUCTION

Recent developments in lighting technology have brought many new possibilities, and widened the field of lighting applications, but also increased the information need for the specification and decision-making process. The business opportunities in the most promising early application fields for SSL are described in (Karlsson et al. 2014). The properties and qualities of the lighting products on the market vary and it has become more difficult to make optimum choices of lighting design, systems and products. It is difficult to find explicit guidance for how to make proper use of the diverse potential of the Solid State Lighting technology (Yuan et al. 2013). This is a sustainability issue because there is a risk for misuse of resources and dissatisfaction that can hamper the interest to invest in SSL development and deployment.

This report focuses on Solid State Lighting and aims to clarify:

- Which real, potential and perceived sustainability issues are there;
- Why those concerns are considered to be sustainability issues;
- What can cities do to alleviate the problems and to enhance the usefulness of SSL as tool for sustainable development.

The overarching sustainable development ambition in the SSL-erate project is to enable both current and future generations to improve their quality of life.

> "In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technical development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." **(WCED, 1987, Our Common Future, The Brundtland report).**

To achieve sustainable development it is vital to find the balance between environmental, social and economic aspects. However this is a very multifaceted and complex goal. The environmental sustainability aspect that has attracted most interest the latest decades is the risk of environmental pollution and degradation of the systems in nature (ILGRA, 2002; Martuzzi and Tickner, 2004).

The most noted positive sustainability issue with SSL is that it enables energy savings. The LED efficacy itself now enables significant energy savings even compared to fluorescent tube lighting. A smart lighting system with intelligent user adaption of the light enables human centric light variations and at the same time can often save 90% of the lighting energy. However there is an environmental rebound risk if LED lighting is used in many more applications and products than the traditional lighting or if users adapt increased energy consumption patterns (e.g. by leaving lighting on).

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The long-term quality of life is, among other things, dependent on lighting investments for the future, the user adaption of the lighting and the quality of that lighting. However, the short-term sustainability effects of human centric lighting are difficult to measure. The long-term societal effects of investments in, for instance, better schools and better working conditions are even more difficult to determine. Both the short term and long-term effects need to be considered in moving towards more sustainable production and consumption patterns necessary for sustainable development.

SSL technology is developing rapidly, starting to enable flexible luminaries and system solutions that provide exactly the needed and wanted light, when and where it is needed. This is a great opportunity from energy effectiveness point of view as well. Depending on the specific application this technology enables 95-99% energy saving on system level, but so far the energy use for standby modes often is quite high. To limit the lighting to the light where it is actually needed, can also limit/avoid light pollution. From a human perspective, the SSL controllability makes effective lighting broadly available, which can enable for all an increase in productivity, studies and hygiene, i.e. "health" according to the WHO definition, making it a significant social sustainability advantage.

The cities most important short-term sustainable development priority for SSL is to promote competence development and introduction of Human Centric Lighting by demonstrations of more advanced light environments. In a long-term perspective, cities can take the lead in eco-cyclic innovation (i.e. circular economy) by clarifying that when they start buying larger volumes of new more advanced lighting systems, they will aim for modular solutions that enable smooth recycling.

A concept that can help clarify the connections between short-term actions and resulting effects is 'Circular Economy'. This concept is relevant for the integration of social, environmental and economic sustainability considerations. Sustainable development research tends to focus on one dimension at a time. Consequently this report has one chapter for each of the three dimensions. The concluding section on *SSL in Sustainable City Development* presents some connections between the different dimensions at city level.

2.1 Circular economy

Circular economy is a generic term for a more sustainable industrial economy that produces no waste and pollution through product-life extension, long-life goods, reconditioning activities and waste prevention. It also encourages new business models to enable this, e.g. functional sales, rather than selling products (Ghiselline et al., 2016).

The most widely known goal for the circular economy is to recycle reusable materials to reduce diffusion of environmentally problematic materials. The superior goal includes maintenance, reuse, refurbishment and remanufacture. The overarching goal is to continue to make value-creating use of the refined resources that have been extracted from nature and produced in earlier industrial production.

A circular economy aims to reflect the natural systems in which waste from one process becomes nourishment for another. The products, components and materials circulate in distinct streams where the renewable organic materials often can be returned to the biosphere while materials in the techno-sphere are designed to circulate while maintaining quality in order to become "nourishment" for industrial processes (Ghiselline et.al. 2016, see Figure 1). The cleaner the flows and the higher the qualities of the circulating materials, the more value can be retained in the economic system.

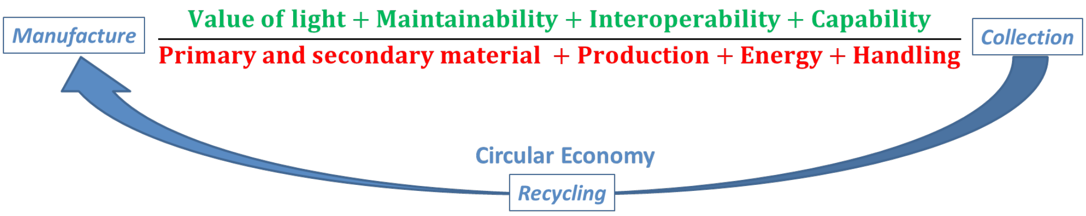

Figure 1 – *The main focus in the circular economy discourse is that the materials should be forwarded in a continual chain of usages. The denominator in the above LCA quotient' contains primary and secondary material denoting first time use of material and renewed use in the circular economy.*

One basic precondition for meaningful recycling is that the societal material stock contains high quality materials worthwhile to recycle. Therefore, it is fundamental to invest in such materials for the primary product manufacturing and to choose recycled materials for the manufacture of new valuable, wanted products.

2.2 Recyclability

The recyclability depends upon the design of the product, the accessibility of the recycling facility and the customers' perception of the likelihood that the product will get recycled in a sensible way and not handled as waste material. When customers consider products to be environmentally benign and relatively easy to sort, in other words 'green', then it is more likely that the customer will make the effort to bring it to the right recycling bin. The statistics vary by European countries whether lighting products are brought to the recycling facility compared to other products (this is covered in more depth in section 4.6). However, today most lamps are crushed and shredded like many other products. A modular design in which the parts are easier to separate can increase reuse of components and the efficiency of the recycling process.

What does it mean that a material is recyclable?

This question is trickier than one would expect. In everyday language "recyclable" often means that the material can be disposed to a separate waste flow that is being taken care of. From a citizen point of view this is a basic level of safeguarding against serious environmental impact. The ambition to establish controlled collection of disused products is also coherent with the need to build awareness, knowledge and an infrastructure of physical source separation systems to enable future establishment of more advanced recycling. However, it is a serious shortcoming if the interest in recycling is limited to waste management to avoid environmental problems (Wagner 2008) as this neglects the circular economy potential of recyclable materials.

There is a basic difference between:

- Recycling of valuable material to produce appreciated products and
- Waste management aiming to dispose of worthless material. In some cases such processes are

used as a kind of conversion, also named recycling, that enables a largely temporary disposal of the (waste) material in products for which there hardly exists any real demand.

The first definition of recyclability implies that a recyclable material has a positive value for sustainability, as a raw material for products for which there is true demand. This evaluation principle is often used in Life Cycle Assessments (LCA) of a product's lifecycle impact. In LCA the "output" of a recyclable material (R in Figure 2), from one product life cycle to the next, can be assessed as a comparison to the avoided "load" of the alternative production activities (N+P) that otherwise would have been needed to acquire a material, with equivalent usefulness. Figure 2 shows a material system with closed-loop recycling (Karlsson, 1998 and Karlsson et.al. 2010). It should be noted that N and R are resources that have enabling values for sustainability and that P, C, U and W denote activities that cause environmental load. For some materials, e.g. aluminium, the recovered resource value of the recyclable material R is significantly higher than the resource value N of the resource from nature, which is used as virgin raw material (bauxite in the case of aluminium), because the environmental load from the re-melting of aluminium is very much lower than the load from the primary production of aluminium. The enhancement of the value level, from N to R, can be conceptualized as an investment of present environmental load that enable a lower environmental upgrading load in future production. In this perspective one basic prerequisite to justify a single loop of recycling is that the value of R is greater than (N + P - U) . When the same quantity of material can be recycled, i.e. reused, several times, this may enable a significant reduction of the total long-term load. A positive sustainability value for R means that the environmental load from the recycling based production is lower than the environmental load from alternative ways to produce an equivalent product.

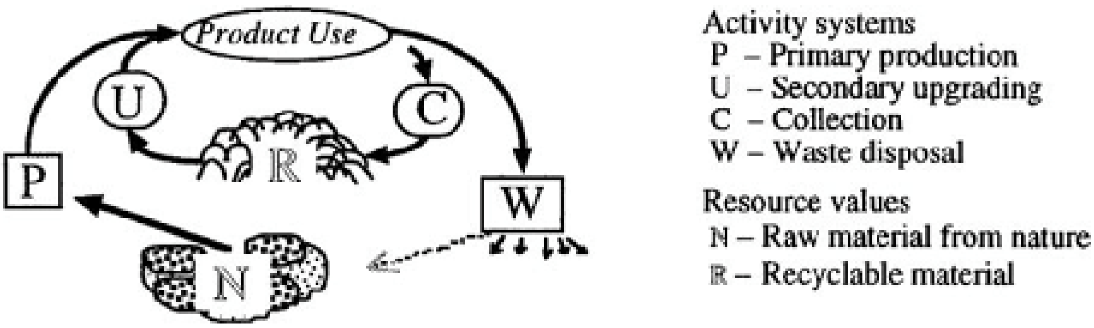

Figure 2 – *Flow diagram for a material market with closed loop recycling, in the basic case e.g. for a single material such as aluminium, when the environmental load for primary production is larger than the environmental load for secondary upgrading. From Karlsson (1998).*

The main message of Figure 2 is that the availability of material with positive recyclability value R is dependent on the choices made in relation to the primary production P and the procurement decisions needed to accomplish this production. In many cases there are cheaper alternatives to P and often the primary production results in materials that are worthless for recycling. One basic starting point for meaningful recycling is the choice of the primary production process including raw materials. Other aspects that have to be noted are (i) that R in Figure 2 describes a collected stock of recyclable material and (ii) that also the collection of products causes environmental loads. There is a principal difference between a potentially collectable recyclable material and a collected stock of material. From public policy point of view it is important to organise and promote the wanted collection system (C in Figure 2). If no such system exists, companies and customers will not invest in the product choices and production process developments that are necessary to build a societal stock of materials with positive recycling value R. The business development opportunities in relation to the build up of a circular economy are described in (Karlsson et al. 2016). The above description takes a starting point in the actual environmental load advantage of a specific case of recycling. However, the main political driver for recycling tends to be legislation and policies that state that certain product categories shall be recycled. This focuses on the societal collection of products and this is also a basic prerequisite to motivate companies to invest in recycling oriented product development.

The collection C is dependent on readily accessible infrastructure and broad awareness about the importance of proper disposal of the disused products. To enable this there is a need for some sort of financing and/or rules and regulation, either through recycling fees, extended producer responsibility and/or markets for the recycled materials.

The WEEE Directives (EU 2002/96/EC and WEEE II 2012/19/EU) states that the companies selling electronics are responsible for providing collection points. However, in the end it is the product user who has to bring the products to the collection site. Therefore, the customers and users have to be made aware and convinced that the recycling process of LED systems is working properly. When users consider products to be environmentally benign and relatively easy to sort, in other words products to be 'green', then it is more likely that the users will make the effort to bring it to the right 'recycling bin'. The statistics vary by European countries whether lighting products are brought to the recycling facility compared to other products (this is covered in more depth in section 4.6). Currently, it is unclear how much of the collected material is brought back into production of new products, and recycling knowledge has to be acquired.

To make recycling worthwhile the product must contain materials that are worth recycling. The incandescent bulb had a relatively simple design with reasonably common materials and it was easy to imagine how it could be taken apart and how the materials could be circulated in closed loops. Standardization of LED modules can enhance the value for reuse.
In addition to the materials themselves, the product value for recycling is related to the modularity of the products, the possibility to dismantle the products and the efficiency of the recycling process.

2.3 Non-replaceable LEDs

One serious environmental concern is that numerous LED luminaries have non-replaceable LEDs. When some of the LEDs or some components of the driver circuitry in such luminaires fail, the whole luminaire could be scrapped. Would this happen after a short usage time, quite a lot of material would be wasted causing an environmental and waste management problem. Non-replaceble LEDs are a recycling challenge and a life cycle cost (LCC) consideration.

There are two approaches to minimize this problem:

- To only allow and procure high quality products, where all the components and the whole product are guaranteed to have sufficiently long life-time;
- To aim for modularization that enables meaningful recycling of different parts, i.e. different materials and different kinds of component blocks.

Today's luminaires are not designed to easily take out the valuable materials, although it is important to aim for this from an environmental point of view. The perceived value of the materials can stimulate the modularization aspect in the product design phase. However, the scarce materials are only a minor part of the diodes, which already are small in comparison to the luminaire material, making it more difficult to see the benefits of collecting the materials.
The long life of LEDs opens up opportunities beyond material recycling and reuse. For example, LED components could be reused, upgraded or repurposed. Reusing whole products or parts avoids the need to shred products to recover materials, which can preserve more of the value (King et al. 2006).

Luminaires with non-replaceable LEDs are a challenge for reuse and extending the life of the product. Luminaires in general are also problematic for recycling at the moment. Even if the LEDs can be removed, they often aren't by the consumer at the end of life.

The recycling challenge with non-recyclable LEDs is a crucial environmental aspect. Luminaires with non-replaceable LEDs are a challenge for reuse and extending the life of the product. Luminaires in general are also problematic for recycling at the moment. Even if the LEDs can be removed, they often aren't by the consumer at the end of life.

But, on the other hand, it should be noted that there are large potential user advantages with the highly optimized lighting that is enabled by specialized LED luminaries. There is great potential for innovative lighting design, functionality, and energy effectiveness and minimisation of light pollution. A mini spot allows you to direct the light so that it illuminates just what you want to illuminate, e.g. a lot of light when trying to get a thread through a needle's eye. The user value and energy effectiveness of optimized LED luminaries can be extremely high, far beyond that of the E27 replacement bulbs.

2.4 From product ownership to access

A circular economy is a driver for innovation in the areas of material, component and product reuse through new solutions, services and business models. Topics seen as challenges, such as toxicity levels in different materials or landfills can trigger and inspire new innovative designs. Future-oriented companies respond to such challenges with innovation helping them to lead the market and in turn contribute to sharpened, new legislation improving the rest of the market. A more effective use of materials enables more value creation, through cost savings and growth of new and existing markets.

We have already seen the emergence of a different type of consumer who is more driven by access and performance of products than ownership. Consumers are looking for online interaction and relationships with brands that go far beyond the transactional ones, e.g. via Facebook, YouTube, Twitter and brand websites. Consumers can convey their ideas through online platforms. This phenomenon is known as 'collaborative consumption', the sharing economy or access based consumption. The sharing economy is referred to quite often in the popular business press such as The Economist, Forbes, Harvard Business Review and New York Times (Satama 2014). The level of consumer involvement and anonymity influences the relationship and the regulation of the relationship. Consumer co-creation is higher in more involved contexts, where the customers are expected to service the equipment themselves. More intense involvement intensifies the relationship with the utilized products and those possessions will influence the so called 'extended self' of the consumers. However, when the whole business model relies on the customers participating in the co-creation of value, more governance is also required (Belk 1988).

SUSTAINABLE SOCIAL DEVELOPMENT

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> "Reducing health inequalities is an ethical imperative. Social injustice is killing people on a grand scale."
> **(WHO Commission on Social Determinants of Health, 2008)**

Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity (WHO 1946). Health should be at the centre of all societal planning because social inequalities in health are costly to the society and counteract sustainable development (Malmö stad 2013). It is one of the main conditions for individual development opportunities through education, work, social relationships and participation in the society (UN 1949). Health is a key to the other human rights and also constitutes a separate right (WHO 2008).

One common social ambition is to provide international aid in the form of manufactured goods (principally food, clothing, and occasionally reconstruction aid) to impoverished or disaster-stricken regions. But the alleviation of immediate problems does not help the community to build its own functioning social structure and is per definition not sustainable (Henderson 2008). Another social concern is to ensure decent working conditions for the (often third world) people who work in mines, fields and industries enabling the production of goods for the wealthy – often considered to be a Corporate Social Responsibility (CSR). The quality of lighting is one aspect of the work conditions: quality lighting can reduce the risk of accidents and also promote productivity, wellbeing and health.

It is also an important social concern for every family to have at least some economically and environmentally reasonable lighting, so that e.g. the children get a possibility to do their homework in the evening, to be able to clean up whenever that is needed, to reduce various kinds of health risks. It is crucial to alleviate poverty (Ravallion 1992) and to evaluate social consequences of various living environments (Göteborgs stad 2011).
One application that provides great social benefits in non-electrified areas is solar powered battery equipped LED lamps. These kinds of solutions facilitate rapid societal development and enable effective use of energy and resources.

> "The lights will be very useful so I can study more. There are lots of problems with electricity here. Recently there was no power for two or three days. If we have lamps we can work at night. I will have more time to study."
> **(Anamika, female pupil, state of Uttar Pradesh)**

Companies are providing LED lamps to UNICEF to light up the lives of children who may not have access to electricity. For example, Ikea has provided one solar powered battery equipped LED lamp for each lamp sold in its stores worldwide. UNICEF is distributing these lamps to schools and women's literacy groups in states in India (UNICEF 2016).

3.1 Social management standards

The standards for Social Responsibility (ISO 26000) and Occupational Health and Safety Management (BS OHSAS 18001) focus on the basic importance of accountable and transparent management principles. The basic environmental management standard ISO 14000 provides tools for companies and organizations of all kinds to manage their environmental responsibilities. One basic principle is to aim for evidence based design, preferably with a scientific foundation. However these standards also suggest that it is imperative to be open minded and to take early action to enhance the learning when something significant is happening or starting to change.

In 2010 ISO (the International Organization for Standardization) launched an international standard that provide guidelines for social responsibility, ISO 26000 (see also Singh 2005). The goal is to encourage businesses and other organizations to improve impacts on their workers, the natural environments and their communities. ISO 26000 contain Seven Key Principles for socially responsible behaviour: Accountability (defined as "being answerable for decisions and activities to the organization's governing bodies, legal authorities and, more broadly, its stakeholders"), Transparency (defined as "openness about decisions and activities that affect society, the economy and the environment, and willingness to communicate these in a clear, accurate, timely, honest and complete manner"), Ethical behaviour, Respect for stakeholder interests (individuals or groups affected by or that have the ability to impact the organizations actions), Respect for the rule of law, Respect for international norms of behaviour and Respect for human rights (ISO 2010).

BS OHSAS 18001 is an internationally applied British Standard that describes the requirements for an occupational health and safety management system (OHSMS). The standard requires that a company or organization establish, document, implement and continually improve their occupational health and safety management system. ISO is working on the Draft International Standard (DIS) of ISO 45001, the world's first international occupational health and safety standard, which should replace BS OHSAS 18001.

3.2 Hazardous Materials

Although LEDs have major advantages, such as better luminous efficacy, longevity, and zero mercury content, there are studies that reveal a potential toxicity in particular in the manufacturing and end-of-life phase (Tuenge et al. 2013, Lim et al. 2013, Thema 2010). Some materials used for LEDs are considered as hazardous materials, which creates the need for special handling. In Europe, LEDs are therefore regulated under the WEEE legislation and need special treatment. Both CFL and LED have a higher toxicity potential than incandescent lights because they contain substances such as antimony, copper, lead and/or zinc. CFL's and LED bulbs both exceed US thresholds for antimony, copper and zinc and thus should be treated as hazardous waste similar to other electronic devices (Tuenge et al. 2013). The plastic materials also contain flame retardants (Thema et al. 2010, Tange et al. 2012, Dawson and Landry 2007).

Doping elements in SSL such as indium and gallium occurring in a metallic stage are non-toxic. Other chemical compounds may have health impacts. Gallium phosphide, for instance, can cause serious skin, eye and respiratory irritations (Hazard Statement [H] 319, H335, H315 in CLP regulation[1]). Indium- and Gallium arsenide, as they contain arsenic, are harmful if inhaled or swallowed (H331, H301) and is a long-term toxic to aquatic life (H410).

As with other e-Waste, SSL contains hazardous materials and therefore contribute to detrimental

[1] Regulation (EC) No 1272/2014 on the classification, labelling and packaging of substances and mixtures.

environmental impacts mainly in terms of ecotoxicity potential and human toxicity potential (Lim et al. 2013). Although some substances are listed as hazardous materials, they must be released before they can provoke negative health and environmental impacts, i.e. due to:

- release during production and manufacturing stage;
- release during use phase;
- release if the products end up in waste incineration;
- leakage from waste dumps after landfilling or illegal dumping.

With regard to the release potential, it should be understood, that no mercury is used in LED lighting as opposed to fluorescent lighting. The release of hazardous substances during SSL manufacturing could occur as concentrations of handled materials are higher than embedded in the products. However, a variety of occupational health and safety measures mitigate this risk. Impacts to human health during the use phase are almost impossible, as the toxins appear in solid and encapsulated form and the fracture risk of LED bulbs is, in contrast to CFLs, relatively small. Leakage from waste dumps can be avoided by special handling, waste treatment, and recycling. It is state-of-the-art in most European countries that such waste fractions are not disposed at waste dumps anymore. Instead, recycling and incineration are applied (Wiles 1996, van der Sloot et al, 2001, Sabbas et al. 2003). Melting technologies are available to stabilize incinerator residues, bottom ash and fly ash in order to make them non-toxic.

Special provisions have therefore to be made for end-of-life management, treatment, and disposal LED and e-Waste in general. In Europe LED are therefore considered under the WEEE directive and other environmental regulations. Major producers such as Osram, Philips and Cree disclose their LED products as being compliant with RoHS and REACH legislation, which is again a major benefit compared to fluorescent lighting that require exemptions for the mercury (Thema 2010).

The RoHS-Directive (2002/95/EC, 2011/65/EC) restricts the use of certain hazardous substances in electrical and electronic equipment in order to preserve the environment and occupational health as well as to improve recycling possibilities. The relevant substances are lead, cadmium, mercury, hexavalent chromium and the flame retardants PBB und PBDE. The RoHS-Directive is relevant to SSL systems because it promotes lead-free soldering.

3.3 Light for health and wellbeing

In the SSL-erate 'Lighting for health and wellbeing' report (Schlangen et al 2014) it was concluded that "light affects our well-being and health much more than most people realize." Light regulates our sleep-wake cycle, immune responses, appetite and many more of our functions and behaviours. Light also has acute effects on mood, alertness and attention that do not run via the 24 hour circadian body clock.

The SSL-erate literature compilation on non-visual lighting effects indicates that in-door lighting is more vital for health and wellbeing than out-door lighting. However most of the public interest in lighting design so far has focused on outdoor lighting. Consequently there is more innovation-oriented user knowledge regarding outdoor lighting.

3.3.1 OUTDOOR LIGHTING

One important aspect in urban lighting is its effect on safety and the normal approach has been to specify the minimum amount of light that is needed to enable good vision, e.g. for motorists to see enough in dark surroundings. This is indeed an important aspect but it is also important to recognise the difference between feeling safe and actually being safe. Our sense of safety affects our perception of the environment, our propensity to go out and therefore it also affects our wellbeing.

A group of innovative lighting designers are shifting their interests from the architectural layer of the city to the social and experiential layer (Uk Kim, Sung-O Cho 2009). Studies on sustainable social lighting have shown that people desire a more meaningful use of interactive and colourful-layered lighting effects. The current SSL technology enables temporal, spatial and spectral control of our light environment, and provides great opportunity to realize non-visual benefits and enhance visual comfort by means of highly innovative solutions. Lighting is primarily intended for peoples' experience and perception of the urban space. The urban design literature stresses the need for public spaces that enable social interaction for social and psychological health. The new urban lighting can shape the identity of the city, it can increase the attractiveness of the city, simplify the navigation in the city, support the collective and interactive use of the city, reinforce the trust relationship between individuals, improve orientation, create interest and separate the important details from the unimportant ones (Boyce 2003).

3.3.2 INDOOR LIGHTING

The most broadly recognized social sustainability priority of indoor lighting is to directly reduce health risks. But it is even more fundamental to promote such developments by making proper investments in physical facilities so that the ability to reduce future risks is enhanced. Indoor lighting in public buildings is an important area that so far has been rather neglected by lighting professionals. Most people in modern societies spend the majority of their time indoors and indoor lighting is vital for health and well-being. The quality and needs adapted-variation of the lighting is one aspect that influences the effectiveness of work places, health care facilities and schools. Lighting designers also know that the character of the light influence many kinds of human experiences and interactions.

3.3.2.1 Work places

Exposure to intense light at work may boost employees' feelings of alertness and vitality and the light variations during the day also affect sleep during the subsequent night. The intensity and light spectrum can influence the employees' ability to sustain attention and performance at work. The light settings are important to the employees' appraisal of the lighting and working environment, but the individuals' preferred light settings vary quite a lot.

Light during night shifts can reduce melatonin secretion and affect the timing of sleep. Shift work can be made more attractive and absenteeism can be reduced (Schlangen et al. 2014).

3.3.2.2 Education

The city of Malmö has installed dynamic lighting in a classroom. The installation includes an automatic variation of the light intensity and colour temperature. The main ingredients of the automatic light variation scheme are: a dose of bluish activating light in the morning, limitation of the strong activating light to 30 minutes, concentration supporting (more red) light after lunch, limitation of the amount of light to avoid stress and avoidance of all rapid changes of the light. The automatic light variation scheme is complemented with manual control buttons to give the teachers a toolbox to adapt the light to the educational situation. One manual control choice is awakening or stimulating light when the pupils are tired. Another choice is to provide a restful light atmosphere, e.g. when reading together with young pupils. The studies indicate that when one light setting has been selected the teachers tend to leave it in that position. The observations also indicate that it is unsuitable to have the activating light on during a large part of the day, because then some pupils tend to get a headache. Consequently there is a need for automatic variation of the light (Karlsson 2015).

In Sweden the lowest recommended intensity in the classroom is 300 lux at the desk, wall lighting minimum 75 lux, ceiling lighting 50 lux and a cylindrical illumination of 150 lux. The colour rendition should be at least Ra 80. It should also be possible to adjust the lighting. Many different activities are performed in the classroom: reading, writing, presentations, school plays, tests, and more. A flexible lighting solution should be able to support all the different activities (Ljuskultur 2010). User adapted variations of context dependent lighting can create more stimulating as well as more relaxing conditions. It is important to promote productivity and reduce stress particularly for children in preschools and classrooms.

One promising application field of dynamic lighting is children with special needs; autism, hyperactivity etc. The lighting can generate a significant branding value for a company marketing themselves as caring for sensitive individuals (social entrepreneurship).

Generally speaking, schools are major consumers of energy, but they also can use resources efficiently and serve as models for environmental sustainability in their communities. More importantly, they have the ability to teach the next generation and communities of families by example. One vital aspect is to build awareness about the importance of light adapted for health and wellbeing. Schools are strategic actors in the drive to transform the worlds' working and living environments and the energy and resource consumption from a destructive model towards a more sustainable pattern of development.

3.3.2.3 Healthcare and nursing homes

Patients and elderly may have to cope with immobility, injuries, pathologies and age-related degeneration of tissue and then require higher quality and more light. Daytime exposure to light with sufficient intensity throughout the day can help the elderly to adapt their circadian rhythms to the natural day-night cycle and for patients in hospitals act as an antidepressant. The visibility for surgeons can be improved, anxiety can be reduced and the recovery time of patients can be decreased. Improved visibility and colour temperature adaption can improve wellbeing, help reduce the need for medication and prevent falling accidents by highlighting risk areas, which is a major concern for elderly people.

3.3.2.4 Domestic applications

Blue-enriched light from TV sets, computers and tablets in the evening and early night results in more alert responses and a phase delay of the circadian clock which may disturb the sleep-wake pattern. It is especially older people exposed to higher light levels in the evening who have a higher risk for insomnia. It is now possible to install a program, e.g. on the computer, that adjusts the light from the screen to the time of the day. The light becomes increasingly red, the kind of light that does not break down melatonin, as the evening hours go by. Dawn simulating light at home in the early morning also has a positive effect on sleeping disorders, well-being and cognitive performance during the day.

It has become a Societal Social Responsibility to take action to make use of the new knowledge to alleviate negative effects of inappropriate lighting and to promote the use of high quality lighting needed for the quality of future life.

3.4 Light pollution

One of the defining characteristics of life in the modern world is the altered patterns of light and darkness in the built environment by the use of electric power. Artificial light has benefited society by, for instance, extending the length of the productive day, offering more time for working and for recreational activities. But when artificial outdoor lighting becomes inefficient, annoying, and unnecessary, it is known as light pollution.

Much of the outdoor lighting used at night is inefficient, overly bright, poorly targeted, improperly shielded and often, completely unnecessary (LRC 2007). Light that is emitted directly upward by luminaires or reflected from the ground is scattered by dust and gas molecules in the atmosphere, producing a luminous background. Stray light, e.g. from street- lights, enters windows and illuminates indoor areas (LRC 2007). To limit this pollution several effective practices can be applied: (i) use shielding on lighting fixtures to prevent direct upward light, (ii) avoid using higher lighting levels than strictly needed for the task, (iii) constrain illumination to the area where it is needed and the time it is useful (Falchi et al 2011).

3.4.1 CONSEQUENCES FOR MAN AND NATURE

Light pollution is a risk factor for biodiversity, which is a main sustainability priority.
The illumination that is not for the benefit of mankind and that sometimes, especially at night, can have serious consequences for the health and well-being, is also a waste of energy. The International Dark Sky Association, started by astronomers, promote the ability to see the stars as an important quality of human experience (Bogard 2013).

Many species, especially humans are dependent on circadian rhythms and the production of melatonin, which are regulated by light and darkness variations: The body produces melatonin at night, and melatonin levels drop quickly in the presence of blue light. When humans are exposed to light before sleeping, melatonin suppression can occur which has been linked to insomnia, stress, and increased risk for a wide range of medical maladies and even cancer (Falchi et al 2016). It has been shown that women living in neighbourhoods where it was bright enough to read a book outside at midnight had a 73% higher risk of developing breast cancer than those residing in areas with the least outdoor night-time lighting (Chepesius 2009).

Light pollution can as well have negative impacts on plant and animal physiology, confuse migratory patterns of animals, alter competitive interactions of animals, change predator-prey relations and cause physiological harm.

Sea turtles provide a dramatic example of how artificial light on beaches can disrupt behaviour. Many species of sea turtles lay their eggs on beaches, and the females return for decades to the beaches where they were born to nest but when these beaches are brightly lit at night, females may be discouraged from nesting in them. They can also be disoriented by lights and wander onto nearby roadways, risking to be struck by vehicles. (Chepesius 2009, Gaston et al. 2012.)

Bright electric lights can also disrupt the behaviour of birds. About 200 species of birds fly their migration patterns at night over North America, and especially during inclement weather with low cloud cover, they are confused during the passage by brightly lit buildings, communication towers, and other structures.

The extent to which artificial light influences any of these processes depends on several factors: the wavelengths of the light emitted with respect to the spectral sensitivity pigments and/or visual receptors, the intensity of light that reaches the organism and the directionality of the light.

A lot of concern has been expressed about the ecological consequences of night-time light pollution and most attention has been focused on the encroachment of artificial light into previously unlit areas of the night-time environment. Maintaining and increasing natural unlit areas is likely the most effective option for reducing the ecological effects of lighting. Other methods to reduce night-time light pollution are to reduce the 'trespassing' of lighting into areas that are not intended to be lit, change the intensity of lighting; change the spectral composition of lighting and to limit the duration of lighting.

To decrease the duration of lighting is also an efficient way to reduce energy costs and carbon emissions. However, this will only alleviate some impacts on nocturnal and crepuscular animals, as peak times of demand for lighting frequently coincide with those in the activities of these species. In large areas with intense night-time illumination it is important to provide dark refuges that mobile animals can exploit. The reduction of the intensity of lighting will reduce energy consumption and limit general brightness – skyglow – as well as the area directly impacted by high-intensity light.

Horizontal and near-horizontal light emittance increases the visibility of light sources from a distance which increases the illuminated area and the potential to disrupt animal navigation. Such lighting also increases the risk for glare significantly. Glare can be disabling or simply uncomfortable, and the sensitivity to glare can vary widely but normally increases with age Due to the long path lengths of near-horizontal light through the atmosphere, such light also produces more skyglow than light emitted upward, and a lot more than light emitted downward.

3.4.2 LIGHT POLLUTION SOURCES

Light pollution is a rapidly increasing form of environmental decline. According to the 2016 "World Atlas of Artificial Night Sky Brightness," 80 percent of the world's population lives under skyglow. 99 percent of the people in the United States and Europe can't experience a natural night. Many people don't know about light pollution or don't understand the negative impacts of artificial light at night (Falchi et al 2016).

A wide variety of lighting devices contribute to night-time light pollution, e.g. public street-lighting, light from advertising, architecture, domestic sources and vehicles. Street-lighting is a major concern as it is often the most persistent, aggregated and intense source of lighting in urban areas.

> "Badly designed street-lighting, which is probably eighty percent of street-lighting, are glare sources. That is, they actually reduce the contrast of things you're trying to see rather than increase it, because of this disability glare problem that occurs due to scatter in the eye."
> **(Bogard 2013).**

In recent decades there have been changes in the street-lighting (and other lighting). Narrow spectrum light sources such as low-pressure sodium (LPS) and high-pressure sodium (HPS) lamps, which emit primarily yellow or amber light, have been replaced by broader spectrum 'white' sources that enable better colour rendering for human vision. Changes in the wavelengths of the light will affect the intensity of, and the area impacted by, skyglow. Due to increased atmospheric Rayleigh scattering at short wavelengths, blue-rich light sources produce more skyglow in the vicinity of light sources than an equivalent intensity of yellow-rich lighting. However, beyond around 10 km from the light source this order is reversed and long wavelengths produce more skyglow.

Flexible control systems may be a useful tool for mitigating harmful impacts of light by providing dark periods sufficient for normal human and ecological function. LED lamps are particularly suited to operating at variable brightness and/or being switched off at times of low demand, as they operate at full efficiency with no 'warm-up' time. However, it is important to take into account that rapid changes in light can be a risk factor for human health and wellbeing. Technological developments in LED lighting systems also present significant opportunities for greater control of the light environment in terms of the wavelengths emitted, timing and intensity. If coupled with an increased understanding of the human and ecological impacts of light pollution, there is considerable potential to mitigate many adverse effects (Gaston et al 2012).

Light pollution, ineffective light design, glare and waste of energy are correlated. Darkness has significant positive qualities. A lot of light is not the same as good illumination.
That stronger outdoor lighting always provides a safer society is also a common misconception. There are two groups that have large business interests in that we use a lot of light during the night, the ones that sell electricity and the ones that sell lighting.

> "At night, when energy consumption falls, energy companies have no way to replace this demand, so they encourage our use of electric lights."
> **(Bogard 2013.)**

3.5 The right light in the right place

The Swedish Energy Agency and other organisations have demonstrated that there are quality LED products on the market (Swedish Energy Agency, et al. 2015), but it is difficult for the normal consumer to sort out the quality products and to find the right product for the right circumstance. One aspect of this problem is that people in general have a low knowledge about light measurement numbers like CRI (Colour Rendering Index) and CCT (Correlated Colour Temperature). Although various manufacturers specify the same CCT, there may be experience differences between brands of LED lighting. CT for LEDs may also change over time.

Another aspect is that the appearance and the perception of the lighting is very much dependent on the colour and texture of the surfaces of the objects in the room. Light and materials are inseparably connected; neither is visible to the human eye until the two come together. Light can be used to draw out contrasts between different materials and the choices of materials influence the ambience in a room. A change of materials can change the feeling of a room and also the level of illumination. The dynamic changes in the light can be made more or less visible depending on the materials in the room (Zambonini 1988). The control of the light is about how the change happens, the degree of impact and the manner in which it takes place. The light can be controlled either by an automatic time schedule, by human presence via sensors and via a user interface allowing people consciously to influence the light settings.

Demonstration facilities in department stores should be available for consumers to be able to test the actual atmosphere that is created by different light sources in different environments, e.g. to motivate people to overcome old habits (Venkatesh et al. 2012). The ability to experience products in full-scale environments provides greater knowledge among consumers and a greater chance that the customers will be satisfied with their choices. More satisfied customers create a basis for consumer trust, which ultimately benefits the reputation and sales of high quality LED products.

3.6 Interrelations between various aspects

There is a broad consensus that social sustainability is an important dimension of sustainable development, but 'Social Sustainability' has no generally accepted definition and different actors use this concept in different ways. Often it is seen more like a vague feel-good concept in the early stages of development than as a specific marker that is being measured and evaluated (Fitzpatrick 2014). Various attempts have been made to define and quantify social sustainability. Indicator systems have been developed to measure, among other things prosperity and development, which can approximate social sustainability. A disadvantage of using metrics and indicators to define sustainability, however, is that they only can consider the addressed, quantifiable aspects. The qualitative aspects are rarely mentioned and thus made invisible (UNECE/Eurostat/OECD 2013).

The links between social sciences and urban planning today is completely different than in the 1960s. Today there is much social science research that is very sceptical of quantitative scientific methods. Qualitative research can build a completely different depth of understanding, but subordinated to the construction industry's economic calculations and technical hard facts qualitative analyses tend to be overlooked in the actual decision-making (Boverket 2010).

3.7 Conclusions on social development

One lighting aspect that tends to be neglected is how the traditional lighting influences our health and wellbeing. For example, the old static lighting cannot provide an awakening effect as natural light does and LED lighting can. LED lighting enables many ways to provide lighting effects giving better guidance and reducing risks. The flexibility to vary the light is much more limited for the old lighting technologies. This is significant, because our sensory vision system is adapted to the light in nature where light varies in very many ways. Intelligent user adaption of SSL-based lighting is becoming a significant tool for social sustainability.

Now that we know that light has a powerful influence on our health and wellbeing it is a Societal Social Responsibility (SSR) to take action to improve the working and living environments in preschools, schools, office, hospitals, for the elderly and in the traffic. Municipalities should enhance the application of SSL in municipal properties, public spaces and street-lighting, not least because municipalities should act as role model.

SUSTAINABLE ENVIRONMENTAL DEVELOPMENT

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4 | SUSTAINABLE ENVIRONMENTAL DEVELOPMENT

The environmental dimension of sustainable development presently focuses on global warming and thereby on energy "consumption" and the associated CO_2 emission (Rockström et al. 2009, Steffen et al. 2015). This relates to the current use of non-renewable fuels, e.g. for electricity for lighting and also for production of materials and products. The long-term survival is also dependent on the availability of raw material resources.

When we use and misplace scarce materials, in a non-circular way, without recycling, two kinds of effects can occur:

1. It gradually becomes more and more difficult to find and extract the material from nature, and to upgrade it to useful form. This results in a growing need for more energy;
2. There is a risk for toxic effects and ecological disturbances, in particular when scarce materials are distributed in nature.

Two other environmental resources, essential for sustainability, are (access to) productive land and earth's biodiversity.

Green land areas are fundamental for life on earth and also for the absorption of the various materials that are distributed in nature. Living organisms break down numerous organic materials and some elementary materials are gradually brought back to new mineralization. There is a risk of bioaccumulation, but the alternative is that several substances accumulate in the atmosphere.

Biodiversity, a contraction of "biological" and "diversity", is a measure for the variety of organisms living in the different ecosystems on earth. It is essential that we preserve a sufficient amount of naturally resilient eco-systems, i.e. ecosystems with an inherent ability to recover after various disturbances.

Sustainable development is related to the ecological footprint, both are affected by human activities. In Section 3.4 an example of human influence on large land areas is given, i.e. light pollution.
This chapter focuses on materials and energy in the change from traditional lighting products to LED products. Topics of particular interest are the potential energy savings in the use phase, the use of hazardous substances, the demand in scarce resources and the end-of-life stage, including take-back and recycling. The main environmental driver is the electricity consumption in the use phase and the significant energy savings that can be achieved.

The environmental impacts discussed in this chapter are related to:

- Upstream processes, i.e. mining and processing of critical materials in SSL, (rare earth elements (REE));
- Manufacturing processes of LED lighting systems;
- Downstream processes, in particular: electricity consumption in the use phase;
- End-of-life and recycling of the systems;
- Dissipated/diluted stream of valuable metals and REEs;
- Hazardous materials.

Like most electronics, some materials used in the production of LED are considered hazardous materials, which create the need for special handling. In Europe, LEDs are therefore regulated under WEEE legislation. As the hazardous substances are solid and encapsulated in the LED luminaries

or lamps, the risk of release and uptake by humans during the use phase is very small, even when the lamps break. This is a benefit compared to CFL, which contain mercury (though in so low concentrations that the danger from release and uptake during use is also small).
Scarcity of certain resources remains a problem for many new technologies. For SSL a supply risk in the long term is not anticipated due to decreased amounts needed (compared to fluorescent technology) and increased availability of alternative supply routes (e.g. new mines). Most research has been directed at the recycling opportunities of fluorescent lamps. The rapid development of SSL technology, with longer lifespans and the resulting very small amount of waste streams presently, means that there are still some unknown factors about how they can be best dealt with at the end-of-life. It is known that the extraction of materials for LEDs, in particular aluminium, precious metals and rare earths can cause significant environmental burdens. Therefore recycling of lamps is desired in order to conserve resources and to limit the environmental and social impact of new resource extraction and processing.

The overall environmental impact from the production and end-of-life phase as well as other life cycle phases such as transport and packaging are rather low compared to the use phase, which dominates the impact of SSL over its lifecycle because of the electricity consumed. A summary of environmental impacts is given in the following illustration (see Figure 3).

4.1 Ecological and Environmental Footprint

The Ecological Footprint is a measure of consumption defined as the amount of biological services provided by the earth and consumed by humans per unit time. The concept was introduced by Rees (1992) and Wackernagel (1994).

In order to assess and calculate footprints for various categories of products (so-called Product Environmental Footprints) the LCA methodology is often used, as described further down in this Section and in Section 4.2.

The following analogy might help to clarify the concept ‘Ecological Footprint’:
A biologically productive land area can be considered to be a capital stock (i.e., a bank account). The capacity of that productive area to generate an on-going supply of renewable resources and to absorb its spillover wastes, the so-called biocapacity, determines the revenue stream produced by that capital (i.e., interest received per month). The Ecological Footprint represents the continuous use of the revenue stream and/or of the capital stock (i.e., monthly payments / bank withdrawals).

Ecological Footprint and biocapacity are given the (area) unit of ‘global (productive) hectares’; a global hectare is defined as the (hypothetical) average productivity of all biologically productive areas (measured in hectares) on earth in a given year. It is unsustainable when the ecological Footprint of an area exceeds its biocapacity (Brown et al. 2014).

RAW MATERIALS	SUPPLIES	PRODUCTION	DISTRIBUTION & TRANSPORT
· Extraction & processing of metals, REE & other commodities	· Production of supplies, i.e. electronical components such as drivers, capacitors & PWB. · Hazardous substances, ozone depletion, water pollution & photochemical ozone creation	· Production & assembly with related electricity consumption for LED die, package & luminaire. · Use of rare earth materials, metals, minerals (alumina) & cleaning chemicals	· Storage, transport of raw materials, upgraded materials, components, complete products, maintenance, reuse & recycling. · Rather marginal impacts due to transport fuels, distribution & packaging. · Transport to/from end user
INSTALLATION & MAINTENANCE	**USE PHASE**	**END-OF-LIFE**	**RECYCLING**
· Installation & maintenance of products & compounds. · Rather marginal impacts due to electricity consumption.	· Major environmental impacts due to electricity consumption, mainly GHG emissions from combustion of fossil energy carriers. · Reduced energy consumption compared to other lighting alternatives.	· Leaching of hazardous substances from landfills. · Marginal other effects.	· Upgrading (pre-treatment) for recycling. · Very low recycling rates expected. · Technologies for recovery available. · Marginal other effects.
ENVIRONMENTAL IMPACTS Environmental impacts related to raw (earth) metal extraction & processing and processing of supplies.		**ENVIRONMENTAL BENEFITS** Reduced electricity consumption in use phase.	
FUNCTIONAL VALUE Value of light (luminous efficacy, light intensity, light quality, light character, light adaptability, spatial distribution & variation in time), maintainability, interoperability (integration for smart lighting systems), capability.			

Figure 3 – *Environmental Impacts of SSL over the entire Life Cycle.*

For populations (nations, cities, ..) and organizations 'global hectares' is the appropriate unit to indicate their Ecological Footprint, because these entities continuously consume from the biosphere. Products, however, are understood to once use biological services of a certain number of global hectares for a specified period of time. Product Footprints are thus calculated as the product of a flow of biological services and an amount of time, leading to the appropriate unit for a product Footprint of 'global hectare x years'.

The ecological footprint is a measure for the human influences on nature, e.g. extraction of natural resources, raw material and land area for energy supply and decrease of green areas due to human settlements and infrastructure. The resource demand is compared to the renewable production capacity of green, biologically productive land areas and their potential to absorb waste (biocapacity). EFP and biocapacity are difficult to assess and to measure (Rees and Wackernagel 1998).

Although the concept of the ecological footprint actually aims at comparing countries or regions, the term has been used in a more metaphorical way to stress environmental impacts of human activities, organisations and products. The European Commission's Joint Research Centre has undertaken efforts to develop the methodology of environmental footprints for organizations and products. The Product Environmental Footprint (PEF) is a multi-criteria measure of the environmental performance of a good or services over its life cycle. The PEF methodology is based on a life cycle approach, i.e. ISO 14001 and ISO 14040 standards for life cycle assessments are respected and harmonized (Manfredi et al. 2012). Hence, most of the aspects that are considered by the EFP are measured in accordance with LCA methodology.

The LED lighting aspect that is highly relevant and also reasonably measureable is the Carbon Footprint. The Carbon Footprint is an indication for the amount of carbon dioxide emitting as a resulting effect of an activity or an organization. The Carbon Footprint is often expressed as the amount (in tonnes) of carbon present in such emissions. The Ecological Carbon Footprint translated the amount of carbon dioxide into the area of productive land and sea required to sequester the carbon dioxide emissions.

The carbon footprint for SSL is normally smaller than for the old alternative technologies, because of the improved efficiency. The more advanced LED lighting enables lower emission of CO2, in particular when the LED lighting is controlled by a smart system that varies the lighting according to the actual needs.

4.2 Life Cycle Assessments

The findings presented here are based on a comprehensive literature review, first considering life cycle assessments (LCA) of LED systems (most often in comparative studies with CFL and incandescent lamps). Also other reports and studies on environmental impacts have been considered. Search terms that have been applied for the search in Scopus, ScienceDirect, SpringerLink and Google Scholar are: "[LED], [SSL] AND [sustainability, environmental impacts, environmental performance, life cycle assessment, LCA, environmental footprint]. The literature search returned more than 700 files. After a screening of the abstracts, about 280 files, i.e. academic papers, review, research reports, conference papers and book chapters, have been included in this study.

4.2.1 LIFE CYCLE ASSESSMENT METHODOLOGY

A Life Cycle Assessment is the compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle. LCA studies are typically carried out in compliance with the ISO 14040 and ISO 14044 standards in which the methodology framework is regulated. LCA is about collecting and analyzing quantified data related to extraction of resources from nature and emissions caused by required processes (e.g. emissions to e.g. air and water, waste generation and resource consumption). The whole life cycle is included in a cradle-to-grave approach, from extraction of raw materials through production and use to final disposal, including recycling, reuse, and energy recovery.

LCA is a relative approach based on a functional unit, to be chosen with the specific aim of the LCA in mind and specific to the system boundaries. The functional unit is a description of the quantified performance of a product system or its functional value[2]. The functional unit is used as a reference unit. This means that all environmental impacts, from materials, production, transport, energy use, handling and waste management, are related to this functional unit:

$$\frac{\text{Functional unit}}{\text{Environmental impact}}$$

The aim of the LCA and the choice of the functional unit is essential for the results (Klöppffer/Grahl 2014, Matthews et al. 2015, Curran 2015, Yabumoto et al. 2010, Tähkämö et al. 2014, Tähkämö et al. 2013). A number of different functional units have been used in LCA studies for SSL (Tähkämö et al. 2014). For example some studies take the duration of light delivery (e.g. between 10000 and 100000 hours), or the quantity of light, in terms of lumens over a certain time (e.g. between 1 and 20 megalumen-hour [Mlm hrs]). The use of different functional units makes direct comparison of studies difficult. As the most coherent and widely applicable functional unit is Mlm hrs, this is also taken as the reference base in this chapter. Table 1 gives the environmental impact categories usually considered in LCAs.

[2] ISO 14040 (ISO 2006)

Table 1: *Environmental Life Cycle Impact Categories*			
	Abbreviation	**Name**	**Indicator**
Air/climate	GWP	Global Warming Potential	Greenhouse gas emissions
	AP	Acidification Potential	Air pollution
	POCP	Photochemical Ozone Creation Potential	Air pollution
	ODP	Ozone Depleting Potential	Air pollution
	HTP	Human Toxicity Potential	Toxicity
Water	FAETP	Freshwater Eco-toxicity Potential	Water pollution
	MAETP	Marine Aquatic E co-toxicity Potential	Water pollution
	EP	Eutrophication Potential	Water pollution
Soil	LU	Land Use	Land Use
	EDP	Ecosystem Damage Potential	Biodiversity impacts
	TAETP	Terrestrial Eco-toxicity Potential	Soil degradation & contamination
Resource	ARD	Abiotic Resource Depletion	Resource depletion
	NHWL	Non-Hazardous Waste Landfilled	Hazardous waste
	RWL	Radioactive Waste Landfilled	Hazardous waste
	HWL	Hazardous Waste landfilled	Hazardous waste

See Appendix 1 for further information on the Life Cycle Assessment methodology and the assumptions used.

4.2.2 THE SSL PRODUCT SYSTEM IN A LIFE CYCLE PERSPECTIVE

When considering the life cycle of LEDs, different stages of the SSL value chain, such as the LED chip, packaged die, LED module, luminaire or lighting system (see Figure 4) and the different process stages, i.e. upstream and downstream, should be considered.

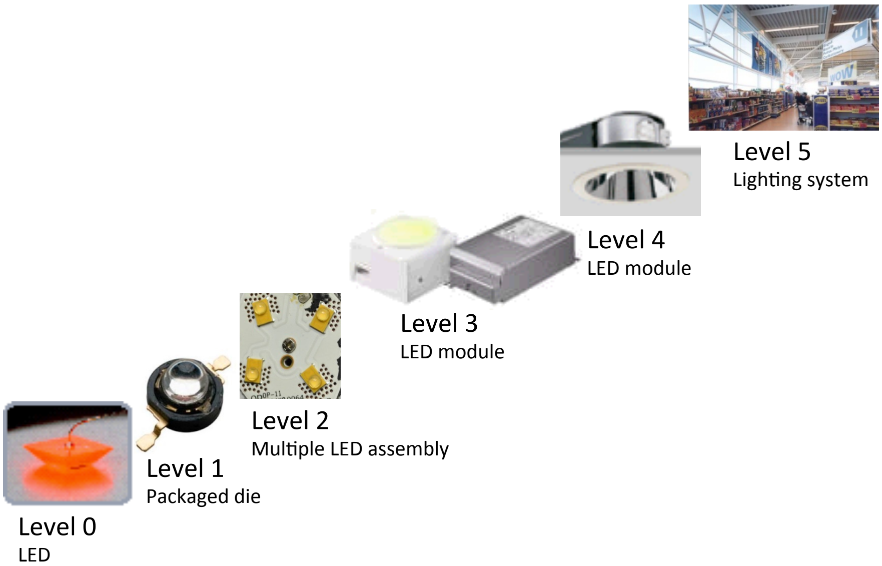

Figure 4 - *SSL value chain.*

Taking a life cycle approach for analysis means examining different stages of product life cycles, from extraction of raw materials, to manufacture and use of products, to end-of-life. These stages are shown in Figure 5. While LCAs consider all stages, not all stages have a large environmental impact for certain products. For example, the use stage tends to dominate the environmental impact profile for lighting while the impacts from transport are generally minimal by comparison. This chapter will therefore focus on the stages of LED life cycles with particular relevance.

4.2.3 SHORTCOMINGS OF LIFE CYCLE ASSESSMENT

The mainstream use of LCA is to focus on the summation of environmental loads and to use a rather simplistic functional unit. In most light source LCAs lumen-hours have been chosen as the functional unit. This may appear to be a clear definition of the functionality. However, the awareness grows about the significant differences in human effects caused by different kinds of light, i.e. different kinds of lighting. In an extreme case a few lumen can have a very positive value, in another extreme case some strong lighting might be negative, e.g. when it is both useless and glary. Moreover, lumen values focus on visibility and they are not representative for the blue light that we now know can have so strong human centric effects, positive in the morning and negative in the evening.

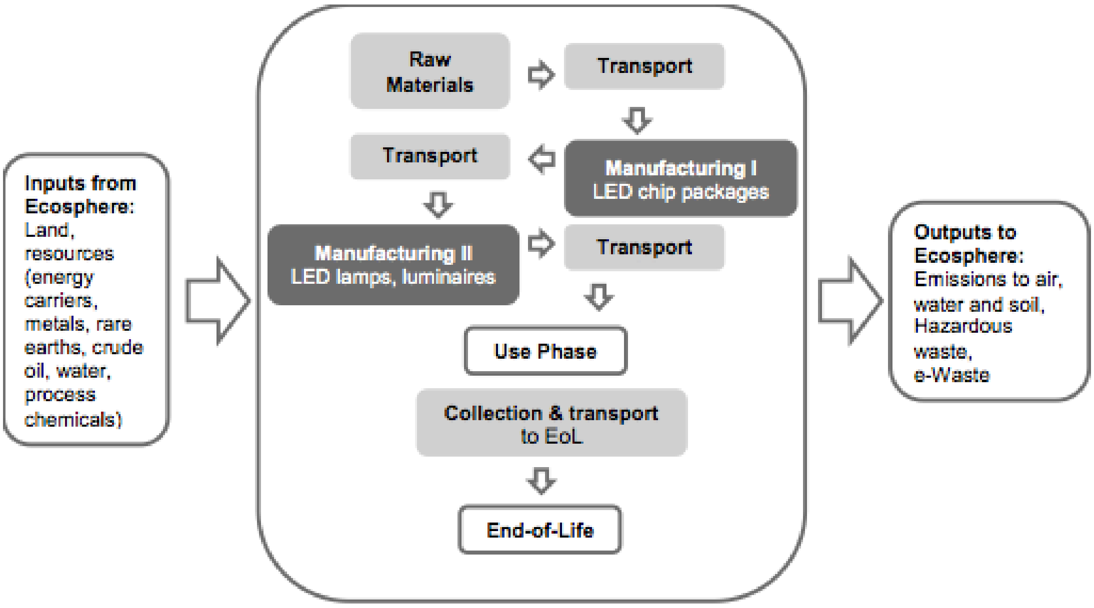

Figure 5 – *Life cycle of a SSL system.*

It is expected that the LED-ification, and the diffusion of intelligent lighting and human centric lighting systems, will introduce new properties with the potential to increase the quality of life in terms of reducing illnesses, accelerating recovery, making learning easier and improving wellbeing.

An important aspect of the user value is the life-time, or more correctly, the time that the installation is delivering appreciated light. When considering the Circular economy, repeated use through refurbishment and prolonged life-time are elements of an extended functionality of SSL. For that reason the following extended functional unit could be defined, i.e. the quotient between the total functional value and the environmental load:

$$\frac{\text{Value of light} + \text{Maintainability} + \text{Interoperability} + \text{Capability}}{\text{Primary and secondary material} + \text{Production} + \text{Transport} + \text{Energy} + \text{Handling}}$$

In addition to LCA the above quotient is inspired by the methodology for Cost Benefit Analysis. An optimization of the value creating abilities of the functions, activities and processes gives the customer the highest possible value and also possibilities to avoid the excessive use of energy and materials. The light has a direct impact on the health and well-being, i.e. an important aspect of social sustainability. Table 2 gives a more elaborate description of the functionalities in the numerator of the quotient. (In Section 2.1 more information regarding the denominator can be found.)

According to methodological conventions (ISO 14040 and ISO 14044) only primary functions, in this case the provision of light, should be included in the functional unit. The functional unit should be quantifiable in measureable terms, which is challenging for most of the aspects mentioned in Table 2. Additional functional aspects (regarding of the value of light) and supplementary functional aspects (i.e. recyclability) are not considered as reference in environmental life cycle assessment (Fleischer and Hake 2002). It is important to understand, however, that SSL provides a much broader functional value than merely the provision of light as measured by total lumen values. Therefore, besides the environmental benefit regarding energy savings, other sustainability aspects, mainly in

Table 2: *Description of the total functional value of SSL in addition to the value usually considered in LCA studies.*	
Value of light	...includes the user value enabled by the installation: • light intensity • light character • light quality • spatial distribution • temporal variation The actual value of the light supply potential is also dependent on the user interface functionality, i.e. the users' possibility to control the lighting.
Maintainability	...is important for the maintenance cost and also influences dependability and upgradeability, e.g. by support functions for supervision, maintenance and recycling.
Interoperability	... describes the openness for integration with other systems and also the value of the lighting system infrastructure and sensors in a smart city and smart building management functions, e.g. for communication, energy management, presence control and traffic supervision.
Capability	... describes the prospective build-up of innovation potential, e.g. by investment in early demonstrations and experimental installations, which promote development of renewal oriented competence and networks.

In summary, LCA is a good tool for highlighting some of the advantages that the LED technology provides in the environmental impact area, compared to conventional lighting. It also provides information on some of the areas where LED lighting has an impact and where efforts should be made to reduce these. It should, however, be kept in mind that the present use of LCA does not consider all the valuable functions and aims of Human Centric Lighting.

The LCA-inspired quotient above is an endeavour to clarify the relation between the various SSL-related sustainable development concerns. One aim is to clarify how the combination of these priorities ought to be conceptualised in relation to policy-making, procurement and the economic calculations and decision-making in the construction industry. However, the quotient is difficult to use in quantitative calculations. The main usefulness is as a conceptual framing for qualitative assessments.

4.3 Material Extraction and Resource Scarcity

Metals such as arsenic, gallium, indium, and some other rare-earth elements (REEs), in particular cerium, europium, gadolinium, lanthanum, terbium, and yttrium that are used in LED semiconductor technology are considered as scarce (Noël, 1989; Wittmer et al., 2011). Gallium is especially relevant for the production of solid state lighting (SSL) components, where rather few substitutes exist to

date (with the exception of selenium and indium). The use of particular materials in light emitting diodes (LEDs) is largely determined by the desired colour and light intensity.
However, most REE are relatively abundantly present in the Earth's crust (Hellman and Duncan, 2014). They are rare because they occur together with other minerals but in dispersed, i.e. not concentrated, deposits, which are difficult to separate in an economical way. Mines with ability to extract and process the minerals are so far only developed in a few countries in the world, with China as the major supplier. Critical metals are often not mined as main products, but rather as by-products when acquiring bulk minerals (e.g. indium (In) or germanium (Ge) from zinc mines or gallium (Ga) from aluminium processing).

Fluctuations of demand for the by-products induced by the dynamics in the electronics sector do not have a strong influence on the supply side. Increasing demand cannot be compensated by an increased supply. The price elasticity of supply is very low because mining investments are strongly correlated with the expected monetary rate of return and are primarily related to the production of the main products (Bakas, et al., 2014). The same is generally speaking true for the production of metals from secondary resources, as recycling activities are basically driven by the main products of the recycling processes (Guitiérrez-Guitiérrez et al. 2015).

Due to missing incentives for mining investments for by-products, the supply-demand-relationship is not balanced and critical materials are often exposed to the risk of insufficient supply. Such scarcity is called structural or technical scarcity as the reasons are not caused by limited ore deposits, but rather by economic or technical boundary conditions for the mining and production of the critical metals (Bakas, et al., 2014). Other types of scarcities include physical, political, speculative, economic (price) and temporary scarcities (time lag between demand and installation of production capacities). These can be caused by imbalanced reserve-to-production ratios, regional concentration of resources (e.g. in China) or lack of suitable recycling technologies and poor economies of scale. Two different issues have to be differentiated when talking about the scarcity and resource depletion potentials:

1. The resource intensity, i.e. the demand for scarce materials for LEDs in comparison to other lighting alternatives;
2. The global supply chains of scarce and precious metals and REEs.

4.3.1 SCARCE MATERIALS IN LED PRODUCTION

The considerable advantages of LEDs in terms of efficacy and GHG emission mitigation come at the price of a higher demand of scarce materials compared to CFLs and incandescent bulbs. In this regard, the scarcity of precious metals and the scarcity of rare earth elements should be distinguished.

The resource depletion potential of LED bulbs is two orders of magnitude higher compared to incandescent and 2-5 orders of magnitude higher compared to CFLs (see Table 3). The main driver here is the content of precious metals such as silver, gold, antimony and copper (Lim et al. 2013). When it comes to REE, the quantities needed for LED phosphors, particularly yttrium and europium, are 1-2 orders of magnitude lower compared to fluorescent lights (Ku et al. 2016, Machacek et al. 2015 referring to Castilloux 2014 and Wu et al. 2014).

There are different projections about the market penetration of LED (Baumgartner et al. 2012, Buchert et al. 2012 and many others; see, for instance, Table 4). If an increase in the adoption of LED is estimated at 5%-15% annually until 2020 and 10% annually beyond 2020 (Buchert et al. 2012), it

seems likely that an increase in the demand for scarce materials will occur especially for europium, terbium, yttrium, lanthanum (Schüler et al. 2011).
However, the demand of phosphors and therefore REE for lighting purposes is likely to peak in the short term, i.e. until 2020/2030, and then decline to current usage levels (Ku et al. 2016, Guyonnet et al. 2015, Rollat et al. 2016)[3]. This argument is based on the assumption that a replacement and phasing-out of incandescent lamps and fluorescent lighting (CFLs) has taken place. The effect of a reduced resource dependency is even stronger if a point of lighting saturation is suggested. This is a point in time, where the level of illumination is not going to increase, i.e. it is stabilized. Although this is possible, it can also be expected that the demand for lighting will grow beyond 2030 (Tsao et al. 2010, Bergesen et al. 2015) at a global scale and in relation to an expected growth in GDP. A rebound effect can be avoided and GHG mitigation goals can be met by a macro scale transition to SSL even if there is an increase of lighting of 2.5 up to 2.9 times (Bergesen et al. 2015).

Table 3: *Rare earth requirements for fluorescent lamps versus LEDs (Rollat et al. 2016, based on Cohen 2014).*

	Fluorescent	**LED**
Phosphors general (g/unit)	2	0.002
lumens/ gREE (Y, Eu, Tb)	3000	54,000

Table 4: *Estimated future demand for gallium and indium for white LED manufacturing (Buchert et al 2012).*

Material	World production 2010, tons	**LED industry demand (white LEDs), tons**				
		2010	2015	2020	2025	2030
Gallium	161	0.75 - 1.56	1.07 - 4.90	1.46 - 5.34	2.00 - 5.35	2.74 - 5.35
Indium	574	0.67 - 1.38	0.95 - 4.37	1.30 - 4.76	1.78 - 4.78	2.45 - 4.78

4.3.2 GLOBAL SUPPLY OF SCARCE AND PRECIOUS METALS AND REE

Most of the REEs required for LED production come from China, and most production facilities are located in Asia (Wilburn 2010). The analysis shows that most manufacturers have long-term contracts with China and that it is likely that China will remain the leading supplier of especially heavy REEs needed for use as LED dopants and phosphors for the next years. The European Union (Com 2014) has derived a list of critical raw materials[4] based on economic importance in industrial sectors, its gross value added to EU GDP and the supply risk, taking into account, political stability and absence of violence, government effectiveness, regulatory quality, and rule of law (see Table 5). The substitutability index is a measure of the difficulty finding a substitute to the material. The

[3] Rollat et al. 2016 even estimates a decrease of 50% in the use of fluorescent phosphors

[4] http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm (2016-05-04)

higher the value the less substitution potential is expected. The "End-of-life recycling input rate" measures the proportion of materials that are produced from end-of-life scrap and other metal-bearing low-grade residues worldwide. Note that this value is 0% up to now for REE (see Table 5, showing 2014 data).

In Life Cycle Assessments typically the indicators abiotic resource depletion potential (ADP) or, more general, resource depletion potential (RDP) is used. The abiotic resource depletion potential (ADP) refers to the severity of resource scarcity, based on ultimate reserves [kg] and rates of extraction kg/yr. ADP values are given in relation to a reference substance in this case antimony. When having a look on the indicators it becomes obvious, that, despite their name, REE are not in particular scarce materials (see Table 6; Schmidt 2012). For example, crude oil is characterized with an ADP of 0.02 kg antimony-eq./kg, whereas europium, terbium, and yttrium show relatively low ADP values.

Table 5: *List of critical metals (COM (2014), 297).*

Raw Material	Substitutability Index	End-of-life recycling
Heavy Rare Earth Elements	0.77	0%
Light Rare Earth Elements	0.67	0%
Gallium	0.60	0%
Germanium	0.86	0%
Indium	0.82	0%
Magnesium	0.64	14%
Platinum group metals	0.83	35%
Silicon metal (silicium)	0.81	0%
Tungsten (wolframium)	0.70	37%

Table 6: *Abiotic Depletion Potential of some metals and rare earth elements, based on ultimate resource reserve and rate of extraction (Guinée et al. 2001).*

Metal or REE	ADP [kg antimony-eq./kg]
Aluminium	1E-8
Gold	89.5
Silver	1.84
Platinum	1.29
Zinc	9.92E-4
Lead	1.35E-2
Arsenic	9.17E-3
Gallium	1.03E-7
Indium	9.03E-3
Cerium	5.32E-9
Europium	1.33E-5
Gadolinium	6.57E-7
Lanthanum	2.13E-8
Terbium	2.36E-5
Yttrium	3.34E-7

Even if an increase in demand is expected, for instance at a rate of 5-10% p.a., there is the question, if this really induces a serious scarcity problem (Buchert et al. 2012, Massari and Ruberti 2013, Binnemans et al. 2013, Du and Graedel 2013, Goodenough et al. 2016, Hatch 2012). Significant long-term constraints or supply shortages that would impede production of LEDs are, based on publicly available studies, not anticipated. Supply will perhaps even outweigh demand for some heavy REE such as europium due to phasing out of fluorescent lights by LEDs (Wilburn 2010, Rollat et al. 2016). However, market forces and geopolitical events affecting supply risks and short-term interruption should not be ruled out. China started gradually to restrict REE exports in 2007 and cut export quotas by almost 70% in 2010, which caused a drastic increase in REE prices of up to 850% ((Golev et al. 2014, Mancheri 2015). With this increase in prices not only the awareness in the public and political agenda began to raise, also other mining companies started to reactivate or initiate mining processes across various countries (Machacek and Fold 2014, Mancheri 2015). After a WTO ruling against China because of breaking free trade agreements, China lifted all quotas from the export of REE. However, supply disruption of REE and special metals could take place if China's exports will (again) be redirected to domestic markets[5].

A strategy to deal with REE scarcity and to foster a circular economy, which is embedded in a comprehensive raw materials policy, compromises three approaches (Binnemans et al. 2013 referring to Jones et al. 2011):

a. Substitution of critical REE by less critical materials (Gutfleisch et al. 2011, cited in Binnemans et al. 2013);
b. Investments in sustainable primary mining from old or new REE deposits (Humphries et al.2012, cited in Binnemans et al. 2013);
c. Technospheric or urban mining (Brunner 2011 cited in Binnemans et al. 2013), including the:
    i. Direct recycling of post-production (pre-consumer) REE residues from processing/ manufacturing (Richter and Koppejan 2016);
    ii. Post-consumer recycling of e-Waste, including SSL (Schüler et al. 2011, Buchert et al. 2012);
    iii. Landfill mining of old urban and industrial waste residues and deposits containing residues.

One has to realize, that the amount of these materials per LED product is quite small and that the cost of the LED dies is dominated by the processing costs rather than the raw material costs. This means that in the context of scarcity, the LED industry will find it easier to cope with increasing material prices, than for example the display industry, that uses vast amounts of indium and gallium, or the CIGS-solar industry, that uses vast amounts of gallium.

4.3.3 REE MINING AND PROCESSING

Rare earths are exploited with different mining and processing technologies from a large variety of deposits. Often REE are exploited as a by-product of other metals such as iron, titanium or uranium. There are major environmental risks in mining and processing REE. For example, there can be site-specific environmental effects, i.e. emission of radioactive materials (thorium, uranium) and water pollution with heavy metals and fluorides, soil contamination, air emissions, biodiversity loss, and impacts on human health. Especially in China there is serious environmental damage at the REE

[5] China had announced to reduced export quota to 35,000 tons a year in 2009 and a further reduction by 20% in 2012. Mancheri 2015 and: http://www.theguardian.com/world/2015/jan/05/china-scraps-quotas-rare-earth-wto-complaint

mines and their surroundings (Weng, et al. 2013 and Yang, X.J. 2013). Advanced REE mines such as Mountain Pass in the U.S. (which closed in the past due to environmental problems) and Mt. Weld in Australia now provide environmental protection systems, including management and monitoring conducted by authorities and operators (Liu et al. 2011). It is worth noting however, the REE market is largely dominated by Chinese suppliers, which makes it more difficult for non-Chinese suppliers to compete and recent low prices have led to the closure of Mountain Pass. While China's government is also intending to install environmental technologies at the large mines, there continues to be a large amount of illegal mining that supplies cheaper REE but at considerable environmental and social costs. Deterioration of the environment such as pollution of soils, air, and water also cause health effects. In some areas in China, farmers having stopped planting and abandoned fields, finally moved away. There are often poor working and occupational safety conditions in the mines and low wage, especially in unregulated, illegal mines which continue to supply a substantial amount of the world's REE (Packey and Kingsnorth 2016, Ali 2014, McLellan 2014).

4.4 MANUFACTURING OF LED LIGHTING SYSTEMS

An environmental assessment of the manufacturing stage, i.e. the production of SSL products is extremely difficult due to the variety of complex manufacturing technologies (see Appendix 2 for details on the manufacturing process). Confidentiality clauses and intellectual property issues make it hard to get reliable and specific data. Only a few studies so far give insight to process material use, energy consumption and process chemicals for LED packaging. The production of LED electronic drivers involves many different manufacturing processes and components as well as integrated circuits, with significant impacts. Major steps in the manufacturing phase of the LED life cycle are displayed in Figure 6.

Manufacturing step I includes:

- Parts from suppliers, such as components made from plastics, steel or aluminium but also electronic components such as arrays, transistors, capacitors, resistors, solders, and printed circuit boards;
- LED chip and packages production.

Manufacturing step II includes the assembly of a lamp or luminaire, mostly electronic components, LED arrays, prefabricated parts (plastics, steel, aluminium) and several auxiliaries. Obviously, the assembly needs electricity as well as packaging materials (see Appendix 2 for more details). The manufacturing typically takes place at different locations and therefore needs to be differentiated.

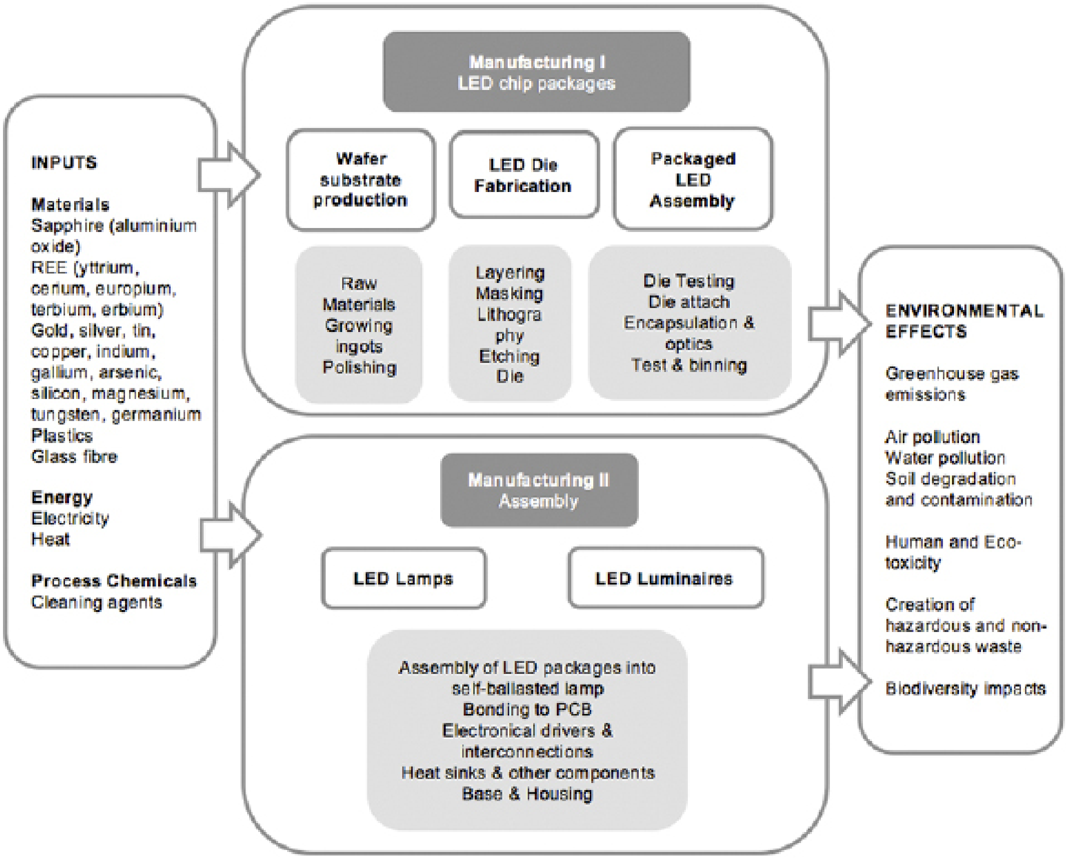

Figure 6 – *Overview of environmental impacts in LED manufacturing.*

LCA studies found that the overall environmental impact of LED lamp manufacturing is in the range of 2 – 20% of the total life cycle impacts. However, certain environmental categories such as hazardous waste and human toxicity may have a higher contribution to the total (DEFRA 2009, Tähkämö et al. 2014). In LED luminaire assembly, for instance, environmental impacts are related to upstream processes such as production processes of components as driver, PCB, LED package, aluminium parts (namely heat sink), remote phosphors, and the luminaire assembly process itself (Tähkämö et al. 2013). While components such as the LED array and circuit boards only have a share of 3% of total weight, they can account for major environmental impacts in the range of 4 to 50% depending on the impact category (Tähkämö et al. 2013).

The main environmental impact in manufacturing is, therefore, to be considered upstream, i.e. impact from aluminium parts. Manufacturing of the driver accounts for environmental impacts such as inert waste and hazardous waste generation, ozone depletion, mainly due to electrolyte capacitors. Other capacitors contribute to water pollution and photochemical ozone creation (Tähkämö et al. 2013). Generally, the energy used for the LED product manufacturing, mainly for LED packaging and arrays as well as aluminium parts (Paraskevas et al. 2016, Ding et al. 2012, Liu and Müller 2012, Tan and Khoo 2005), is found to be (up to 1.5 times) higher compared to traditional light sources (Tähkämö et al. 2014). There are LED lamp designs available that have reduced, substituted with thermoplastics and nanoceramics, or even eliminated the use of aluminium for heat sinks (Philips Slim Line). Another option is that, because of technological progress, more input wattage is converted to useful lumens of light instead of waste heat.

4.5 Electricity consumption in the use phase

The replacement of low-efficacy lamps[6] with LEDs is recommended to gain strong environmental benefits. There are estimations that due to replacement of incandescent light bulbs, reductions of environmental impacts in the order of 3 to 10 times are possible (Scholand and Dillon 2012). Substitution will cause savings of (conventional) electricity and life cycle cost. With every kilowatt-hour electricity saved, especially if the electricity originates from high carbon energy carriers, a net environmental benefit is the result[7] , i.e. in terms of reduced emissions of GHG, sulphur dioxide, nitrogen oxides and mercury from coal fired power plants.

To put it in the right context, the use phase of a lighting product in general, is responsible for the major share of energy-related environmental impacts. About 85% of the environmental impacts are linked to electricity consumption in the use phase (Tähkämö et al. 2014).

For a sound environmental assessment, the following issues should be carefully reflected:

a) Beneficial effects of longer life-times;
b) The influence of site-specific electricity mixes;
c) Luminous efficacy vs. use of scarce resources and hazardous substances;
d) Rebound potentials.

4.5.1 BENEFICIAL EFFECTS OF LONGER LIFE-TIMES

In addition to the much better luminous efficacy of LED compared to CFL and incandescent lights, another important parameter of environmental benefits is the useful life-time, i.e. hours of providing appreciated light during the life-time. As LEDs are expected to have a longer life-time, in comparison to other alternatives, fewer inputs in terms of materials and energy are demanded to provide the same function. For instance, when the lamp life-time of CFL is suggested to be around 8000 hours but LED is expected to work for 25,000 hours, more than three CFL are needed to provide the same lighting service (Scholand and Dollin 2012).

The environmental impact from the manufacturing and disposal of LED are higher or comparable to those of CFLs. But due to its longer life-time, the impact will be compensated by the reduced electricity consumption in the use phase, with a break-even point estimated at 40,000 hours under the precondition of a constant luminous efficacy higher than 90 lm/W.

As the useful life-time is so crucial for the environmental performance, the definition of this number is highly controversial and often based on theoretical assumptions which are difficult to verify such as the L70 metrics (NGLIA 2014). The range of estimations is between 10,000 up to 100,000 hours (Scholand and Dillon 2012, Bergesen et al. 2015). However, reliability test and surveys suggest this maybe not appropriate, as it is very difficult to verify and the number of possible failure modes increased with the evolution of light (De Groot et al. 2013, Pecht and Chang 2013 in: Van Driel and

[6] such as incandescent lamps for indoor and HPM lamps for outdoor use

[7] Bergesen et al. 2015 applied a so called Megawatt approach, analysing positive environmental impacts due to avoided environmental burdens of electricity generation.

Fan2013). Different causes of failure or early replacement exist (Casamayor et al. 2015, Van Driel and Fan 2013) and can be related to:

- Technical aspects (i.e. failure of drivers, LEDs itself for instance due to die crack, cooling systems, dimmers, interconnects, control units and gradual lumen depreciation, yellowing, delamination);
- Convenience aspects (i.e. illumination of the object with desired colours/temperature/ CRI, provision of less light than needed);
- Preferences for new products or new aesthetics.

Driver and other premature failures may cause a limitation of the useful life-time to 15,000 – 25,000 hours. If this is true, this might have some effect in the comparison of CFL and SSL.

In this regard, the definition of life-time has to be critically analysed and is a source of major uncertainty in life cycle assessments of LED systems in general.

4.5.2 THE INFLUENCE OF SITE-SPECIFIC ELECTRICITY MIXES

The GHG emissions, measured as potential contribution to global warming (GWP), are related to emissions during electricity generation. Therefore the results of the impact analysis phase of the LCA are also sensitive to the electricity mix applied. The more low-carbon energy, such as renewable energies or nuclear power, the less GHG emissions are occurring.

A switch to low-carbon energy carriers, e.g. renewable energies, will therefore contribute to improvements of life cycle environmental performance. With an increase of low-emission electricity, due to political measures and consumer decisions, the importance of the use phase is reduced in relative terms, while the importance of the manufacturing stage and other life cycle stages will be increased. For instance, when the calculations are done with the French electricity mix, the relative importance (% of total life cycle impacts) of the manufacturing phase is increased because the consumption of low-carbon electricity is not related to serious GHG emissions. When the calculation is done with the European electricity mix instead, the environmental burden is shifted from manufacturing to use phase (Tähkämö et al. 2013).

A combination of both strategies, a switch to low-carbon energies and increased adoption of high efficacy lighting systems in addition to technological advances in SSL technologies will achieve the greatest environmental improvements. There is an estimated potential, that life cycle GHG emissions of global lighting services can be reduced by factor seven (Bergesen et al. 2015).
However, a transition to low-carbon electricity supply will also increase the demand for metals and rare earth elements used for instance in permanent magnets in wind generators (Hertwich et al. 2015, Bergesen et al. 2014 cited in Bergesen et al. 2015, Schüler et al. 2011, Elshaki and Graedel 2014). This will cause other environmental impacts in relation to energy infrastructures that typically are not considered.

4.5.3 LUMINOUS EFFICACY VS. SCARCE RESOURCES AND HAZARDOUS SUBSTANCES

The environmental benefits due to luminous efficacy come at the cost of increasing overall metal depletion, the use of scarce resources and hazardous substances. However, this was not better for fluorescent tubes and their auxiliary equipment. It should be noted that resource scarcity and climate change are two different categories that cannot be directly compared to each other. However, resource scarcity is an anthropogenic category, focusing on surplus extraction cost and future availability, while climate change poses (mostly negative) impacts to ecosystems as such. Hazardous wastes, if treated and disposed with best-available technologies, do not pose a high risk, if they are not released to the environment[8] .

4.5.4 THE POTENTIAL OF REBOUND EFFECTS

Efficient lighting leads to cost savings from reduced energy consumption. This can potentially induce an increased use of lighting (direct rebound effect) as well as higher expenditures, increased demand for other products and services and thus higher energy use (indirect rebound effect). The direct rebound effect is defined as the elasticity of energy demand for lighting with respect to changes in lighting equipment and related to behaviour changes, i.e. increasing the luminosity of bulbs, letting the bulbs burn longer or using additional lighting services (Schleich et al. 2014). A certain saturation level can, however, be assumed[9]. Several studies have tried to investigate the possible magnitude of rebound effects from lighting and made conclusions of ranges between marginal effects to the extreme of offsetting all energy savings (Borenstein 2013, Hertwich 2005, Hicks and Theis 2014, Saunders and Tsao 2012, Tsao et al. 2014). In that case, the overall environmental performance deteriorates related to a "per-kWh-saved" basis from a macro perspective. However, the environmental performance of single lighting systems, measured on a per lumen-hour basis would not be influenced.

Robust and scientifically defensible models predicting the range and long-term magnitude of rebound effects are not available. A sensitivity analysis has shown that a direct rebound effect of about 97 to 99% would be needed to cancel out the GHG savings provided by the replacement of incandescent lamps with CFLs or LED respectively. A modest rebound of about 40 to 80% however, could erode the savings from replacing CFLs with LED lamps. (Bergesen et al. 2015)

It is suggested that a saturation level of lighting is yet not achieved and energy efficient lighting alone will not reduce overall energy consumption (Hicks and Theis 2014). Another empirical study suggests an average rebound of 6% related to the switch of CFL or LED mostly due to increasing luminosity. However, the study concludes that the magnitude of the rebound effect is rather low and the energy savings from a switch to LED are unlikely to be dissipated by substantial increases in lighting use (Schleich et al. 2014). An intelligent use of LED-lighting, with the right light, in the right place, at the right time has a huge potential of saving energy. However, rebound effects should not be a deterrent to better lighting. If more lighting is needed in certain places, for example in developing countries which may currently have less light than needed, it is important to carefully weigh the human benefits to the environmental concern.

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[8] This is a value-laden statement. LCA methodology usually tries to avoid weighting of different impact categories. And if a direct comparison is made, the weighting factors used need to be legitimized (i.e. by expert panel judgements)

[9] Day 2014a at: http://www.greentechmedia.com/articles/read/in-defense-of-leds (2016-07-04) and Day 2014b at: http://www.theenergycollective.com/rob-day/2144556/defense-leds-why-rebound-effect-solid-state-lighting-may-be-overblown

4.6 Recycling

The environmental impacts of end-of-life (disposal or recycling) due to energy inputs and transport are found to be marginal, i.e. 1% of the life cycle emissions (Quirk 2009 in Tähkämö et al. 2014). However, SSL contain valuable materials that could be recovered in a circular economy. Enhanced collection and recycling of lighting products will not only avoid hazardous waste in landfills or nature, but also conserve valuable resources. The value of the materials, however, is dependent on future product design and whether there will be available technology to economically extract the small amounts of critical materials.

4.6.1 LEGAL BACKGROUND

The European WEEE Directive (EU 2002/96/EC and WEEE II 2012/19/EU) has implemented Extended Producer Responsibility (EPR), (Tojo 2004), banned landfilling of e-Waste and imposed recycling when the products reach end-of-life. EPR also should lead to outcomes such as fostering design for environment, closing material loops and improved waste management practice (Tojo 2004, cited in Richter and Koppejan 2016). LEDs are, as other lighting equipment, considered as waste category III "Lamps" in the scope of the WEEE directive. This category includes LED retrofit lamps, replaceable LED modules, non-household LED luminaires and LED street-lighting. So far household luminaires are not in the scope of WEEE Directive[10]. In addition to household and non-household lighting products LED from LCD screen backlighting, widely used in laptop monitors, tablet, and smartphone displays, are considered in the WEEE directive.

The WEEE directive defines targets for recovery/reuse and recycling of 70-80% of collected lamps and lighting equipment in different periods from 2012 to 2018 onwards. The recycling rates are related to collected waste and the general collection target of 4 kg/capita[11].

Producers, importers or anyone who puts new lamps on the market[12] must take responsibility for their products. In this way, the responsibility for waste management is shifted to private industry, which is considered as having the greatest control over product design and the greatest ability to reduce toxicity and waste. EPR takes the form of collection, transportation treatment and recycling. Often so-called producer responsibility organizations (PRO)[13] are commissioned to deal with this. PRO's are organizing retailer/ in-store take-back programs and collection from recycling stations of municipal collection sites and/or other waste management approaches.

The EU member states have organized the implementation of the WEEE directive in different ways (Sander et al. 2007, Ylä-Mella et al. 2014, Richter and Koppejan 2016). In Germany, for instance, a mechanism known as 'divided product responsibility' was implemented for WEEE disposal[14]. The responsibility is shared between producers and municipal recycling companies. Those are required to establish recycling centres where WEEE from households is accepted free of charge. Currently, there are more than 1500 municipal recycling centres in Germany. Retailers with a sales floor or

[10] Annex II of WEEE 2012/19/EU expressly excludes luminaires used in private households from the disposal obligation and this also applies to lights from fitted LED modules.

[11] EU 2002/96/EC and WEEE II 2012/19/EU

[12] Companies importing from other EU member states or re-brand products are included.

[13] Such as Lightcycle Retourlogistik und Service GmbH, El Kretsen AB, El Retur, Elektronikåtervinning I Sverige, Elker Oy in Sweden

[14] https://www.umweltbundesamt.de/en/topics/waste-resources/product-stewardship-waste-management/electrical-electronic-waste (2016-06-03)

storage > 400 m² are also obliged to take back household appliances free of charge[15]. Also, smaller retailers are allowed to voluntarily offer their own collection schemes. Producers are therefore free to provide own take-back and recycling infrastructures (physical responsibility). However, they have to bear the financial cost (financial responsibility) and have to provide containers for collection. The costs are allocated to each producer in relation to its market share (Sander et al. 2007:127 ff.). Allocation of fees on a monthly basis is calculated by a clearinghouse institution (Stiftung EAR Elektro-Altgeräte-Register[16], the national register for waste electric equipment). Entrusted with sovereign rights by the Federal Environmental Agency (UBA), the clearinghouse registers all the producers and coordinates the provision of containers and the collection of e-Waste.

Foreign and domestic producers have transferred responsibilities to a producers association which in turn appoints private recovery companies who provide reverse supply logistics from different collection points to sorting and pre-treatment plants (see Figure 7). This perspective focuses on the collection and the recycling of collected material. A broader circular economy perspective is presented in (Karlsson 1998) and (Karlsson et al. 2016).

Official statistics on EU collected kilograms of e-Waste on a per capita basis is based on producer reports. It is even more challenging to derive data for lighting systems and lamps, as waste nomenclature is not consistent with market data, EU WEEE waste categories and some national waste categories.

In order to derive percentage values, i.e. collected e-Waste of certain waste categories versus products put on the market; estimates have been calculated based on three years market average. In the EU the collection rate is somewhere around 35% on average ranging from 0 to near 70% depending on the country (Eurostat 2016)[17]. Nordic countries and Northern Europe generally perform better in terms of collection rates and recycling of lighting equipment compared to other European countries (see Figure 8). This is in line with other collection rate scenarios of lighting systems.

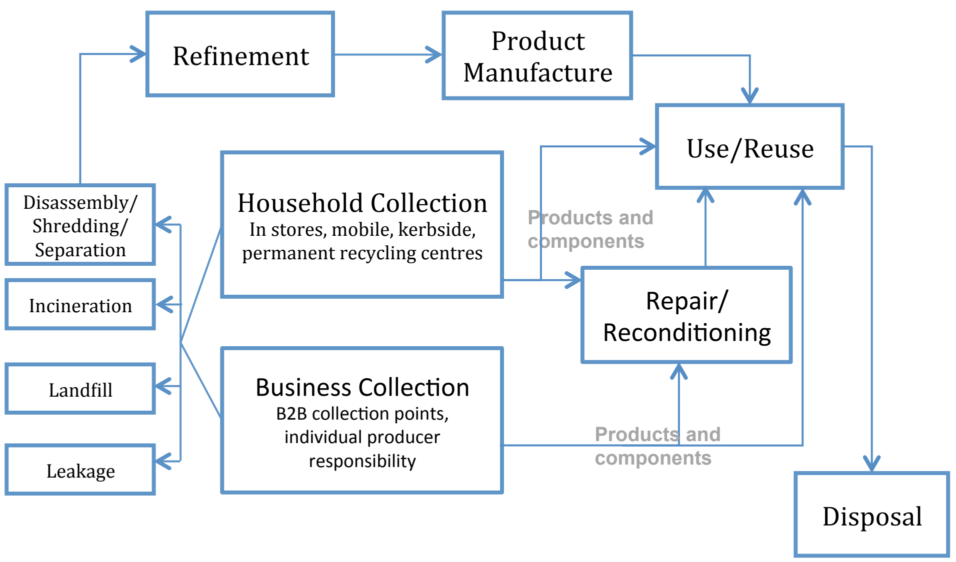

Figure 7 – *Stages of WEEE collection and recovery.*

[15] https://www.stiftung-ear.de/fileadmin/download/Vertreiber_Flyer-Download.pdf (2016-06-03)
[16] https://www.stiftung-ear.de/en/ (2016-06-03)
[17] http://closedloops.blogg.lu.se/good-lamp-and-bad-data-collection/ (2016-06-18)

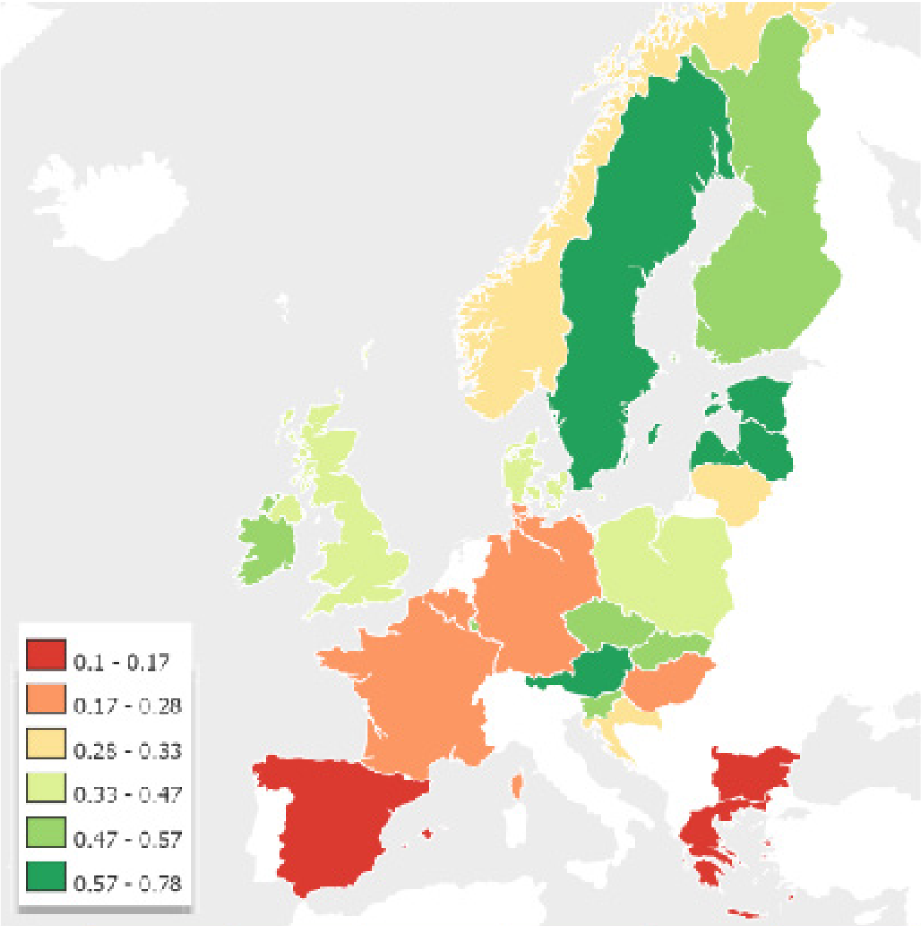

Figure 8 - *Collection rates for lighting products 2013 / 2010-2012 average put on market (source: created at Knoema.com based on data from Eurostat and www.lwf.no).*

However, EU average collection rates are rather low, between 30% to 40% (Buchert et al. 2012 referring to BMU 2009, Huismann et al. 2007, Richter and Koppejan 2016 referring to EuroStat 2014, average values).

Reliable information on LED collection rates in particular is still missing as LED is a relatively novel technology and due to the expected long life and time lags due to delayed disposal, return flows up to now are a small percentage (<5%) of the lamp waste stream. Still, there are examples of good practice, as in Sweden about 70% of gas discharge lamps are collected. The well-functioning collection and recycling of gas discharge lamps in Nordic countries can be attributed to a robust system architecture. Apart from system architecture, the success can be attributed to high awareness of environmental issues in Nordic countries, strong civic support of environmental protection and willingness to use the WEEE systems.

4.6.2 COLLECTION

Collection of e-Waste from private households is organized in different ways, the most common ones are (Ylä-Mella et al. 2014, Richter and Koppejan 2016, Wagner 2013):

- Drop-off collection
  o Permanent collection points (municipal recycling centres and B2B collection points);
  o Retailer take-back in stores;
  o Collection points in grocery stores (e.g. Samlaren in Sweden);
- Pick-up systems
  o Kerbside collection (or kerbside collection) is a service provided to households to remove household waste. A special wheelie bin for (precious) metals and or e-Waste would be necessary or, alternatively, plastic bags or boxes to be attached to the top of regular bins (as have been done in Sweden and Denmark) or small bins in apartment complexes (Richter and Koppejan 2016);
  o Bulk collection is a service provided to households where waste types that are too large to be accepted as regular household waste are collected regularly or on demand. Beside discarded furniture, large appliances such as refrigerators, washing machines or TV sets, also smaller e-Waste should be accepted.
- Producer-take back and distance collection

By law in the EU, consumers can return discarded devices free of charge to permanent collection points, retailers (sometimes purchase is required, depending on size of the store) or to special containers (drop-off collection). This approach seems to be cost effective and convenient to users (UNEP 2012). In pick-up systems, e-Waste is collected directly from homes or offices in the form of regular or scheduled kerbside collection, often together with other waste fractions. Distance collection is a form of producer-take-back, where the consumer sends discarded products to the collector or recycler through public postal services. This is typically framed by take-back media campaigns and is also considered as consumer-friendly, as it provides an easy return service at, however, higher cost of logistics (Ylä-Mella et al. 2014).

4.6.3 PRE-TREATMENT

The intended pre-treatment of e-Waste, mostly taking place in municipal recycling centres or collection points, is twofold:

1. e-Waste streams should be separated and classified into different waste categories as well as any waste that can be prepared for reuse. Estimations have been made that 2.4% of e-Waste collected in Europe is containing LEDs . According to EU WEEE, there are six e-Waste categories: temperature exchange equipment, screens and monitors, lamps, large equipment, small equipment, small IT and telecommunication equipment. In order to increase the degree of separation other categories have been suggested. The UNU KEY nomenclature distinguishes 54 categories. Several forms of lighting equipment can then be separated, for example, compact and straight-tube fluorescents, LED lamps and LED luminaires. Separation is usually performed manually;
2. In the subsequent step target materials, such as precious metals and lighting phosphors containing REE, should be isolated from other chemical compounds and material fractions. Pre-treatment operations are carried out in the form of dismantling and mechanical treatment (shredders).

Past technology did not have much potential for reuse, other than reusing tubular glass or reusing phosphors (only possible if the process has homogenous products returning). However, depending on the design, there is potential for SSL technology to enable reuse or repurposing of components and products. This could be desirable in a circular economy model and there have been successful examples of reuse centres operating in municipalities, as well as other initiatives promoting reuse before recycling, for example in Belgium and the UK (Hickey and Fitzpatrick 2016). However, at present the focus with lighting products continues to be on preparation for recycling and recovery of critical materials.

4.6.4 RECYCLING STRATEGIES

Theoretically, almost all material from lighting equipment can be recycled or even reused, i.e. such as glass tubes for retrofit-LED and phosphors (Nordic Recycling 2014, cited in Richter and Koppejan 2016). Availability and development of recycling technologies and capacities has made material recycling from traditional lamps already a reality (Richter and Koppejan 2016).

Steps involved are (see Figure 9):

- Collection of residual lighting material (e-Waste and recyclable material) from different sources (municipal, commercial, private) in different categories;
- Pre-Treatment and separation of e-Waste streams (including dismantling and removal of metal scrap);
- Further separation of lighting equipment;
- Recovery of fractions such as metals, precious metals, and rare earths.

It is still not possible to find reliable studies on the percentage of recycling for LED as there are only a few studies available (Bergamos and Hölting 2011). Instead, in this chapter, we will generally refer to recycling of e-Waste and in particular to recycling of waste fluorescent lamps. Research on the recycling of REE from lamp phosphors is so far restricted to (large and compact) fluorescent lamps (Binnemans et al. 2013, Buchert et al. 2012).

There are different approaches on recycling routes. Some countries just store shredded lamps, especially when they contain mercury in special locations such as salt mines. Other countries send shredded lamps to central recycling locations in Sweden, Finland, Belgium, France or Germany, which maybe increases economies of scale but also creates challenges with regard to returning glass and other materials back to producers which makes a closed-loop recycling nearly impossible. Transporting glass fractions over long distances from recyclers and back to producers (i.e. closing the loop) is economically not feasible. Much of the glass is therefore currently used as construction or landfill material (Richter and Koppejan 2016).

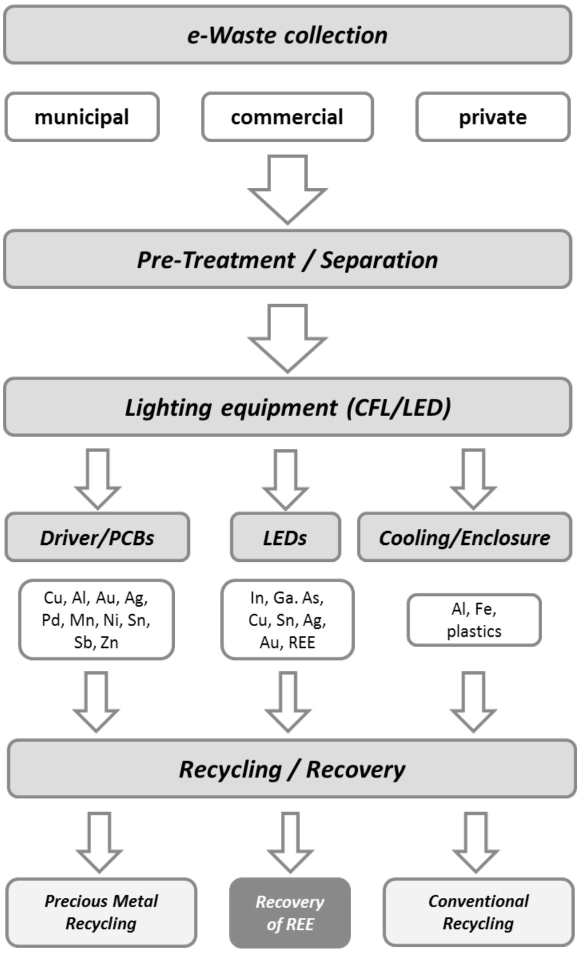

Figure 9 - *Recycling options for LED products.*

Recycling technologies for e-Waste are available, for instance in Japan (Behrendt and Scharp 2007), Sweden, Germany, Belgium, France, Italy and Estonia (see Table 7).

Table 7: *Examples of recycling plants for electronics material including lighting products (Buchert et al. 2012 and http://closedloops.blogg.lu.se/)*

Recycling Company and Site	Recycling process
Aurubis, Lünen, Germany	350 kt/a with KRS-technology, Aurubis plant in Hamburg.
Boliden, Sweden	Copper smelter to recover secondary copper and precious metals from e-Waste, 120 kt/a.
Umicore Hoboken, Antwerp	Valuable metals are recovered (Remove this) from over 350,000 t of raw material (catalytic converters, PCBs, mobile phones, industrial intermediate products and residues, slag, fly ash, etc.) using a complex pyro-metallurgical process.
Sylvia-Rhodia, France[19]	Separating REE/REO from lamp phosphors for use in new phosphor powders.
Nordic Recycling, Hovmantorp, Sweden[20]	Nordic Recycling is entrusted by international lamp manufacturing companies to perform environmental friendly recycling of lamps and TV screens.
Relight pilot REE recycling facility, Rho, Italy[21]	Relight is a lighting producer organization in Italy that has worked with multiple partners in EU projects (e.g. ReClaim and HydroWEEE) to develop pilot projects recovering REE (Eu/Y) from waste lighting products for use in other industries.
Silmet, Estonia[22]	Separation of lighting REE.

4.6.4.1 Recycling Lighting products

Almost all materials from lighting products can – theoretically – be recovered and recycled, such as:

- Glass - can be reused for fluorescent tubes, lamp glass, glazing, glass wool insulation, fusion agent with black copper foundry, abrasive sand for cleaning, under layer for asphalt, sand replacement, silicon substitute, landfill cover;
- Ferrous metals (steel) and non-ferrous metals, i.e. by permanent and electric magnets and eddy current separators;
- Lead - by treating residues of reverberatory furnaces
- Copper - from black copper as a residue from treating e-Waste in blast furnaces and subsequent electrochemical and metallurgical treatment;
- Precious metals - in a subsequent treatment of residues of copper recovery, i.e. in electrochemical treatment of anode sludge and high-intensity electrolytic refining processes;

[19] Richter and Koppejan 2016
[20] http://www.nordicrecycling.se/nr/11-fl-blad (2016-07-04)
[21] http://www.relightitalia.it/en/follow-up/projects-and-cooperation/
[22] mentioned in Rollat et al. 2016

- Mercury – recovered but due to EU legislation mercury cannot be recycled and must be stored safely as per guidelines;
- Rare earth elements[23] – recovered with the mercury and can be further separated to recover a REE mix. The mix can be reused by the same lamp manufacturer or repurposed in a different (e.g. automotive) application. Pure element recovery involves a two-step process, e.g. Solvay's recycling process from lamps[24] ;
- Plastics – most often burned for energy recovery. Environmental problems related to flame retardants can be avoided by suitable controlled incineration conditions. There are also approaches for recycling of flame retardants (Tange et al_2012, Landry and Dawson 2002, Dwason and Landry 2007).

In Nordic countries, for instance, more than 90% of the collected lamps are recycled exceeding the minimum 80% recycling quota set by the WEEE Directive. On average, WEEE Directive data shows more than 80% recycling of collected lamps in EU countries (Richter 2016)[25]. However, it is important to note materials being 'recycled' does not necessarily mean all the materials are sold or used in the highest value application. For example, while the glass in lighting products can be even reused or recycled to be used as glass again, this is dependent on the transport distance to glass producers/recyclers and competition with other recycled glass streams. This is the case in Sweden, where recovered glass is used as landfill cover, though recyclers are looking at the possibility of selling it for use in construction foam[26].

There can often be an issue in finding markets for recycled fractions, and this may be something a municipal actor can help with, e.g. through procurement or networking actors.

4.6.4.2 Barriers and options for recycling of REE from LED

The recycling of REE (Rare Earth Elements) in general and from fluorescent lamps, in particular, has been demonstrated in real-life applications. It is considered to be beneficial in comparison to mining of virgin materials, i.e. recycling had an 80% lower human toxicity potential and less than 60% energy was used (Sprecher et al. 2014)[27]. REE from e-Waste streams, in general, requires more complex process technology for recovery as they have unfavourable chemical characteristics for pyrometallurgical treatment (see e.g. Liu et al., 2014). Due to their base character, they are not absorbed with high yields in a copper phase, unlike the precious metals. Instead, they end up diluted in the form of their oxides in slags and need specific metallurgical treatment (UNEP 2009, Schüler et al.2011). The effectiveness of commercial post-consumer recycling of REE, measured as end-of-life recycling rate including collection, preparation, and refining, is estimated at being less than 1% and therefore extremely low (Graedel et al. 2011, Binnemans et al. 2013).

The general options for recovery of REE from lighting products are shown in Figure 10 below.

[23] More on recovery processes for REE can be found in Appendix 3.

[24] http://www.solvay.com/en/innovation/european-life-projects/loop-life-project-objectives.html.

[25] Based on Eurostat reported WEEE statistics available from http://ec.europa.eu/eurostat/en/web/products-datasets/-/ENV_WASELEE.

[26] Nordic Recycling, personal communication.

[27] Analyzing environmental impacts of producing a kilogram of the rare earth metal neodymium for magnets by recycling computer hard drives versus mining the same amount of virgin material.

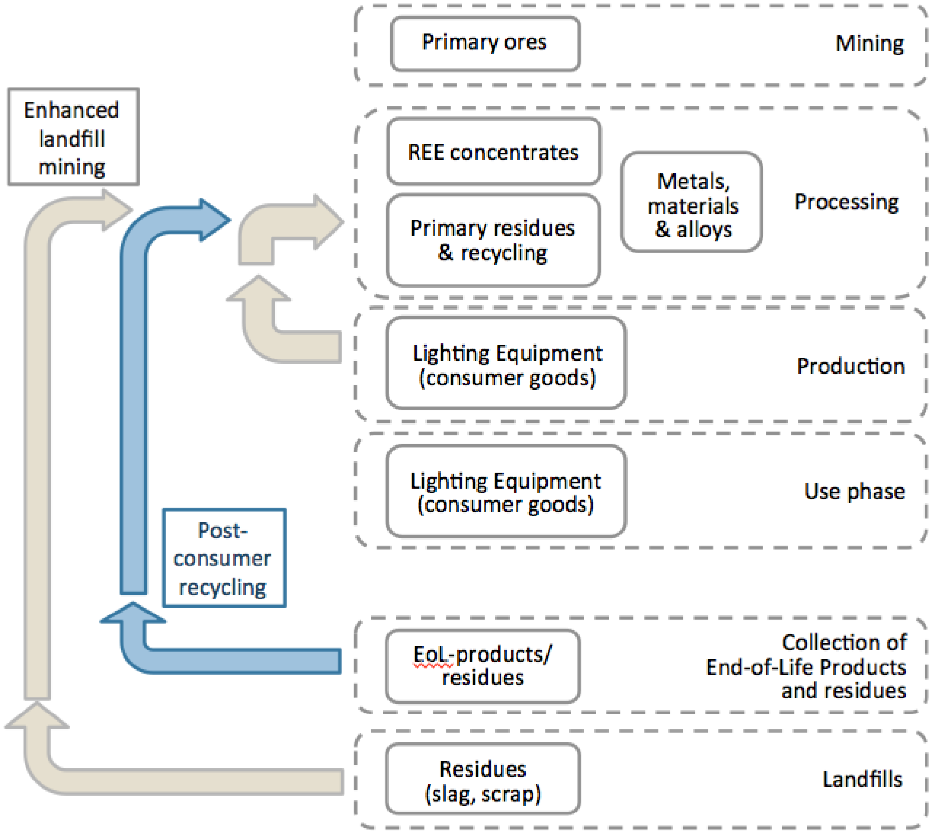

Figure 10 – *Approaches to recycling REE from lighting products (based on Binnemans et al. 2013).*

The end-of-life recycling potential for REE from lamp phosphors depends on the collection rate which is between 15% and 35% - 70% (Binnemans et al. 2013, Machacek et al. 2015 ref. to Eurostat 2014), the recycling rate of phosphors from lamps 55% - 95% (Machecek et al. 2015) and finally the recycling process technology to separate pure phosphor powder fractions 80% (Binnemans et al. 2013). The total end-of-life recycling potential for REE from lamps is assumed between 7% in a low ambition scenario and 53% in a high ambition scenario (Machacek et al. 2015).

While in Europe recycling plants and technological infrastructure for lighting equipment exist, the availability on a global scale is rather limited. However, the majority of phosphor powders from CFL/ LFL is still landfilled or disposed off underground with the option for retrieval (Huber and Schaller 2013 cited in Mueller et al. 2015). LED contain much less REE elements than CFL. Thus there are doubts that it will be possible to recover them in an economical way (Thema 2010).

The central driver regarding the feasibility of REE recycling is their marketability ('the right price at the right time'; see Table 8). For instance, the estimated value of the gallium content of one LED is estimated to about 0.03 EURO (Thema 2010:28). The costs for lamp recycling, in contrast, can be relatively high (between 0.15 and 2 EUR/kg lamp waste according to Machacek et al. 2015) compared to the price of the LED product. Avoided cost for primary REE should also be considered.

This can be significant and involves costs for energy and solvents, operating cost and handling of hazardous and non-hazardous waste materials, radioactive materials, effluent (Machacek et al. 2015) as well as future costs for land rehabilitation which are often externalized. However, it is not a large profit, depending on the recycling process and the scale of centralization (economies of scale) (Richter and Koppejan 2016).

It seems therefore that there is at the moment a lack of incentives (i.e. irrespective of legal enforcement of REE recycling, financial support) that are required in the absence of significant supply risks and/or high commodity prices. Even during the Chinese export restrictions, a long-term stability of the prices on a high level was not guaranteed, which is a pre-condition for economic recycling processes (Buchert et al. 2012). Other than purely economic aspects (Machacek et al. 2015) should be considered when assessing the recycling potential, such as resilience as a factor for sustainability and business opportunities (Sprecher et al. 2015), job creation and R&D innovation for closed-loop recycling.

The argument of lacking economic feasibility, low volumes, and diluted streams was often used to not have to take action[28]. However, the concentration of REE containing phosphor powders in lamp-waste, in general, is often even higher compared to natural ores (for instance 15 times – see Mueller et al. 2015).

[28] Using the same argument then there would be "only a dozen natural minerals [that have] high enough quantities to be worth the cost of extraction" (cit. Meyer and Bras 2011, in Machachek et al. 2015)

Table 8: *Prices for selected REE and REO[29] in 2012, 2013 and 2016.*

REE/REO	2016 [30]	2013 [31]	2012 [32]
Europium (Oxide)	420-470 USD/kg (99% FOB China)	951 USD/kg	2582 USD/kg
Lanthanum (Oxide)	3700 - 1400 USD/mt (99%min FOB China)	8 USD/kg (99.9%)	25 USD/kg (99.9%)
	3.40 - 3.50 USD/kg (99.9% min US)		
	6.60 - 7.60 USD/kg (99.999% min FOB China)	23 USD/kg (99.999%)	63 USD/kg (99.999%)
Terbium (Metal)	970 - 1020 USD/kg (99% FOB China)	1421 USD/kg (2013)	3286 USD/kg (2012)
Terbium (Oxide)	780 - 810 USD/kg (99% min FOB China)	837 USD/kg (2013)	2168 USD/kg (2012)
Yttrium (Metal)	53 - 58 USD/kg (99% min FOB China)	48 USD/kg (2013)	190 USD/kg (2012)
Yttrium (Oxide)	9.50 - 10.50 USD/kg (9.999%min FOB China)	23 USD/kg (2013)	146 USD/kg (2012)
	9 - 10 USD/kg (9.999%minEurope)		

The in-use stocks of REE in lamp phosphors (from CFL and LED) are estimated to 25,000 tons in 2020 (Binnemans et al. 2013). Given that other lighting systems, including fluorescents, will be replaced, an end-of-life stock of REE in lamps is expected to increase to more than 4000 tons (Machacek et al. 2015). The potential recycling of REE could be between 1300 - 2300 tons and 13000 tons in 2020[33], however, the closing of recycling operations announced by Solvay in 2016 makes these scenarios increasingly unlikely.

[29] Rare Earth Oxides (REO) and Rare Earth Elements (REE)

[30] ISE 2016: http://institut-seltene-erden.org/aktuelle-und-historische-marktpreise-der-gangigsten-seltenen-erden/ (2016-06-04); Disclaimer: Prices are not based in stock exchange statistics but on monthly expert interviews and therefore approximations.

[31] Pilarsky_2014_Wirtschaft am Rohstofftropf.pdf

[32] Pilarsky_2014_Wirtschaft am Rohstofftropf.pdf

[33] Binnemans et al. 2013 according to Curtis 2010 for the low ambition scenario and Machecek et al. 2015 for the high ambition scenario assuming collection rates of 70% and highly efficient phosphors recovery (95%) and separation process technology (80%).

4.7 Conclusions on environmental considerations

This review of SSL from an environmental life cycle perspective confirms and validates that solid state lighting, in particular LED, can reduce the amount of energy needed for lighting services and therefore reduce GHG emission. This is in part due to the luminous efficacy, expressed as the luminous flux divided by electricity consumption [lm/W], being high compared to less efficient electrical light sources such as incandescent lamps. Replacement of old lamps, especially incandescent but also fluorescents, therefore, allows significant electricity savings. More recent studies and future projects give reason to assume that due to advances in LED technology, i.e. the improvements in luminous efficacy and controllability, and changes in the electricity mix, environmental performance is at least at the same level and will be superior the coming decades.

Primarily due to the higher content of aluminium, and other metals, LED and CFL are considered as having a higher toxicity and resource depletion potential compared to incandescent bulbs. While this notes an area where there could be improvement, it is worth reiterating that LCA studies show modern energy efficient lighting has significantly less environmental impact over the lifecycle compared to conventional lighting. Demand for rare earths is a problem of LED and for electronics in general, but the content of REE in LED is low and long-term supply risks are not anticipated. In the short term, supply shortages may occur due to geopolitical events. From a technological point of view, some promising processes for REE recycling from lamps including LED are available.

Environmental risks due to hazardous substances in the end-of-life stage are considered low if proper waste handling and management is applied. It is also important to manage the anthropogenic stock of REE (contained in disused lighting products) in order to develop high concentration urban deposits, which can be exploited in the future. Thus municipalities have a certain responsibility. The options municipalities have depends on the degree of influence, which is high in the use and EoL phase of lamps (see Figure 10).

This means that the Carbon Footprint and the Environmental Footprint of SSL are smaller than for the old lighting technologies and that scarcity issues for LED are comparable to other kinds of electronics.

SUSTAINABLE ECONOMIC DEVELOPMENT

5 |

5 | SUSTAINABLE ECONOMIC DEVELOPMENT

> 'For poor countries, one can see that economic growth can also give greater prosperity, but when you reached a certain level of growth, which we in the rich world have achieved long ago, more growth does not give more welfare. Therefore there is no reason to seek it.'
> **Kenneth Hermele, PhD in Human Ecology at Lund University**

The basic principle for sustainable economic development is to promote a process of change in which the direction of investments, the orientation of technical development and institutional change are all in harmony and enhance the potential to meet human needs and aspirations (Barbier 1987). To enable this, the societies must activate their populations in the development and production that is needed to enable both current and future generations to achieve sufficient quality of life.

Economic sustainability is generally defined as the ability of an economy to support a defined level of production indefinitely. At present the worlds' nations define their top economic goal in terms of Gross Domestic Product (GDP). GDP is the total amount of production within a nation, usually within one year. In real life the top political priority of most nations is economic growth, aiming for a never-ending rise in total GDP of several percent per year. Stagnation or recession should be avoided at all costs. However, this can be misleading because, when growth in GDP is generated, the origin of that growth does matter (production of hazardous and unnecessary products create growth the same way education, health care and construction of new roads do). There is a positive correlation between per capita GDP and living standards (at least for poor countries), but GDP is a measure of economic activity, not welfare.

There is an on-going discussion on the substitution of the GDP (see, for instance, Constanza et al. 2009). ISEW (Index of Sustainable Economic Welfare) is just one in a series of alternative welfare measures. Some prioritize environmental factors; others have put health and well-being first. Recently, voices have been raised to measure happiness rather than economic prosperity.

It is crucial to minimize social and environmental loads, as discussed in the preceding chapters. It is also crucial to avoid misuse and wastage of the available economic resources. Important parts of the production systems that we have are bound to become out-dated and obsolete, sooner or later. To handle this there is a need for prospective investments in build-up of effective production potential for the future. There is a need for experimentation to enable various kinds of gradually needed systemic changes, but it is difficult to economically motivate such investments. The values for the future tend to be treated as externalities in economic accounting.

The long-term aspects are often difficult to internalize in economic assessments and consequently it is relevant to also consider the long-term motives for social and environmental effectiveness as drivers (Whiteman et al., 2013). A firms' efficient use of natural capital is the most broadly accepted criterion for corporate sustainability. The most noted CSR issue is worker's health and safety and also health risks for the people in the neighbourhood. Eco-efficiency is normally calculated as the economic value added by a firm in relation to its ecological impact. The World Business Council for Sustainable Development (WBCSD) has popularised this idea with the following definition: Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity

throughout the life-cycle to a level at least in line with the earths carrying capacity (DeSimone and Popoff, 1997: 47).
Electric light enabled a great expansion of human activity and appropriate lighting is now a prerequisite for the modern way of life. Effective lighting is an important element for a modern lifestyle, whereas so far the primary aim has been to produce a sufficient amount of light at lowest possible cost. The consumer interest has primarily been the cost of lighting. In a life-cycle perspective these costs are mainly energy costs, in particular for incandescent bulbs.

5.1 Green Public Procurement of SSL

Public institutions can lead by example in procuring SSL and opening up markets for new products, lighting solutions and business models. A green system solution with energy efficient lighting tends to have a higher procurement cost but saves operating costs throughout the life of the building. LEDs are efficient, and can have long life-time and minimise maintenance cost. When the number of bulb replacements becomes less, the maintenance time is reduced, which leads to less injuries and working time. Lighting is an attractive opportunity for global energy conservation, but this opportunity is small compared to the financial benefits that can result from improvement in productivity, and well-being and health of people working and living under optimized lighting conditions.

However there needs to be a driving demand to motivate the needed investments. This is a role that can be filled by green public procurement and, in particular, Public Procurement for Innovation (PPI) and Pre-Commercial Procurement (PCP), both supported in the EC's 2014-2020 funding programme for research and innovation Horizon 2020. PCP refers to the procurement by authorities of R&D services while sharing risks and benefits of R&D, when trying to solve challenges of public interest. PPI could be the next step in procurement. With PPI, contracting authorities, possibly in cooperation with additional private buyers, can act as lead customer by procuring 'innovative' solutions not yet available on large-scale commercial basis. For example, there could be diverse actors involved in procurement processes (shown in Figure 11), e.g. a procurement department, a legal department; a facility management department; hired consultants; or even a completely outsourced procurement process. These actors have various degrees of competence in lighting issues and strategies in procurement that may, when combined, encourage green or innovative procurement processes. When aiming for innovation it is important to involve user representatives and managers for the activities in the facilities.

[34] International Energy Agency, "Advanced Lighting Solutions for Retrofitting Buildings". 2014, Solar Heating and Cooling (SHC) Program, International Energy Agency. IEA-SHC Task 50. p. 75.

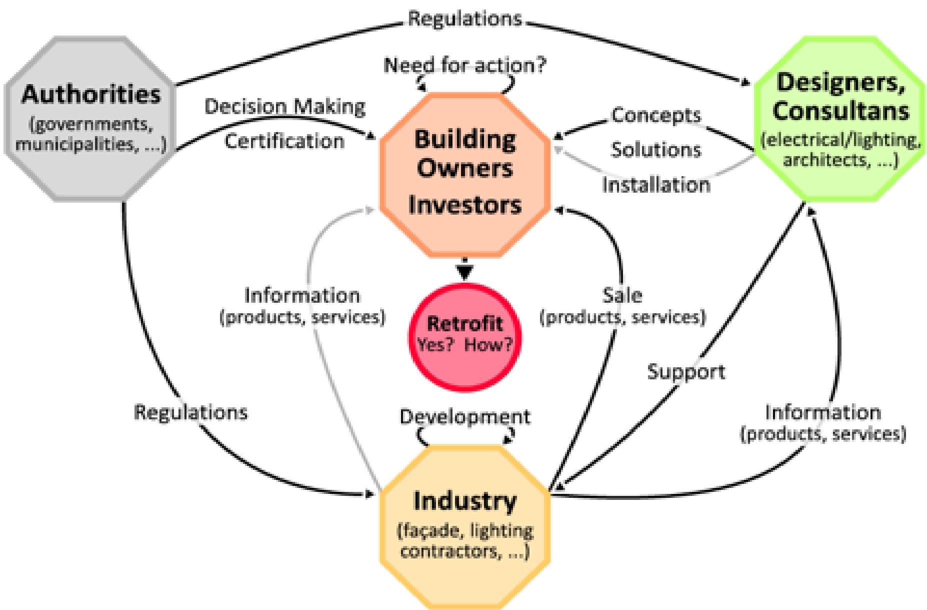

Figure 11 – *Relations of actors involved in decision-making on retrofitting of building*[34].

The overarching economic sustainable development goal is to enhance the quality of life for more of the present world population and to enable quality of future life. To achieve this wise investments are needed to enhance the systemic effectiveness. This includes a need to overcome some of the present societal characteristics, primarily short-sightedness and a limitation to the direct self-interest. However it is difficult to concretely define the quality of life. It is more comprehensible to focus on technical system effectiveness and energy effectiveness for lighting , but it is more difficult to define what the system should or could do.

The political ambition for deployment of SSL focuses on the energy efficiency. When the management of those actions is related to a broader sustainability framing, the focus on energy efficiency may be quite strong as a driver for change. But we want to stress that this does not happen automatically. There is a risk that primitive energy savings hamper productivity, health, well-being and quality of life options. Still, it is descriptive to focus on the energy efficiency and quite a lot has been done in this field, some of which is summarized below.

5.2 Obstacles to energy efficient investments

There are numerous publications[35] dealing with the energy-efficiency gap or energy-paradox, i.e. the question why energy efficiency measures hardly are implemented, even though they are environmentally and financially beneficial. Barriers to energy efficiency investments may be classified to four categories (see Table 9). While a general overview is given here, these are also relevant barriers to procurement of and investment in SSL.

[35] An overview can be found in Thollander and Palm (2013)

There are various obstacles that seem to prevent investments in energy efficiency. The cost of energy in some areas, such as engineering industry or non-residential buildings constitutes only a small share of the overall cost (Schmidt 2010, Hufen and De Bruijn 2016). Thus, there is no urgent economic motive with regard to energy efficiency. The payback time needed to recoup investments is often considered as too long and fluctuations in energy prices bring uncertainty to business case assumptions (Van der Heiden 2015 cited in Hufen and De Bruijn 2016).

Table 9: *Classification of barriers to energy efficiency investments (based on Thollander and Palm 2013 and Sorrell et al. 2004).*

	Theoretical Barrier	Explanation
Market failure	Imperfect information	Lack of information may lead to cost-effective energy efficiency measures not being undertaken
	Adverse selection	If a seller knows more about the energy performance of a technology than the buyer does, the buyer may select goods on the sole basis of price or visible aspects such as colour and design
	Principal agent	The most common principal agent problem is the landlord tenant problem that a facility owner doesn't want to invest because it is the tenant that will harvest the advantage, e.g. energy saving, that the investment enables.
	Split incentives	If a person or department cannot benefit from an energy efficiency investment, the most likely outcome is not to support the measure
Non-market failure	Hidden costs	Hidden costs include overhead costs related to the investment, cost of collecting and analysing information, and production disruptions
	Access to capital	Limited access to capital may inhibit cost-effective energy efficiency investments
	Risk	Risk aversion against new solution may result in cost-effective energy efficiency measures not being undertaken
	Heterogeneity	A technology or measure may be cost-effective in most locations but not in others, leading to distrust
Behavioural barriers	Form of information	Research has demonstrated that to increase the diffusion and acceptance of information on cost-effective energy efficiency technologies, the information should be specific, vivid, simple, and personal
	Credibility and trust	The source of information must be considered credible and trustworthy by the receiver in order to successfully deliver information about cost effective energy efficiency technologies
	Values	Energy efficiency improvements are more likely to be of interest if the organization consists of individuals with sustainability ambitions
	Inertia	Individuals are often hesitant to change, which may, in turn, result in the overlooking of cost-effective energy efficiency measures
	Bounded rationality	Instead of being made based on, for example, perfect information and complete rationality, decisions are often made in constrained environments that result in limited, or bounded, decisions
Organization	Power	Low status of environmental staff may lead to energy issues being assigned a low priority in industrial organizations
	Culture	The core values of an industrial organization may inhibit or promote energy efficiency

Large-scale industrial consumers are benefiting from energy (or carbon) tax deductions, which is prolonging payback periods even more, and, thereby, reducing financial incentives for investments (Vollebergh 2014, Hufen and De Bruijn 2016). As technological progress in lighting has been impressive the last decade, it is attractive to wait-and-see, i.e. delaying investments in anticipation of even less expensive solutions (Hufen and De Bruijn 2016).

Another important barrier is narrow-minded considerations in procurement with emphasis on short-sightedness (Ajzen 1991) and divisions of responsibility among actors in the municipality, as well as the landlord/tenant problem (split incentives; Wuennenberg 2016).

5.2.1 LANDLORD-TENANT PROBLEM

The landlord-tenant problem occurs when the interests of the landlord, i.e. the owner of a property, and the tenant, i.e. residents or tenant, are misaligned and finding agreement in a common strategy for energy-efficiency improvement is difficult. The problem is a principal-agent dilemma: one person or entity (the "agent") is able to make decisions on behalf of, or that impact, another person or entity: the "principal".”). This dilemma exists in circumstances where the agent is motivated to act in his own best interests, which are contrary to those of the principal.

The landlord typically does not want to invest too much money in the property and therefore in energy efficiency, while the tenant wants to lower its cost, i.e. monthly rent and energy bills.

In a study by the International Energy Agency (IEA 2007) it was found that for lighting 5 % of the households are affected by principal-agent problems.

While the landlord tenant problem of split incentives is mostly discussed in relation to rental housing, it also applies in other areas. For instance, in organisations, the bias towards short term paybacks may result from it. If managers remain for relatively short periods of time, there are no incentives to initiate investments that have a longer pay-back period. The incentive structure instead is directed towards more rapid returns (Sorell et al. 2011).

In case of larger organisations, investments in energy efficiency occur likely only when the departments are accountable for the installations in their premises and their own energy cost, i.e. by submeter availability, so that benefits and energy cost savings are not recouped elsewhere in the company (Sorell et al. 2011). As with landlords and tenants, high transaction and information cost may prevent the incentive structure from being modified.

Another example is the CEO – employee issue where the CEO’s choice of lighting affects the employees’ health, wellbeing and performance. This problem is more likely to occur in times of recession, limited budget and high unemployment. If the transport department (or other responsible department) has a limited budget for the investment and maintenance of the street-lighting in one area it might result in accidents.

In municipalities, the procurement and maintenance are often divided into different budgets, which can cause problems in relation to street-lighting or lighting in public buildings. If the procurement team has not thought through the upgrading and maintenance possibilities it might cause extra (unnecessary) spending, time and frustration. For SSL the investment (procurement and installation) is normally higher than for traditional lighting while the maintenance (the traditional shift to new products when the old ones are broken) rate is lower. If the installation is advanced there might be a need to hire a specialist to upgrade the system. Advanced SSL systems provide ability to save large amounts of energy in comparison to traditional lighting.

5.2.1.1 Solutions

The landlord-tenant dilemma is a form of the split incentive phenomenon (Astmarsson et al. 2013, Pelenur and Heather 2012):

1. The landlord does not pay for the energy cost, as the costs are shifted to the tenant, thus there are only few incentives to invest in the energy efficiency of the building;
2. Instead, energy efficiency measures will only be implemented, when the landlord can recover the investment (Thollander and Palm 2013), i.e. from the party benefitting. That is, typically the tenant who has then to pay a higher rent in case that energy savings are interpreted as improvement. The higher rent must then be compensated with the corresponding reduced energy bills;
3. Similarly, tenants are unwilling to invest in energy efficiency measures for properties that they do not own.

Even when energy prices are increasing, this situation does not change (IEA 2007, Astmarsson et al. 2013). There is a need for combination of regulative and informational instruments to overcome that barrier:

a) Increasing the rents for pay off the investment: For the case of profitable projects, landlord and tenant may agree on sharing the cost of energy renovation, which may increase transaction cost of developing such a saving contract. This can be done by increasing the rent to recap the investment. This approach assumes that landlord and tenant both agree on how much the rent can be increased and that the rent will decrease when the investment is paid off. Generally it is presumed that the tenant is financially capable to cope with increasing rents;

b) Green leases (IMT and COSE 2014): A green lease is a regular commercial lease with additional agreements or requirements upon energy efficiency (or other sustainability issues) making them a priority and thereby aligning incentives. Green leases encourage both parties to collaborate and paving the way for energy efficiency improvements, for example by adding the following clauses:
    1. Pass-through clauses that allow the landlords improvement cost to be shared with tenants;
    2. Operational clauses that mandate practices for the rented space and to get the tenant to be committed to more efficient and sustainable modes of use;
    3. Sustainable purchase clauses, i.e. of materials, appliances and energy based on labelling or other certified environmental benefits;
    4. Reporting clauses encouraging to regularly provide energy consumption data and distance-to-target indicators.

    Usually within a green lease, the tenant accepts a higher rent for a period of time and gets the benefits of cost savings. However, the lease may lead to reduced cost for both parties in the longer term and to a better image of the landlord's company, i.e. within a responsible property investment strategy (UNEP FI 2011);

c) Another option is to cooperate with Energy service companies (ESCOs). This is discussed in Section 5.4.

If the project is not profitable in the short or midterm, say one to three or five years , funding or subsidies from the government may be necessary to balance the incentives. Another option, which is not a solution to the dilemma but which enforces landlords to invest, is mandatory energy savings for (new) buildings (EnEV in Germany) and mandatory energy labelling of buildings ('Gebäudeenergieausweis' in Germany). This also applies to many other countries.

5.3 Product service systems

Product Service Systems (PSS) address economic, environmental and social needs simultaneously, but a precise definition still has to be drafted. One of the most frequently cited PSS definitions is provided by (Mont 2002) and states that a PSS is 'a system of products, services, supporting networks and infrastructure that is designed to be competitive, to satisfy customer needs and to have a lower environmental impact than traditional models'. The term 'system' captures the variety of involved actors in the value creation and delivery process and the integrated nature of products and services. The purpose is to provide a function to the customers rather than physical equipment.

5.3.1 LIGHTING AS A SERVICE

The transition from goods to services is redefining the relationship between consumers and products. The introduction of lighting as a service and paying per lux instead of per product enables a move from transaction to relationship. The company retains responsibility for the performance of the lighting system, which means that they have more incentive to begin to design for longevity, multiple re-use and recycling.

The lighting sector has traditionally been product focused as well as sales and volume driven. The value creation and delivery is ensured through incremental efficiency gains which benefit and incentivise the consumer to replace old, less efficient lighting equipment. The business model relies on the value proposition that new lighting technologies are more energy efficient than their predecessors, which allows producers to charge a higher price and thereby ensure sufficient revenues. The ever-increasing efficiency is a priority for the economic sustainability of the lighting sector and the LED technology fits into this logic. However the supply side is expected to face price competition and the market is believed to suffer from saturation due to long-living products.

Although the lighting sector is dominated by product focused sales logic, several characteristics of LED and new business model approaches of some adjacent market segments have potential to overcome this logic. The most noted aspect of light as a service is that the longer durability enables the consumer to buy functionality with lower life cycle cost due to less frequent replacements, so that the producer can capture economic value through service fees. Another great potential is that light as a service can enable the introduction of Human Centric Lighting system solutions and upgradeability that enable much higher user value than procurement for ordinary lighting products. The PSS business model (used by Lighting Service Companies, LISCOs) promotes a functional shift from manufacturing products to maximising consumer use value of products and system solutions (as shown in Figure 12). The solution is facilitated by energy efficient light technologies and smart service systems that enable delivery of efficient and customer adjustable lighting solutions. These functional and service-oriented prospects simultaneously enable profit for consumers, because of lower operational costs, and facilitate sustainable societal development.

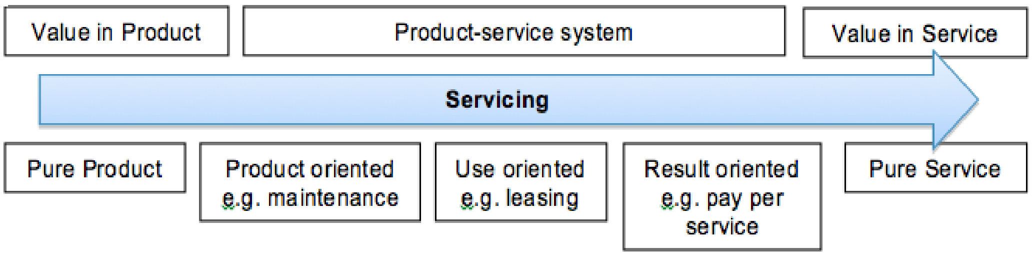

Figure 12 – *Types of product service systems, adapted*[37].

One major advantage of service oriented business models is that they open up for a much broader application of lighting design knowledge and more advanced, open and upgradeable system solutions. This is vital to harvest more of the development potential and user value potential enabled by SSL, i.e. to make the potential of advanced SSL more popular.

One reason why this is important is that it is difficult to measure the user characteristics of an illuminated environment. Lighting design is considering numerous user aspects that rarely are measured. The lack of measurements means that the feedback is primitive, i.e. that the quality and character of the lighting tend to be neglected. This should be vital for each assessed facility, but it is even more crucial for the long-term learning and ability to improve the user value of the lighting. To be able to optimize the lighting design of an environment special lighting considerations are are needed in the design process. To trigger a broader interest in better lighting it is important to facilitate evidence-based assessments of the basic light characteristics. One interesting method is to take energy mapping of lighting installations as a starting point.

The only analyses that so far regularly are made for lighting systems are energy (kWh) analyses. Those analyses sometimes already include basic logging of how the electric power (kW) varies.. Power variation analyses can be used to make 'lighting maps' that provide an overview of which different light sources are present in the premises, which parts of the day and night the different light sources are switched on at which respective power level (dimming) at different times. Electric power (kW) maps can be used to assess how the amount of light varies between different areas and between different points of time. Electric power variations mappings can be the start for a dialogue about the wanted characteristics of an illuminated environment. Service oriented business models can be used to extend and speed up utilization of the lessons learned how to improve the lighting and simultaneously to save energy.

[37] Tukker and Tischner (2006)

5.4 Energy Performance Contracting and Energy Service Companies

Energy Performance Contracting (EPC) involves outsourcing of energy-related services to a third party, i.e. an energy service company or energy savings company (ESCO). An ESCO is a commercial or non-profit business that provides several different energy solutions, e.g. design, procurement and implementation of retrofitting of primary or secondary conversion equipment and infrastructure.

5.4.1 MODES OF ENERGY PERFORMANCE CONTRACTING

Typically ESCOs are suppliers of primary and secondary conversion equipment, suppliers of control equipment, energy utilities, engineering contractors or facility management companies (according to Sorell 2007) (see Table 10).

The ESCO approach usually focuses on energy performance contracting and product-service combinations, e.g. pay-per lux models. In energy performance contracting, contracts are made to deliver energy services and the capital investments necessary are recovered from cost savings (Sorrel 2005, Sorrell 2007). A contract rate is paid by the client to the contractor, which is lower than the cost savings compared to current and projected energy bills (see Figure 13).

Table 10: *Scopes of energy services included in Energy Performance Contracting.*

Primary conversion equipment	Secondary conversion equipment
Provision of • hot water, process heat/steam • Coolant • Electricity by means of CHP or other energy conversion technologies (boilers, CHP, PV)	• Space heating • Ventilation • Motive power • Refrigeration • Lighting • Compressed air
Additional energy services	
• Energy audits • Energy purchasing • Financing • Operation and control • Measurement and verification • Staff training	• Planning and specification, design and engineering • Purchasing • Installation • Commissioning • Maintenance

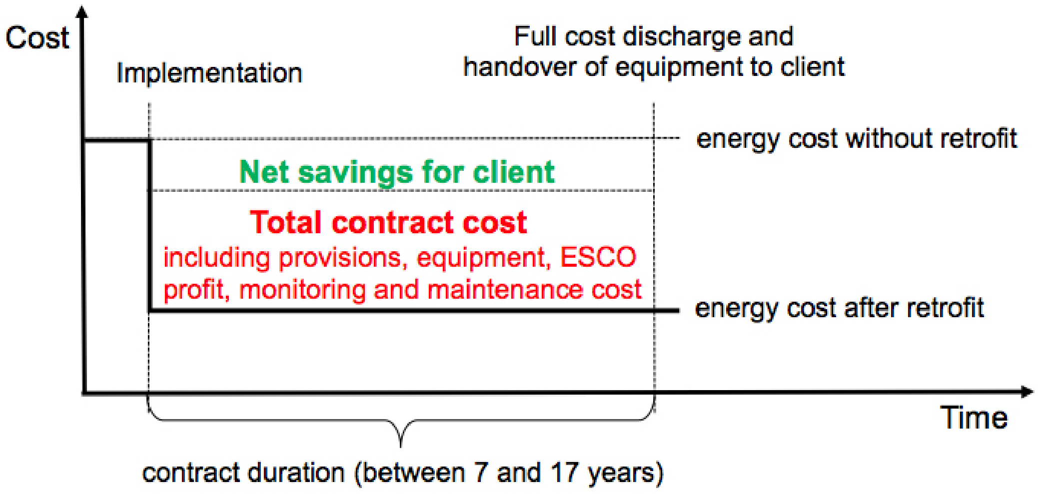

Figure 13 – *Financial model for Energy Service Contracts (after Von Flotow and Polzin 2015).*

The scope of an energy contract, final energy services, and additional services that are completely or partially in the control of the contractor, naturally differs. There are simple and more sophisticated forms of ESCOs.

For instance, the ESCOs may guarantee merely the supply of the same level of energy services, i.e. lighting or hot water, at a reduced cost (delivery or supply contract). In other EPC models, the ESCO guarantees not only supply but certain performance levels of lighting, room temperatures, humidity or comfort.

An extensive form allows the client to minimise the total energy bill and the contractor is responsible for all energy services needed at the entire site (Sorell 2007). In supply contracts, one or more streams of energy are covered, but with little or no demand control. In performance contracts, however, the contractor usually has some control over the energy equipment e.g. through occupancy controls for lighting.

Furthermore, there is a differentiation between 'shared savings' and 'guaranteed savings' in other EPC contract models. This reflects the distribution of investments, saving and related risks between the client and the ESCO (Bertoldi et al. 2014, IFC 2011). More information about the different models can be found in Appendix 4.

As a necessary feature of an energy service contract, the decision rights over energy equipment is transferred to the ESCO under the terms and conditions of a long-term contract which also includes to maintain and improve equipment performance over time.

In a typical ESCO project the contractor (Sorrell 2007):

- Installs energy conversion, distribution and control equipment at the client site;
- Guarantees a particular level of savings in energy consumption or energy costs;
- Assumes decision rights of useful energy streams, energy infrastructures, equipment, and assets as well as organizational activities needed for the provision at the client site;
- Finances the investment or assists in obtaining finance for the client;
- Takes the majority of risks, i.e. energy price risk, equipment performance risk and credit risk.

Typically the ESCO involves new investments in energy saving technologies and the question of financing arises. Although financing is not the key part of an ESCO offer, it is common that ESCOs provides support or even arranges the financial terms of the project. Different options are available and are presented in Appendix 4 (Sorrell 2007, Sorrell 2005).

5.4.2 EXPECTED BENEFITS

Usually, the ESCO provides turnkey services and provides also project management and acts as guarantor and financier. ESCO projects are beneficial from several viewpoints (see Table 11). The property owner benefits by the mere fact that an investment can be made also when not much budget is available or the payback time is considered as too long.

Table 11: *Benefits from ESCO project*

Property owner (client)	Municipality
• Energy cost savings (or other utility cost) • No, or low upfront cost • Healthier indoor environment • Increase of comfort • Building value increase • Additional renovation aspects (aesthetics, status improvement, extension, etc.) • Public image/prestige	• Jobs – more balanced community • Growth of the value of the building stock and more attractive district/area • Healthier district • Development of communities -> competitive advantage
Contractor / ESCO	**Macroeconomic effects**
• Workplace • Profit • Long-term, reliable partnership	• Jobs • Development of real estate market • Motivation of residents' and/or investors to spend money locally • Energy security

Making use of an ESCO can be a way for a real estate company to market themselves as taking their Societal Social Responsibility (SSR). Municipalities aiming at climate change mitigation and cost savings often face budgetary constraints because upfront cost for implementing energy-efficient technologies such as smart LED lighting are significant. In a financially and capacity-constraint environment, outsourcing can be an advantage as investments can be enabled.

Although an ESCO contract can have great benefits and therefore can help to realize energy efficiency investments, this does not necessarily mean that such a contract is always the most cost effective solution. The total cost of an ESCO contract could be higher compared to an in-house solution, especially if ownership and risk management, technological and procurement competencies are available, which is typically the case in larger cities (Polzin et al. 2016).

The landlord-tenant problem can be avoided if an ESCO is responsible for the procurement as well as the maintenance (Roehrich et al. 2014, Bennett 2006, Sorrell 2005 cited in Polzin et al. 2016).

5.4.3 SUCCESS FACTORS AND BARRIERS FOR ESCO PROJECTS

ESCO projects represent a niche application in European Countries. In Germany for instance, only 3% of municipalities use ESCO projects (Polzin et al. 2016). This indicates that severe barriers and conservativeness exist in institutional environments. However, there are also major drivers such as minimising financial exposure, and risks as illustrated in Figure 14 (Polzin et al., 2015; Hannon and Bolton, 2015).

Some of the general barriers to energy efficiency such as high upfront cost, long payback periods (Suhkonen and Okkonen 2013), uncertain future energy prices and technological factors related to the quality and durability of energy efficient equipment investments may encourage outsourcing and ESCOs. Financial constraints and missing funds for lighting and other energy efficiency infrastructure are significant drivers towards engaging with ESCOs and could be mitigated by outsourcing (Polzin et al. 2016, Pätäri and Sinkkonen 2014; Marino et al. 2011; Aasen et al. 2016).

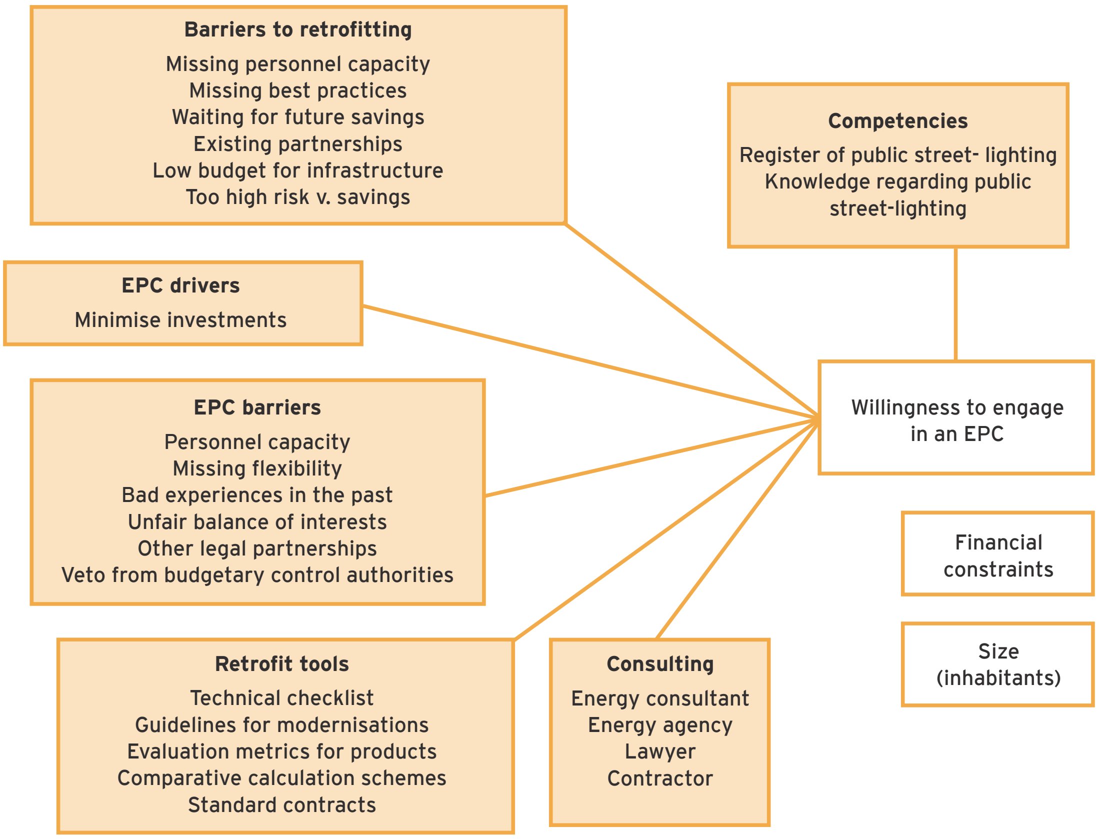

Figure 14 – *Energy Power Contracting drivers and barriers (Polzin et al 2016).*

As shown above, there are different risks associated with EPC and the degree of risk aversion. The potential for risk mitigation could influence the tendency towards outsourcing, especially when risks are perceived to be transferred to the ESCO (Polzin et al. 2016, Sorrell 2005).

Existing long-term contracts with multi-utility and energy utility providers, such as "Stadtwerke" in Germany, may prevent outsourcing to ESCOs. Multi-utility companies (MUCo) usually provide a wide range of services such as gas, electricity, municipal waste management, public transport etc. In some cases, the MUCos are strongly embedded in local communities or even regions and enjoy quasi-monopolies (Polzin et al. 2016). Conventional energy service contracts, without a particular saving goal, typically last 5 up to 30 years (Hannon et al. 2015). This lock-in-effect has hindered a strong market penetration and diffusion in the past.

In addition, governmental support mechanisms, supportive regulatory frameworks and measures (i.e. subsidies) are lacking (Hannon et al. 2015) or, in some cases, do not include the possibility of engaging a third party (Polzin et al. 2016). Often within the public procurement process, there are separate calls for tenders for project design and project implementation, which are generally unsupportive towards EPC models (Garnier 2013). Subsidies sometimes need to be rejected because of EPC-contracts. An appropriate policy framework is, therefore, a major determining factor for ESCO markets on a national level (Hannon et al. 2015; Marino et al. 2011, Alsaleh and Mahroum 2014, Bertoldi et al., 2014).

An important reason for the occurrence of ESCOs and similar business inventions is that numerous municipalities have a lack of investment capital and that they are struggling with the effects of the regulation for public procurement. However, there is a risk that the overall long-term result of this will be a transfer of public money to various private public actors, and thatthe public actors, and thereby the citizens, will have to pay a high price for the municipalities' inability the fund and manage the needed investments.

5.5 Conclusions on economic considerations

The consumer often focuses on the cost of the lighting equipment whilst in a life-cycle perspective the energy cost has been the major part of the cost. Great economic benefits can result from improvement in the well-being, performance and health of people working or living under optimized lighting conditions. Public institutions can lead by example in procuring SSL and opening up markets for new products, lighting solutions, and business models. A green system solution with energy efficient lighting tends to have a higher procurement cost but often saves on operating costs throughout the life of the building. One obstacle to investments, observed often in municipalities, is that different departments (with their own budget) are responsible for the procurement, operation and maintenance. Another important barrier is short-sightedness, for which the consideration that the payback time of the investments is too long is an example. Pre-commercial procurement (PCP) and public procurement for innovation (PPI) can be used as a drivers to put new SSL innovations on the market.

The project management of retrofitting processes requires certain skills at the clients (municipality) side. In a financially and capacity-constraint environment, outsourcing e.g. to an ESCO can be an advantage as investments and financial risks can be reduced. There is a need to enhance expertise of consultants and energy managers to effectively facilitate the deployment of more advanced lighting.

The introduction of lighting as a service enables a move from transaction to relationship. The supplier takes responsibility for the performance of the lighting system, which gives them more incentive to design for enhanced functionality, user satisfaction, longevity, multiple re-use and recycling. The solution can be facilitated by energy efficient lighting technologies and smart service systems that enable customer adaptable lighting solutions.

The basic economic sustainability goal is to enable present and future generations to support themselves. To a large extent this is coherent with the ambition to promote growth of GDP. However GDP measure the sum of all financially accountable activities, and not only the activities that are good for quality of life. Lighting for health and wellbeing promotes both GDP growth and quality of life. Investments in energy savings can promote quality of life but to achieve this it is crucial that these investments focus on the adaptation the lighting to human needs and wishes.

SSL IN SUSTAINABLE CITY DEVELOPMENT

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6 | SSL IN SUSTAINABLE CITY DEVELOPMENT

SSL have significantly less environmental impact over the entire lifecycle, largely due to the energy savings in the use stage, when compared to traditional lighting The resource depletion issues with SSL and the use of critical materials like rare element earths will likely continue to be an issue in the future, but less the lighting itself.

Our sensory vision system is adapted to the light in nature where light varies in many ways. LED enables many ways to provide lighting effects providing better guidance and reducing risks. The flexibility to vary the light is much more limited for the old lighting technologies. Public institutions can lead by example in procuring SSL and opening up markets for new products, lighting solutions and business models.

6.1 SSR and green public procurement to invest in better lighting

Now that we know that light has a powerful influence on our health and wellbeing it is a Societal Social Responsibility (SSR) to take action to improve the work and living environments in preschools, schools, offices, hospitals, for the elderly and in the traffic. Cities can lead by example with green procurement practices. Municipalities should enhance the procurement and application of SSL in municipal properties, public spaces and street-lighting, not the least because municipalities should act as role model. To start with they should be familiar with the ecolabel criteria for light sources (Ecolabel 2016).

LCA is a good tool for highlighting some of the advantages and disadvantages that LED provide in the environmental impact area, compared to conventional lighting. According to methodological conventions (ISO 14040 and ISO 14044) only primary functions should be included in the functional unit choice and this unit should be quantifiable in measureable terms. Additional functional aspects (regarding other aspects of the value of light) and supplementary functional aspects (i.e. recyclability) are not considered as reference in environmental life cycle assessment. However, SSL provides a much broader functional value (e.g. reducing illnesses, accelerating recovery, enhance productiveness and learning and improve wellbeing) than merely the provision of light than which is typically reflected in Life Cycle Assessments. Besides the environmental benefit regarding energy savings, other sustainability aspects, mainly in relation to individual well-being can be enhanced. One aim of the LCA-inspired extended functional unit (quotient of total functional value and total environmental loads) (see Section 3.5.1) is to clarify how the combination of these priorities ought to be conceptualised in relation to policy-making, procurement and the construction industry's economic calculations and decision-making.

6.2 Business models on disposal

Generally speaking, collection and recycling of e-Waste require increasing motivation, convenience, and availability of recycling technologies in particular because there are no direct (economic) incentives for collection in the absence of corresponding regulations. Compared to other e-Waste streams (such as TV, washing machines etc.), lamps are rather small which means that they can easily be disposed off together with other residual waste or glass recycling streams. It is even conceivable that old lamps are simply stored at home not ending up in any waste stream (Richter and Koppejan 2016). If lamps are not separated from other waste and e-Waste streams, precious metals and REE may end up diluted in residues from incineration or as pulverized particles after shredding. Most likely they are then lost from any recovery (Schüler et al. 2011, Buchert et al. 2012). Factors of a good practice in e-Waste and lighting equipment collection are (Richter and Koppejan 2016):

1. Legislation and a robust regulation base , i.e. mandatory EPR and WEEE regulation. Compared to a situation without waste management policies and regulation, the EU WEEE Directive improved the situation, prescribing targets for recovery/reuse and recycling of collected lamps and lighting equipment (see Section 4.6). It is estimated, for instance, that 95% of fluorescent lamps in Australia are landfilled and the recycling rate in countries such as Canada, Japan and Mexico are estimated to be less than 10% of waste lamps. The collection and recycling rate in the US is estimated around 23% because existing regulation is not enforced (Richter and Koppejan 2016 referring to EU Commission 2004);
2. Enforcement of rules and reduction of counterproductive incentives (for example, when non-compliance is cheaper in absence of strong financial sanctions);
3. Availability of collection (and recycling) infrastructure;
4. Sound financial management to guarantee financial stability of the collection system (whether by state guarantees, incorporation of end-of-life cost in EPR and WEEE financing, financial management by PROs).
   The contractual agreement between municipal waste management services and producers to provide services is a consideration for municipalities. Ideally, municipalities involved in WEEE management should be given compensation for the cost of service provision;
5. Promotion of voluntary actions, for example by providing information to key actors and consumers through media campaigns or collection events[38];
6. Enabling convenient collection (Wagner 2013), which depends on the following elements: (i) knowledge requirements (accessibility of information about what and how to separate and where to bring the materials, information about drop-off procedures and fees), (ii) attractiveness of the collection points (proximity, opening hours, cleanliness, security) and (iii) general ease of the collection process (segregation, storage, cleaning requirements, physical effort, access to vehicles).

However, as the low collection rates in some countries implies, there are challenges remaining in particular with lamps and small e-Waste which are simply stored at home and thus not ending up in any waste stream or become impurities in other streams such as glass or residual waste.

It is, therefore, important to combine and strengthen the different factors contributing to higher collection rates (see Figure 15), for instance by (i) information/ education campaigns, (ii) financial incentives and (iii) minimizing barriers, i.e. fostering retailer take back regardless of purchase. Policies and legislations and strict enforcement are required to improve a collection infrastructure in contrast to incentivizing a focus on low-cost options or avoidance of compliance with regulations.

[38] However, the effects on awareness raising and responding behavior still need to be analyzed in further studies (Richter and Koppejan 2016).

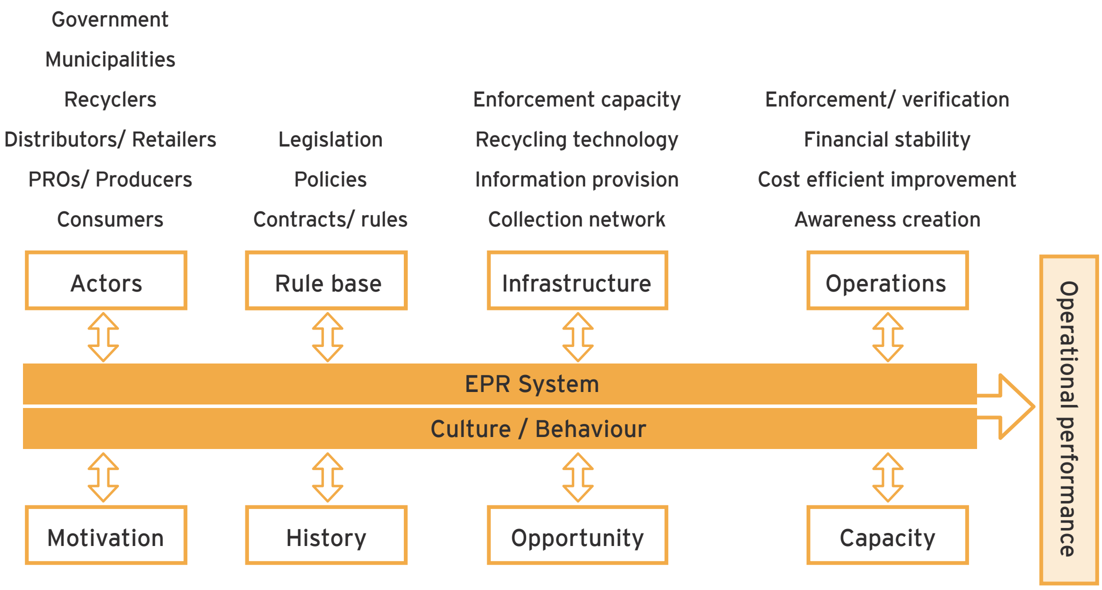

Figure 15 – *Factors contributing to operational performance of collection systems (Richter and Koppejan 2016).*

6.2.1 STAKEHOLDER ENGAGEMENT

The level of stakeholder engagement (connectedness, understanding of roles and responsibilities) along the entire chain is crucial. However, the stakeholder engagement varies. The PROs (Producer Responsibility Organizations) influence the entire logistics, set prices, sign contracts and move material nationally and internationally. They have insight in the entire system and relationships with all the stakeholders. Most PROs organize internal and external forums for awareness raising, education, policy lobbying and intent to improve the operation and possible benefits.

Municipalities' key concern is compliance with the WEEE directive and partnering with the PRO to ensure that lighting equipment is collected. Recyclers should engage more directly with producers to insist on significant improvement of the lighting equipment material treatment and recycling possibilities.

6.2.2 CLOSING THE LOOP

In theory, gas discharge lamps are largely recyclable. Some claim that LEDs are comprised of 95 % recyclable materials (LEDinside 2012). In practice there are few closed loops. One exception is fluorescent tube glass and aluminium cap ends.

Mercury is a serious environmental pollutant and it is important that it is collected. In the Netherlands it is captured by active carbon and sent to landfill as mercury sulphide. Plastics that are used for electric products, including LED replacement bulbs, can contain plastics with flame-retardants such as brominated substances, which are a serious environmental concern. Major producers of LED lighting such as Osram, Philips or Cree have disclosed that their products are free of such flame retardants (compliance with, among other regulations, RoHS and REACH). Those products and plastics should be burnt in the best practice waste incineration facilities, and residues disposed safely. Phosphor powders contain valuable rare earth metals but they are difficult to recycle. So far they are normally stored awaiting a treatment solution. One of the key problems in closing the loop is that a continuous volume stream must be guaranteed, which is reliant on a large network of waste and resource transport and treatment of materials (Guide and van Wassenhove, 2009). Research has identified some critical reasons why EPR closed loop recycling is (yet) not adopted in practice: pricing and quality, available technological solutions, diversity of product materials and the so far limited volumes of LED products. Another reason is that collected LED products have various designs and contain a complicated mixture of product materials. LED products are heterogeneous, non-standardized, manufactured by many producers and rapidly changing in material content.

The virgin materials are currently cheaper than reprocessing or buying back secondary raw material. Philips is pointing to the importance of investing in circular economy solutions such as their "pay per lux" product service business model. Philips has a 50 % financial stake in specific light PROs such as LightRec and RecoLight. But there are gaps, such as the individual motivation and reward and a lack of information systems support such as the ability to fully track materials. The next generation of Philips lights are planned to have strict tracking.

6.2.3 ECO-DESIGN

The CE-marking (EU Directive 2014/35), indicating the self-declaration of the industry concerning the compliance with product and safety requirements (such as the Eco-design Directive and the Restriction on Hazardous Substances Directive), the Energy Efficiency Directive and the EcoLabel regulation are the most instrumental EPR tools for eco-design of lighting products. Possible changes in the industry are phase-out of less energy efficient lamps, maximized energy efficiency and also a new focus on Human Centric Lighting, big data and the Internet of Things.

Designers are mainly focusing on the financial bottom line of key investors, mainly the producers, and this is a challenge in achieving a closed loop as the issues are related to a lack of industry standardization resulting in issues around quality assurance, a lack of direct input from downstream treatment and recycling experts and a possible lack of awareness of critical issues supporting EPR, mineral conflicts, climate change, green procurement etc.

There are increasing discussions, e.g. among Philips, Cisco and Zumtobel, around product service systems, IPR and retaining ownership of products across the life cycle. Through Philips "light as a service" they are responsible for installing, maintaining, refurbishing and recycling its lighting equipment. E.g. Sony are offering repair stations for products and through this they are hoping to identify better design attributes for longevity.

6.2.4 BARRIERS AND INCENTIVES

To achieve a well-functioning system a systemized engagement of actors and infrastructure is needed. This is lacking across the chain, with influence held by specific stakeholders e.g. producers, designers, PROs and municipalities. The current volumes, technology and markets do not support a closed loop partly due to lost lighting equipment as household residual waste, business and illegal markets. It is important to design for improved environmental impact and there is a willingness among business to invest in eco-design. But the global supply chain consists of thousands of manufacturers, a lack of standards and a rapidly evolving lighting technology.

6.2.4.1 Barriers

Highly variable local policies, infrastructure and educational approaches have resulted in a low residential understanding about the necessity to keep the lighting equipment out of the general waste stream and what to do with it. Local externalities such as degradation of road networks and amenities, noise and light pollution can negatively impact municipal depots.

The stakeholder engagement between recyclers and producers is important but too limited. There is a lack of understanding of the full life-cycle costs of EPR in lighting equipment. The fractions, including REE, are not valued enough to ensure recovery and there is a lack of secondary raw material markets. There is also a lack of material tracking systems and incentives for producers. Co-mingled collection systems entails that there is no price incentive for less harmful or better designed products.

6.2.4.2 Incentives

Modified behaviour can be encouraged through a reduced waste bill, deposit refund initiatives, additional residential education, regional EPR awards for greater consistency between local waste policies and implementation of unsorted take-back system to reduce confusion. Take-back along with sales of products should be promoted, services can be kept within the store for customer convenience and loyalty points can be offered on deposits.

6.2.5 CASE STUDIES ON COLLECTION OF LIGHTING PRODUCTS

LED lighting is a new product that has a rather long life-time. So far there is limited recycling of LED and consequently even less research. It should also be noted that the LED materials, components, products and system designs are in rapid development.

From legislation point of view LED products is a kind of electronic waste. Considering recycling infrastructure and public awareness it should be noted that collection of fluorescent tubes is in operation in several countries. The tradition is to try to handle the collection and flow of lighting waste as a separate waste stream, which is denominated as recycling to make it more attractive to collect the lamps.

This report focuses on what cities and other public actors can do to alleviate the problems and to enhance the usefulness of SSL for sustainable development. The following paragraphs describe earlier examples on investments in more efficient recycling. More detailed information on case studies in Sweden, the Netherlands and the United Kingdom can be found in Appendix 5.

6.2.5.1 Sweden

The Swedish Environmental Code (EC) states that every municipality should have a waste management directive ("Renhållningsordning") with a waste management plan and directives on management and treatment. Electronic waste has been covered by the Producers' responsibility (PR) in Sweden since 2001. Elretur, a collaboration between the Swedish municipalities and the producers' organization El-kretsen, states that every municipality has the responsibility to provide recycling stations where the public can hand in waste electronics free of charge and information to consumers about the importance of recycling, source separation, location of recycling stations and recycling results. El-kretsen is responsible for organizing transportation, treatment and recycling of electronics. The Nordic countries are leading with 8-20 kg WEEE collection per capita per year (Richter and Koppejan 2016). Less than 1 % of Sweden's trash ends up in landfills.

Samlaren ("The Collector") is a waste cabinet collection system designed by Renova and students from Chalmers University to make small electronics collection more convenient. Collectors are positioned in grocery stores. The project is led by municipal waste companies and (partly) financed by producers[39]. In Hässleholm, all household waste is taken care of by Hässleholm Miljö AB. Apartment blocks have sorting rooms. Though only 50 % have containers for light bulbs, 6 bigger recycling centres are available for hazardous waste free of charge. From the villas, trash including light bulbs and batteries is collected on spot regularly (Eriksson 2013). Suggestions for improvement are better information, closer recycling centres, more generous opening hours, better signs on garbage containers and stricter control.

6.2.5.2 The Netherlands

The Netherlands averaged 4.91 kg WEEE collection per capita per year 2005 to 2013, has 22 landfills and a ban on opening new landfills (WMW 2013). In 1999 they became the first country in Europe to introduce a national system for collecting and recycling electronic equipment and paved the way for the European-wide 2002/96/EC Directive on Waste Electric and Electronic Equipment (WEEE).

The producers are responsible for all non-household WEEE collection and for collection of household WEEE from municipal drop-off centers and retailer in-store collection. The producers have organized this by the Producer Responsibility Organization (PRO) LightRec which has a service agreement with PRO Wecycle. Each Municipality is responsible for providing a minimum of one location for private drop-off for free. Retailers with floor space of ≥400m^2 are obligated to take back small WEEE (≤25cm). The Producers are responsible for reporting all data to the Dutch Government through the Producer founded (W)EEE Register, to show the WEEE symbol on each product and to provide information on the re-use, recycling and further treatment of the products. The Netherlands has one of the most dense permanent collection facility ratings in the world (one per 1,596 residents), even compared to Norway with an equivalent 1,889 residents per collection facility. Considering that lighting equipment is becoming increasingly digitalized and recognized as a valuable for the REE, ICT PROs may become more interested in ICT take-back. The City of Eindhoven has a "Quadruple helix" program focused on community-led city development and aiming to increase the level of community participation. Distributors are looking beyond legislation to align with broad corporate social responsibility goals.

[39] http://www.sysav.se/Privat/Produkter-och-tjanster/Inlamning-av-farligt-avfall/Samlaren/

6.2.5.3 The United Kingdom

The UK WEEE Regulations were decreed 11 December 2006 and came into force 2 January 2007. The UK WEEE collection 2007-2013 was 5.83 kg per capita per year. There are 725 active landfill sites in the UK. 1700 landfills have ceased their operations since 2001. The UK is seeking alternatives as a response to land scarcity, attitudinal change and EU directives.

The producers are responsible for all non-household WEEE collection and for collection of household WEEE from municipal drop-off centres. There are three different ways for distributors to organize WEEE take-back: in-store collection, via collection Municipal DCF facilities or via facilities shared with other distributors. The UK allocates responsibility for data provision to relevant authorities and regarding end-of-life product take-back to the producers and distributors. For UK producers and importers, responsibility to report all data to the national data-house for all PCS data (the "Settlement Centre") is critical. The "Settlement Centre" transfers all the data to Eurostat. The WEEE symbol has to be on products and information regarding EEE POM (the collection rate of WEEE) has to be provided to AATFs to assist with treatment and recycling options. The UK has 37 permanent collectors, most of them for take-back of all forms of WEEE. Two are lighting equipment specific: Lumicom and RecoLight. The landfill taxes have increased in the UK over the years and therefore some municipalities seek to minimize their landfill. Lighting equipment is neither heavy nor currently valued and municipalities tend to focus on other items.

6.2.5.4 Germany

Germany has a mechanism known as 'divided product responsibility' for WEEE disposal[40], shared between manufacturers and public sector recycling companies. Those are required to establish recycling centres that accept WEEE from households free of charge. There are more than 1500 municipal recycling centres in Germany. Retailers with a sales floor or storage > 400 m2 are obliged to take back household appliances free of charge[41]. Manufacturers are free to provide own take-back and recycling infrastructures. However, they have to bear the financial cost and provide containers for collection (Sander et al. 2007). Allocation of fees on a monthly basis is calculated by a clearing house institution (Stiftung EAR Elektro-Altgeräte-Register[42], national register for waste electric equipment). Entrusted with sovereign rights by the Federal Environmental Agency (UBA), the clearing house registers all the manufacturers and coordinates the provision of containers and the collection of e-Waste.

6.2.5.5 Finland

Foreign and domestic manufacturers have transferred EPR obligations to five producers associations, which in turn have appointed or founded WEEE recovery service providers (Elker Ltd., SERTY, ERP Finland) providing collection, transportation, sorting and disassembly of products, storage, and selling of material fractions, reusable products, and parts. The service providers have implemented a centralized reverse supply chain, i.e. for transportation from collection to treatment.

[40] https://www.umweltbundesamt.de/en/topics/waste-resources/product-stewardship-waste-management/electrical-electronic-waste (2016-06-03)

[41] https://www.stiftung-ear.de/fileadmin/download/Vertreiber_Flyer-Download.pdf (2016-06-03)

[42] https://www.stiftung-ear.de/en/ (2016-06-03)

Elker established a decentralized logistic network sourcing from several regional operators such as private social enterprises and public institutions. The permanent collection at around 450 collection points allows private users and households to bring e-Waste. Non-private users have separate b-2-b collection points. E-Waste including lighting equipment can be returned to retailers and grocery stores (with > 1000 m2 sale floor). From the local collection points, the e-Waste is transported to regional sorting and pre-treatment stations across Finland. Waste fractions are then transported to recycling and recovery plants, hazardous waste is treated in special treatment plants and a minor fraction is disposed in landfills (Ylä-Mella et al. 2014).

6.3 PRODUCT SERVICE SYSTEMS

To achieve a sustainable society, it is necessary to transform the industrial structure so that it does not reduce the earth's resources. A product service system is a business model in which a firm offers a mix of products, services, supporting networks and infrastructure to enable a higher competitiveness, satisfaction of customer needs and lower environmental impact than traditional models.

To enable the uptake of PSS lighting solutions it is important for municipalities to have established priorities for lighting. This can be realised either through a municipality-wide lighting strategy or the distinct planning and implementation responsibility of one municipality department. Company representatives state the importance of distinctly defined customer preferences to be able to submit optimized offers and project implementation with reduced transaction costs associated with identifying priorities and convincing decision makers. Entrepreneurs within municipalities are vital to support innovative procurement and to overcome risk avoidance attitude in the public sector. Many municipality representatives find it difficult to judge whether a lighting solution that comprise lighting equipment and several services is an economically appropriate investment. One important aspect for the municipalities to consider is to make such product choices that the production of those products promotes accumulation of a societal stock of materials with high resource value/usefulness and viable possibilities of recycling.

The municipalities need knowledgeable people to invest time in pre-procurement dialogues to find suitable lighting solutions. In functionality oriented procurement it is vital to clarify the lighting needs and to translate these needs into tender requirements. One factor that causes distorted judgement is that responsibilities and budgets in municipalities are often divided among different departments.

For small municipalities the solution could be to create or engage in capacity complementing organisations at a regional level; either regional energy agencies or county-based procurement organisations (Wuennenberg 2016). One example of such a joint organisation is Lyse, which is owned by 16 municipalities in the Stavanger region, Norway.

Section 6.3.1 gives two examples on PPS lighting refurbishment in municipalities, more case studies on refurbishment can be found in Section 6.4.1.

6.3.1 CASE STUDIES

6.3.1.1 School Lighting Refurbishment in Tierp Municipality

20 to 30 % of the electricity consumption in Swedish schools is consumed by lighting and 70-80% of schools in Sweden have outdated lighting systems. Tierp Municipality in Uppsala County in Sweden have 12 schools and unlike other small municipalities in Sweden, has its own procurement department. A municipality owned organisation for municipal properties is responsible for the maintenance, renovation and procurement of new lighting solutions. The schools are tenants in the buildings and pay rent to the organisation for municipal properties. The organisation for municipal properties receives additional budget for renovation projects. The property manager has opportunities to initiate renovation projects for the whole school building. When the start-up company Två Punkt Ett approached the organisation for municipal properties the property manager took over responsibility for enabling implementation. Två Punkt Ett sells light as a service to public schools for a regular lighting fee and offers test installations to municipality owned schools to demonstrate good light and service quality. Initially, Tierp Municipality decided to have one test classroom and in 2015, the property manager decided to have more installations in several classrooms of another school. Since the fee is rather low the organisation for municipal properties so far issued the investments as "testing money". An official public procurement did not yet take place. For a small Municipality with limited resources and experience it can be difficult to prepare a tender for procurement. In 2013 the project UppLyst 2020 (financed by the Swedish Energy Agency, Uppsala County Council and involved municipalities) was initiated in Uppsala County to diffuse knowledge about LED technology and its procurement among local municipalities. The foundation STUNS Energi implemented and evaluated the project.

6.3.1.2 Street-lighting Refurbishment in Sala Municipality

Sala Municipality, Sweden, has a population of 22,000. The entire street-lighting infrastructure, including cables and poles, is owned, operated and maintained by the local energy company Sala Heby Energi AB (SHE), which is owned by the Sala Municipality and the Heby Municipality. SHE is quite autonomous and steers own projects.

In 2014, SHE decided to switch to LED lighting for 5,166 light points. Energy efficiency gains were the main objective and SHE also had other requirements. As a municipality owned company, they need to follow public procurement law. SHE started a pre-procurement process to identify the best available lighting manufacturers as well as possible ways of funding to minimize the need for upfront investments by the municipality.

The economic target implicated a need for significant energy savings. SHE identified four potential suppliers during pre-procurement and launched a call for tender. SHE did not list technical requirements but addressed technical aspects during the procurement negotiation process with the four potential suppliers. SHE was using this a learning process and a lot of time was invested.

SHE decided to include a control system and selected Philips as supplier, mainly due to their reputation and control system CityTouch. The street-lighting refurbishment is completed. For Philips, it represents the largest LED street-lighting project with integrated CityTouch management system in Europe.

6.4 ESCO models

The project management of lighting retrofitting processes, including tendering, negotiations, implementation etc. requires certain skills at the clients (municipality) side. Limited or missing in-house competencies pose barriers to municipalities for energy and retrofit projects. Outsourcing to an Energy Service Company (ESCO) is one possible solution to this problem.

The landlord-tenant problem is a form of split-incentives phenomenon where the involvement of an ESCO also can have a positive influence.

Design and elaboration of an ESCO contract is challenging and includes different sorts of complexities and legal issues. Especially, to prevent disadvantageous contract design, i.e. a lack of flexibility, a fair balance of savings, life-time and maintenance backlogs, expert personnel is needed to manage contracts. Section 6.4.1 is a summary of a few real-life examples involving ESCOs.

6.4.1 CASE STUDIES

6.4.1.1 City of Dormagen[43]

The city of Dormagen, situated in North Rine-Westfalia, began with its owned technical operations provider TBD to replace old mercury vapour lighting with efficient sodium vapour high pressure lighting. Between 2006 and 2008 about 4.900 street-lights have been replaced within a performance contracting model.

In a pilot project the city shifted to even more efficient LED lighting and subsequently announced another contracting tender for additional 4045 lights. The magnitude of the tender allowed an EU-wide announcement. The company LUXSAR GmbH, based in Cologne, Germany, received the contract for the LED retrofit. LUXSAR GmbH as contractor pre-financed the LED luminaires (LED Retrofit CB Straßenlampen, 20 W, 2100 lm ± 50 lm, 4000-4500 K and 27 W, 2900 lm ± 100 lm, 4000-4500 K).

The lamps have been supplied by LUXSAR GmbH and installed by TBD during 2014 and 2016. Approximately 58% of electricity could be saved, compared to the situation before which is equivalent to a reduction of 254 t CO2 per year. The contractually guaranteed monthly electricity cost amount was 7.425 EUR.

The city of Dormagen relied on a standard contract (SBI XXXX). Beside net present value of lamps other aspects such as contract duration, product durability, length if warranty and polluting potential where considered. Life cycle costs have been carefully analysed, allowing a rational decision. Other key success factors have been the level of responsibility taken by the decision makers, a transparent and comprehensive data base (partly derived from European energy award (R) activities) and political will.

[43] https://dormagen.de/bauen-umwelt-verkehr/klimaschutz00/ (2016-06-23); http://gpp-proca.eu/bestpractice/city-of-dormagen/ (2016-06-23), http://www.klima-log.de/projekt.asp?InfoID=8415 (2016-06-23), http://www.energieagentur.nrw.de/effiziente-straenbeleuchtung-trotz-knapper-kassen-dormagen-ruestet-ueber-finanzierungs-contracting-4000-leucht (2016-06-23), von Flotow/Polzin 2015

This excellent frame conditions allowed also coping with difficulties such as:

- documentation and data collection
- different owner structure of street-lighting
- budgetary law
- finding a decision between in-house vs. external realisation
- procurement law
- project management during negotiations and complexity of contracts
- building trust and confidence towards the contractor

6.4.1.2 City of Bad Schallerbach, Austria (Fedarene 2016a)

Refurbishment of old lighting technology, i.e. high-pressure mercury lamps, was necessary because of the age of the lighting systems and the phasing out decision. 100% of the street- lighting system was therefore retrofitted from candelabrum HQL to LED. Bad Schallerbach municipal authorities announced a tender and awarded the contract to a local ESCO (Elektro Kliemstein). It was the first EPC project of this ESCO, but the company was already responsible for maintenance work prior to the refurbishment, thus a trustful relation was existing. For the retrofit in the 3400 inhabitants' city, a total investment of 550,000 EUR was necessary. The project was co-financed by the European Street-light EPC project and also received subsidies of about 60,000 EUR. The contract duration was about 10 years. Because of the LED retrofit, the following goals have been achieved:

- Electricity cost savings of 19.500 EUR/a (based on baseline electricity prices);
- Reduced electricity consumption: 131,000 kWh/a;
- GHG emission reduction of 39 tons/a;
- Maintenance cost savings of 20,000 EUR/a.

6.4.1.3 City of Bad Antiesenhofen, Austria (Fedarene 2016 b)

The municipality with 1000 inhabitants was confronted with financial constraints while the lighting system was outdated and represented a large share of the energy cost. An EPC model was used to improve the lighting technology without compromising service quality levels. The contract with the ESCO EEW Group was about 10 years. Although maintenance was not included in the EPC, the municipality nevertheless benefited from significant reduction of maintenance cost, as LED lighting systems are low-maintenance technologies. With an investment of about 300,000 EUR the following result have been achieved:

- Electricity cost savings of 1600 EUR/a (based on baseline electricity prices);
- Reduced electricity consumption: 11,000 kWh/a;
- GHG emission reduction of 3.2 tons/a.

6.5 Concluding recommendations for cities

Cities can lead by example with green lighting procurement practices to improve the work and living environments in pre-schools, schools, offices, hospitals, for the elderly and in the traffic. Municipalities should act as a role model and enhance the procurement and application of SSL in municipal properties, public spaces and street-lighting. Table 12 summarizes some of the actions that a municipality should consider in its endeavour to become a sustainable city.

Table 12: Summary of sustainable city development issues and actions (with reference to respective Section for more detail).

Type/Stage	Municipality role	More detail
Procurement	Enhance the ability to specify the wanted and needed individual, spatial and temporal light variation, as a basis for light design, energy optimization and to clarify the functional value. Use a more comprehensive definition of functional value when considering costs and benefits of lighting solutions	3.5 4.2.3 (Table 2)
	Address barriers inhibiting green public procurement and innovative procurement	5.1
	Use ecolabel criteria to guide criteria for Green Public, but also go beyond these where possible. Indicate to producers and suppliers an interest in eco-designed (i.e. for recyclability, durability, modularity) lighting products.	2.2 6.2.3
	Indicate an interest to suppliers in reuse or using recycled products/ content where possible	5.1
	Consider procurement of lighting services instead of products	5.4
	Strengthen the control measures to make sure that the system installations have the specified user characteristics and quality, e.g. by clarifying how the resulting lighting and energy variation will be measured.	
Demonstration	Use demonstration facilities in pre-commercial procurement to avoid mistakes in the tendering process and to achieve a better final solution.	5.1
	Make use of evidence based design	3.1
	Educate and inform citizens about the potential benefits of SSL for health and wellbeing	3.3
Use	Demonstrate the potential of SSL solutions through public installations	
	Work with partners (e.g. universities) to test and measure benefits of SSL	
End of Life	Enable re-use centres to encourage reuse of disused electronics (WEEE including SSL), through component or product reuse, remanufacturing, or repurposing.	4.6.3
	Educate and inform citizens about responsible disposal of WEEE, including lighting products. Consider using framing not only about avoiding environmental impact but about conservation of valuable and scarce resources	4.6
	Work with other actors to ensure a well-functioning Extended Producer Responsibility system with convenient take-back locations for citizens	4.6

While production patterns may be hard to influence or steer from a municipality's perspective, actions should be considered in two distinctive areas:

a. Enhancing the application of SSL in municipal properties, public spaces and street-lighting, not least because municipalities should refer as role model;
b. Organizing and supporting local and regional e-Waste collection schemes:
    i. Enforcement of legally compliant e-Waste disposal;
    ii. Support of waste handling providers and engaging with social enterprises in the sector;
    iii. Promotion of voluntary actions, for example by information and awareness raising campaigns.

Figure 16 is an attempt to describe where the municipalities have the greatest opportunity to influence the actions towards a more sustainable perspective on SSL.

The key point of actual decision making is the procurement that influences the choices of installation design, type of products and selection of manufacturers.

Policy making is important to enable city staff to make the proper investments that are necessary to harvest the full human health and wellbeing potential of SSL and for development of a circular economy.

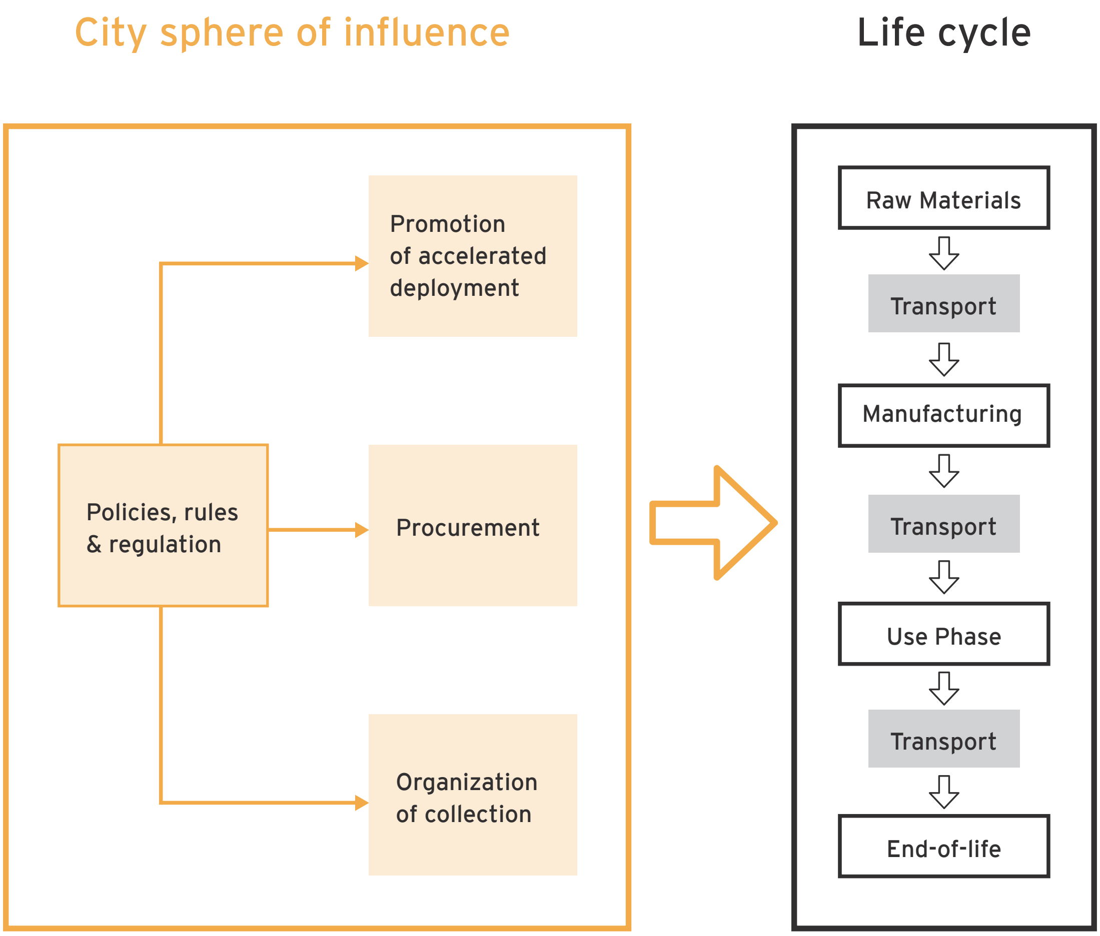

Figure 16 – *Areas of influence for sustainable deployment of SSL in municipalities. The municipalities' decisions and actions directly influence the use phase and end-of-life. Indirectly this also influences the manufacturing and raw material production.*

CONCLUSION

7

7 | CONCLUSION

SSL, in combination with today's Information and Communication Technology (ICT) and the new knowledge about the human effects of various kinds of light, enables significant social, environmental and economic development advantages. Technically, user adapted design and light variations can save 95-99% of the lighting electricity, on system level, but so far the energy use for standby modes often is high. The possibility to limit the lighting to the actually needed light is also vital to reduce light pollution.

Specialized LED luminaries and controls enable lighting designs that provide very high effectiveness, functionality and also health and wellbeing advantages. But so far luminaries with not removable LEDs and electronics are a challenge from recycling point of view. The new lighting is an important application field for value enhancing innovation and development of Circular Economies.

7.1 SUMMARY OF SUSTAINABILITY ISSUES

There are two kinds of sustainability issues. One is that new technology, e.g. SSL, tends to introduce new kinds of sustainability risks. On the positive side SSL enables energy savings and better light environments. Table 13 summarises a number of positive as well as negative social, environmental and economic sustainability considerations.

The Carbon Footprint and the Environmental Footprint of SSL are smaller than for conventional lighting technologies and scarcity issues for SSL are comparable to other kinds of electronics. Eco-design of effective system solutions enables Human Centric Lighting, i.e. social sustainability advantages and simultaneously significant energy savings.

The breadth and quality of research on possible environmental effects of SSL implies that the risk for devastating effects is comparatively low and that the environmental risk is comparable to electronics in general.

7.2 CHALLENGES FOR CITIES

The cities most important short-term sustainable development priority for SSL is to promote competence development and introduction of Human Centric Lighting by demonstrations of more advanced light environments. In a long-term perspective, cities can promote eco-cyclic innovation (i.e. circular economy) by clarifying that when they start buying larger volumes of new more advanced lighting systems, they will aim for open modular solutions that, among other things, enable smooth recycling.

The Principal agent problem often hampers investments in more advanced lighting products and effective system solutions. Recycling is technically possible for parts of the SSL material. Municipalities can take an important role by development of recycling infrastructure, dissemination of information and build-up of awareness.

Table 13: Summary of sustainability issues for SSL.		
	Risks	Possibilities
Social	• Difficult to make user adapted choices of SSL solutions • Difficult to assess product qualities • Public distrust due to inferior products • Complicated control systems • Uncertainty about flicker and blue light hazard	• SSL enables better adaption to human sensory system than traditional lighting • SSL enable light environments that promote health and wellbeing. • SSL can improve work & living environments in pre-schools, schools, offices, hospitals, for the elderly, traffic safety & social city lighting • SSL controllability enables dynamic user adapted solutions
Environment	• Extensive use of LED results in broad dispersal of electronics in very many small products • Luminaries with non-replaceable LED and electronics • Scarce and critical materials used in SSL => shortage of supply • Flame retardants in plastics • LED products on market that are not RoHS compliant (e.g. lead soldering) • Higher energy use in LED product manufacturing • Low recycling rates for WEEE and lighting in many cities and countries • Integrated design and use of low quality materials hamper recycling	• Significant energy savings in the use phase and thereby lower overall environmental impact • Mercury avoided through use of LED • Less REE (Rare Earth Elements) compared to fluorescent lighting • Many EU agencies have indicated increased market surveillance for lighting • Effective take-back systems for lighting and electronics already developed in EU • Reuse or repurposing of products and components • Design for recycling and reuse
Economic	• Landlord-tenant problem • High investment cost • Lack of modularity and standardisation in design • So far limited capacity for upgrading of collected SSL including electronics • Lack of markets for recycled materials and competition with cheaper virgin materials • Functional ownership models are relatively new and untested in this field, with barriers	• SSL enable lighting that promote higher productivity & lower health care costs • Life Cycle Cost savings through energy saving & longer life-time that reduce the need for replacement work • Less maintenance due to longer life-time & supervision possibilities • Circular economy strategies could drive more opportunities for value in reuse and recycled products, components, materials • Functional ownership/service demonstration models emerging and barriers can be addressed

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APPENDIX 1: LCA CONTINUED

APPENDIX 1: LCA CONTINUED

Life Cycle Assessment Methodology

A Life Cycle Assessment is the compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. LCA studies are typically carried out in compliance with the ISO 14040 and ISO 14044 standards in which the methodology framework is regulated.

Typically, a LCA consists of four major phases:

1. During the definition of goal and scope, the framework of the study is developed. Amongst other things, this includes a description of the product system to be studied, the system boundaries, the functional unit and allocation procedures as well as impact categories;
2. The Life Cycle Inventory (LCI) is about collecting and analyzing of quantified data related to extraction of resources from nature and emissions caused by our processes (e.g. emissions to e.g. air and water, waste generation and resource consumption). The whole life cycle is included in a cradle-to-grave approach, which means that environmental burdens from the extraction of raw materials through production and use to final disposal, including recycling, reuse, and energy recovery have been included;
3. The Life Cycle Impact Assessment (LCIA) is the estimation of potential environmental pressures in terms of e.g. climate change, pollution, resource depletion, acidification, human health effects, etc. (typical indicators for impacts are shown in Table 1) The environmental pressures are associated with the environmental interventions attributable to the life-cycle of a product;
4. Interpretation of the findings, providing conclusions and recommendations as well as stating assumptions and limitations of the study.

The term product system – according to ISO 14040 – refers to this. A product system includes all unit processes necessary to fulfil a certain functional unit including related inputs from and outputs to the environment. It is crucial to carefully define which unit processes are included in the system boundaries considered in the LCA in order to accurately compare different product alternatives.
In the production and manufacturing stage all raw materials from upstream are delivered to the production plants of the LED chip and the LED packages. It is expected that the extraction and processing of raw materials, especially of metals and rare earths and the production of the LED chips and packaged diodes take place at different locations, i.e. in China or Asia. The manufacturing of the actual lighting products, i.e. multi LED assemblies, the LED modules, luminaries and so on, can also occur in other geographical regions for instance in the US or in Europe. Environmental impacts related to transport emissions over various distances need to be considered here. As a rule of thumb, inland truck transports of about 1000 km and transoceanic ship transport of about 10,000 km can be assumed. Downstream processes, taking place after manufacturing, are related to distribution and transport of the LED product to the point of sale and to the end-user. Subsequent stages in the life cycle are installation and use phase as well as end-of-life.

APPENDIX 2: TECHNICAL PRODUCTION PROCESSES

APPENDIX 2: TECHNICAL PRODUCTION PROCESSES

Production and use of LED

A) LED chip production

LED technology is based on a semiconductor diode, where the materials are doped with impurities to create p-n junctions. When an electric field is applied, i.e. the LED is powered, electrons flow from the n-side (cathode) to the p-side (anode) leaving holes. When an electron meets a hole, it falls into a lower energy level and releases energy in the form of photons. The wavelength and thereby the light emitted by the LED depends upon the band gap structure (electron-hole recombination) and the materials selected. When the correct materials are used and the wavelength of the light is modified by coating the LED bulb with phosphor, an LED is able to produce white light. This is a widely used application. Blue light from an indium-gallium nitride (InGaN) LED is absorbed by an yttrium aluminium garnet phosphor to produce white light. Another way to produce white light is to combine different coloured LED's, usually red, green and blue. Generally speaking, LEDs of all colours usually include small amounts of metals such as gallium (Ga), indium (In) and arsenic (As).[44]

Manufacturing of LEDs is a complex high-tech process. The production of a blue (InGaN / ThinGaN)-LED chip comprises the following stages[45] (see also Table A2.1:

Sapphire Wafer Substrate Manufacturing: The initial step is focusing on preparing a polished and cleaned sapphire wafer to be used subsequently in an MOCVD reactor for LED die fabrication. The wafer manufacturing starts with the growth of large sapphire crystal boules. For the boules, a large amount of aluminium oxide is melted and a seed crystal is introduced in the molten solution. By pulling a rotating seed crystal slowly out of the solution, circular crystal growth occurs. The growing process is a function of the melt temperature, the speed of rotation and pulling. In the following steps the wafer is grounded and sliced into wafers of a specific diameter. In additional steps slices are polishing and cleaning. Major inputs to this process are alumina, electricity/heat, water and ultrapure water, cleaning detergents (e.g. ethoxylated alcohols), diamond slurry.

Fabricating the LED die itself is subdivided into the epitaxial growth, front-end and back-end processes. Epitaxial growth or crystallizing is used to produce epi-wafers of semiconducting materials (III-V semiconductors) under - depending on the epitoxy method - high temperatures and/or vacuum[46]. The substrate can, for example, be mounted in a metal organic chemical vapor deposition (MOCVD) reactor (see Table A2.2). The substrate is heated, followed by the deposition of the nucleation layer, the n-type-layer, several active layers and finally the p-type layer.

[44] Wilburn 2012 according to Bergesen et al. 2015
[45] Van Driel and Fan 2013:19ff.
[46] Van Driel and Fan 2013:23ff.

Table A2.1: Main steps and inputs in substrate production (Scholland and Dillon 2012: 25ff).	
Production step	**Selected Inputs (amounts)**
Boule growth in a reactor by melting aluminium oxide (Al_2O_3) to grow a large sapphire crystal boule (Czochralski method).	**Energy:** Electricity (18.3 kWh/wafer) **Materials:** Aluminia (16.6 g/wafer) Chemical cleaning agents, e.g. alkali cleaning or ethoxylated alcohols (3.5 L/ per wafer) Diamon slurry (830 g/wafer) Ultrapure Water (150.3)
Core fabrication: The sapphire crystal boule is drilled with diamond tools to cores in appropriate diameters.	
Wafer slicing: The cores are sliced in thin wafers with a diamond saw and deionized cooling water.	
Lapping and bevelling: Using a diamond slurry and water, the cut-wafers are cleaned in order to remove saw marks and other defects.	
Polishing and chemical-mechanical planarization to remove any irregularities making a flat wafer.	
Geometry and optical inspection to detect any defects, such as pits or micro-cracks. Final cleanings to remove trace materials and particles by using NH_4OH, dilute HF acid, deionized water rinse, HCL and H_2O_2.	

Table A2.2: Stages and estimated inputs of Gallium Nitride Epitaxy (Scholland and Dillon 2012: 28).	
Production step	**Selected Inputs (amounts)**
Heating and bake-out of the sapphire substrate at high temperatures in a hydrogen and ammonia atmosphere	8.75 kWh/wafer 0.06 m³ H_2 / wafer 0.02 kg NH_3 / wafer
Deposition of the nucleation layer at temperatures around 550°C and stabilization of the nucleation layer at very high temperatures of 1200°C	4.74 kWh / wafer 1.46 kWh / wafer 0.02 kg NH_3 / wafer
Growing of the buffer layer, a thin amorphous film of gallium at temperatures around 550°C followed by heating up in order to grow mirror-like gallium nitride layer. Next to that, a layer of negatively doped gallium nitride is deposited, with silane (SiH_4) as electron-donating dopant.	9.77 kWh/wafer 1.38 grams TMGa / wafer 0.42 kg NH_3 / wafer 1.54 m³ H_2 / wafer 1.54 m³ N_2 / wafer 0.06 g SiH_4 / wafer
At temperatures around 750-850°C the active layer, consisting of several indium gallium nitride quantum wells are grown.	4.74 kWh/wafer 0.03 grams TMGa / wafer 0.01 kg NH_3 / wafer 0.01 m³ H_2 / wafer 0.01 m³ N_2 / wafer 0.01 g TMIn / wafer
Deposition of a confining layer (P layer) of positively doped aluminium gallium nitride (AlGaN). The layer confines the charge carriers in the active layer. This layer is called P layer.	3.28 kWh/wafer 0.06 grams TMGa / wafer 0.02 kg NH_3 / wafer 0.06 m³ H_2 / wafer 0.06 m³ N_2 / wafer 0.00 g TMAl / wafer

The LED epitaxial wafer is then subject to a series of front-end and back-end processes.
Front-End processes:

- Mesa forming includes defining a conductive area for exposing n-type GaN;
- Forming of a transparent conductive layer (TCL) to improve the current spreading and electroluminescence;
- Pad forming includes depositing of metals to provide a current path;
- Passivation with SiO_2 to protect the LED against moisture.

Within back-end chip forming processes, the LED chips are separated to individual ones by:

- Grinding: grounding the wafer;
- Dicing means to individualize the neighbouring GaN LED by melting and ablation;
- Binning and sorting is to separate and collecting high quality products.

An overview of material and energy consumption of LED die fabrication is given in Table A2.3.

Table A2.3: Overview of Energy and Material Consumption in LED Die Fabrication (Scholland and Dillon 2012:32).	
Material	**Amount**
Acetone	467 g/wafer
AuSn solder	0.29 g/wafer
Developer (usually an inorganic chemical)	115 g/wafer
Etchant Ag (usually a hydrogen fluoride)	30 g/wafer
Etchant Metal (usually a hydrogen fluoride)	60 g/wafer
GaN Etchant (usually a hydrogen fluoride)	192 g/wafer
Hydrogen H_2	136 g/wafer
Nitrogen N_2	5527 g/wafer
Ammonia NH_3	447 kg/wafer
Oxygen O_2	2.3 kg/wafer
Photoresist (usually sort of organic chemicals)	19 g/wafer
Energy (electricity mix)	42.57 kWh/wafer
Sulfur hexafluoride SF_6	13 g/wafer
Silicon carbide SiH_4	0.242 g/wafer
Slurry	2.3 kg/wafer
Target Ag (silver)	0.005 g/wafer
Target Al (alumonium)	0.003 g/wafer
Target Ni (nickel)	0.004 g/wafer
Target Ti (titanium dioxide)	0.002 g/wafer
Target W (primary or secondary palladium)	0.06 g/wafer
TMAl (aluminium)	0.003 g/wafer
TMGa (gallium, semiconductor-grade)	1.47 g/wafer
TMIn (indium)	0.01 g/wafer
UPW (ultra pure water)	240 kg/wafer

B) LED chip packaging

In a next phase, LEDs are packaged to ensure electrical connection as well as mechanical protection, integrity and heat dissipation. The packaging phase involves, depending on different chip specifications, several steps. Conventional LED[47] packaging consists of mounting / housing the LED die, making electrical connections (which includes electrical lead and wires), die attach, as well as applying phosphor, encapsulants and optics (see Scholland and Dillon 2012:33). In Table A2.4 energy and material consumption for conventional LED packaging are listed.

Table A2.4: Overview of Energy and Material Consumption for LED Packaging assembly (Scholland and Dillon 2012:34, Tab. 5-8)

Material	Amount
Ceramic Substrate (2-layer Alumina, aluminium oxide)	0.0135 g/LED
ESD diode (Silicon)	0.055 g/LED
Gold	0.00006 g/LED
Underfill (silicone product)	0.0196 g/LED
Silicone (epoxy resin)	0.00006 g/LED

C) MULTI-LED ASSEMBLY AND ATTAINING ACCEPTABLE CRI

As LED packages have a small dimension (4 x 5 mm^2 to 10 x 10 mm^2), several LED packages are assembled into a self-ballasted LED lamp that can be inserted to a voltage socket. This step includes attaching several LED to a PCB (printed circuit board) by a bonding process with solders or epoxy glues.

A single LED can only generate a particular wave length. The light from LEDs have to be treated in a special way in order to reach acceptable colour temperature and CRI values. Several approaches are known for this, basically:

- Wavelength conversion involves converting the LEDs' emissions to a visible wavelength spectrum to generate white light. Most commonly[48], a thin coating containing a mixture of yellow (YAG-Ce^{3+}c[49]) and red phosphors is applied on top. Most of the blue light emitted by the LED is converted in the phosphor coating to yellow/red light, while some blue light passes unconverted. The resulting combined light spectrum resembles white light[50].
- Colour mixing means that several LED are mixed to generate white light. For example two (blue and yellow), three (blue, green, red) or four LEDs (red, blue, green and yellow) are mixed. As no phosphor is used, there is also no loss of energy during the conversion process. Colour mixing is more efficient than wavelength conversion but requires LEDs of different colour and the resulting spectrum shows the peaks of the individual LEDs.
- A blue LED placed on a homoepitaxial ZnSe substrate emitting yellow light. This technology can generate white light with a colour temperature 3,400 K and a CRI of 68[51].

[47] There are several other packaging approaches such as High Brightness LED packaging and Wafer-Level Chip Integration (WLCI) Technology.

[48] Van Driel and Fan 2013:33ff.

[49] YAG is the acronym for a cerium(III)-doped Yttrium aluminium garent.

[50] https://en.wikipedia.org/wiki/Phosphor#White_LEDs (2016-04-29), Kitai 2008, Ronda 2014.

[51] Van Driel and Fan 2013:33ff. referring to Katayama et al. 2000.

Table A2.5 presents an example of resource demand for an LED lamp with 12 diodes.

Table A2.5: Overview of Energy and Material Consumption of a 12.5 W LED lamp with colour mixing in 2012 (Scholland and Dillon 2012:35, Table 5-9).	
Material	**Amount per lamp**
LEDs (blue light, from above sections)	12 units
Remote phosphor (rare earth concentrate, 70% rare earth oxide, e.g. from bastnaesite	1.0g
Plastic phosphor host (rare earth concentrate,70% REO)	11.1g
Aluminium heat sink (cast alloy)	68.2g
Copper	5.0 g
Nickel	0.003g
Brass	1.65g
Cast iron	4.0g
Chromium steel	0.0002g
Inductor (copper)	5 pcs.
Integrated circuit chip	2.0 g
	8 pcs.
Capacitor electrolytic type	6 pcs.
Diode (diode, glass-, SMD type, surface mounting)	6 pcs.
Printed Wiring Board	15.0 g
Resistor SMD	35 pcs.
Resistor wire wound	3 pcs.
Transistor, wired	6 pcs.
Resin Glue (epoxy resin)	4.5g
Solder paste	0.3g
Electricity (electricity mix China)	5.0 MJ
Assembly LCD screens	178 g

D) LED MODULES

LED lighting requires a constant current of DC power, therefore an electronic driver is needed for converting AC power into DC or from one DC level to another. The electric driver and interconnections are needed in addition to the optical part. The electronics are also expected to provide protection functions to avoid overvoltage, overload and overheating (temperature shutdown). The driver can have additional functions as needed, for instance, for dimming and colour changing. As SSL is a digital technology by nature, the lighting function can be combined with other functions such as sensing, communication and control, for instance to create smart home functions[52].

[52] van Driel and Fan 2013:35

E) LUMINAIRES

A luminaire, or light fixture, is a device that simply holds the packaged LED, the driver, controller and thermal management part and often also some optics to enhance the light distribution. In order to accelerate market penetration and to allow retrofit/replacement of incandescent lights, LED light bulbs have been designed with the fixture design for traditional lighting (retrofit LED lighting). Customers can directly replace their bulbs. So- called "beyond retrofit" products have directly integrated LEDs and driver electronics in the luminaire. In Table A2.6 an example is given of material and process input for the manufacturing of a LED downlight luminaire.

F) MATERIALS[53]

LED modules and luminaires consist of multiple compounds and materials such as:

- Copper
- Aluminium
- Tin
- Silver
- Indium
- Iron
- Plastics, including flame retardants

The main functional materials in LED dies are:

- Gallium
- Indium
- Arsenic
- Aluminium
- Silicon
- Magnesium
- Zinc
- Tungsten
- Germanium
- Aluminium Oxide (Sapphire)

In the die package stage the following materials are used for the phosphor coating:

- Yttrium
- Cerium
- Europium
- Terbium
- Erbium

[53] Gielen 2011, Buchert et al. 2012

Table A2.6: Raw material and process inputs during manufacturing of a LED downlight luminaire (Tähkämö et al. 2013).

	Material	Amount per lamp
Driver	PCB, 2-sided, 50 % SMT, 50 % THT, lead-free, including mounting processes	0.009 m^2
	Capacitors (electrolyte, film, or unspecified)	18 g
	Diodes	0.6 g
	Resistors	2 g
	Transformers	48 g
	Integrated circuits	0.1 g
	Transistors	0.3 g
	Other components (unspecified)	0.7 g
	Plastics	130 g
	Connectors (65% nylon 66, 27% copper, 7% iron, 1% tin)	5 g
LED Array	Light-emitting diodes	16 pcs., 28 g
	Silicone product	3.74 g
	Aluminium	23 g
Aluminium parts	Aluminium (heat sink and reflector), processing	700 g
	Coating	0.17 m2
Other parts	Steel	17 g
	Plastics, injection moulding	26 g
	Cable	7g
	Paper	3 g
Remote Phosphor cover	YAG (yttrium aluminium garnet) coating	0.2 g
	Electricity, French mix	0.002 kWh
	Aluminium oxide	0.1 g
	Organic chemicals	0.1 g
	Plastics, injection moulding	7 g
Assembly	Electricity, French mix	0.029 kWh
EoL	Waste treatment, recycling of intermediary cardboard packages	175 g

G) DISTRIBUTION AND TRANSPORT

This phase covers the transportation from the point of fabrication to the point of installation (e.g. 10,000 km transoceanic freight ship from China and 1000 road transport by trucks to the point of sale[54]. Packaging material, such as corrugated card board (about 37 g per lamp[55]), needs to be considered here, too. Environmental impacts due to transportation can however be considered as marginal in relation to production and use phase.

H) INSTALLATION OF SINGLE OR A COMPLETE LIGHTING AND LARGE SSL SYSTEMS

Lighting systems are usually complex, composed of various interconnected parts such as multiple luminaires, smart sensors, control schemes and data mining and management devices. Examples for lighting systems are street-lighting, building lighting and city lighting.

I) USE PHASE

Use phase environmental impacts are tied to electricity consumption which is depending on the one hand on the number of lights installed, the level of lamination and the operating hours and on the other hand on the type of electricity generation.

J) RECYCLING AND END-OF-LIFE TREATMENT

Obviously environmental loads and benefits due to end-of life treatment and recycling are dependent on collection rates and recycling rates. Scholland and Dillon 2012 estimate that the LED lamp is being recycled only 20% of the time and the packaging about 30% of the time[56]. The rest of the waste streams collected is landfilled. It remains unclear how to deal with waste that is never collected.

Other estimations are made by Tähkämö et al. 2013:

- Scenario 1: 95% landfill, 5% recycling treatment with recycling of metal parts with 95% aluminium recycling and 5% disposal of hazardous waste; other parts of the luminaire are disposed as municipal hazardous waste.
- Scenario 2: 40% landfill, 60% recycling treatment.

[54] Scholland and Dillon 2012
[55] Scholland and Dillon 2012
[56] Please note: this is for LED lamps not for luminaires

APPENDIX 3: RECYCLING

APPENDIX 3: RECYCLING

Different processes for recovery of REE

A) DIRECT REUSE OF PHOSPHORS

The direct reuse of the recycled phosphors in new lamps, which involves no chemical processing. Applying the "end cut" method, the ends of linear glass tubes are cut and the phosphor powder, about 3 wt% of a fluorescent lamp, is blown out. For LED the phosphors contents is much lower. Other shaped forms of light bulbs are crushed and shredded. Phosphors can be reused after separating unavoidable glass, metal and plastic particles in a dry or wet sieving process. The remaining glass can, however, deteriorate the quality of the phosphors. Direct reuse of phosphor powders is only applicable to one type of fluorescent lamps with exact the same phosphors composition or by the same lamp producers. Additionally, the phosphors deteriorate over the life-time of a lamp, in terms of luminescence efficiency.

B) SEPARATION OF PHOSPHORS

Separation of phosphor powder mixtures by physicochemical methods, such as flotation. By flotation[57], air bubbles selectively adhere to specific mineral surfaces and thereby separate mineral particles from crushed materials. This approach is widely used in mining industry and relatively simple process where no or limited amounts of chemicals are consumed. However, it is complicated to obtain pure phosphor powders, as components of the powder have a similar hydrophobicity and a small particle size (< 10 µm)[58]. Other process technology such as pneumatic separation showed only moderate results. Again, the re-use of separated phosphor powders in new lamps cannot be recommended as they partly deteriorate in the long term.

C) EXTRACTION OF REE

If the reclaimed phosphors cannot be used for a reuse in new lamps, still the REE can be recovered. Phosphor mixtures can be considered as a rich source, sometimes with much higher concentrations compared to natural sources. The same process technology known from the extraction of REE for extraction of rare earths from primary ores can be used. Many chemical intensive process steps are required here to produce pure REO and large amounts of wastewaters are created. Here the recycling process is only beneficial in terms of resource prevention as environmental impacts of processing are similar.

The first two options require a take-back system of the same manufacturer in terms of a reverse logistic ("closed loop supply chain management", Guide and Van Wassenhove 2009"). The third option, which also reflects the Solvay approach[59] represents an open-loop approach to recycling, where the recycled high-purity phosphors may be used for other purposes than lighting.

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[57] More specifically this is froth flotation and two-liquid flotation

[58] Hirajima et al. 2005, Takahashi et al. 2001 cited in Binnemans et al. 2013

[59] http://www.solvay.com/en/innovation/european-life-projects/loop-life-project-objectives.html

APPENDIX 4: ESCO CONTINUED

APPENDIX 4: ESCO CONTINUED

ESCO Models

- Shared savings-model: The ESCO model provides financing for investment and the ESCO company gets a share of the savings. The split of the savings (see 5.2.1 landlord-tenant problem) is not standardized and subject to negotiations taking into account the length of the contracts, the payback time and the risks take[60]. This approach is common in starter markets or when clients, such as municipalities are faced with financial constraints[61].
- Guaranteed savings-model: The client provides a project budget and pays the contractor for its services, i.e. implementation and operation based on a performance or energy savings guarantee. This model is very much related to product-service-systems. The client is guaranteed a reduction of total cost of energy compared to a specified baseline level. In case that the actual savings fall short of the guaranteed level, the ESCO pays the difference. If the savings exceed the guarantee, client and ESCO share the benefits based on a negotiated agreement.
- First-out-model: The ESCO is paid 100% of the energy savings until the investment and project cost, including the ESCO profit, is fully paid. The duration of the contract depends on the level of savings to be achieved, i.e. the larger the cost savings, the shorter the contract[62].
- Chauffage model: The ESCO is a form of delivery contracting and quite common in Europe. The fee for the services is calculated based on the clients existing energy bills reduced by a certain level of cost savings and a guarantee of the service provided. The customer can alternatively pay the service per square-meter. In some cases the ESCO also takes over the purchase of electricity, trying to benefit from long-term delivery contracts and special rates[63].

ESCO Financing

The different options for ESCO financing include:

- Internal financing by working capital that is provided by the contractor (ESCO) or by the client. ESCO financing means that the contractor participates with its internal funds and pre-finances the investment and other related cost. In customer financing, the fund is given by the client and the ESCO instead only provides technical and managerial aspects;
- Lease financing, e.g. operating lease or capital lease. In leasing the payments are usually lower than loan payments . Capital lease, analogous to the installment purchase of equipment, means that the ownership of the equipment is passed to the client at the end of the lease term. In operating lease, analogous to the rental of equipment, the contractors retain ownership throughout. However, sometimes the client gets the chance to purchase at fair market prices after the end of the lease term[65];

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[60] Bertoldi and Rezessy 2005, cit. in Bertoldi et al. 2014.

[61] Bertoldi et al. 2014.

[62] Bertoldi and Rezessy 2005.

[63] Bertoldi and Rezessy 2005, Bertoldi et al. 2014.

[64] Sorrell 2005:27.

[65] "A key difference between the two is that capital leases lead to an asset and a liability appearing on the client's balance sheet, while an operating lease provides off-balance sheet financing. The downside of operating leases is that the client is unable to benefit from any tax allowances for depreciation [...].The majority of energy equipment leases are capital leases." (Sorrell 2005:28).

- Third party financing involves debts that are undertaken whether by the contractor or by the client, which do not use any internal funds. A third party, such as a finance institution, gives a loan and requires collateral in return. The bank takes a security interest of the installed equipment or other property of the borrower or assumes the rights to the energy savings. If the client takes the loan, the client is secured by the performance guarantee issued by the ESCO so the financial risk for the client, i.e. the municipality is reduced[66];
- Forfeiting or factoring involves the long-term sale of (future) receivables, i.e. the bank wires the cost of hardware to the ESCO at the time of project setup and installation. The customer is obliged to complete periodic fixed payments to the bank based on a direct agreement with the bank;
- Project financing, sometimes supported by state subsidies as regulated in the National Energy Efficiency Action Plans (NEEAPs) of European countries.

ESCO Associated Risks

ESCO accepts some degree of risk, in particular, the technological risk of the achievement of reduced energy consumption in the client's facilities and a financial risk arising from high upfront investment cost and uncertain and volatile energy prices[67]. Both aspects are central to the ESCOs business model and place risks related to uncertain return of investment.

Of course, the ESCO is exposed to the risk that the client goes out of business, which is a marginal risk in the case of municipalities or other government entities considered as creditworthy[68]. While the energy prices are volatile and cannot be influenced by the ESCO, the technological risks are related to user behavior and the technological maturity of LED, i.e. regarding life-time and light quality over time.

On the other hand, the client, be it a business or a municipally also faces risks, which may escalate to barriers, namely disadvantageous contract designs, high transaction cost, insufficient in-house capacities to engage with the ESCO or even the risk of bankruptcy of the ESCO and related risk of supply. In that case, penalty provisions for supply outages should be included.

In addition, there are other significant risks associated with the limited contract and legal enforceability, transparency of financial information etc. that especially the lender has to consider and that are common in developing markets.

However, municipalities indeed consider outsourcing as a particular mean to reduce their own risks[69]. Examples of risks associated with ESCO contracts are given in Table A3.1.

[66] Bertoldi et al. 2014

[67] Jackson 2010, cit. in Polzin et al. 2016

[68] IFC 2011

[69] Pätäri and Sinkkonen 2014

Table A3.1: Examples of risks between the contractor and the client[70]	
Construction Risk	**Volume Risk**
• Related to difficulties in completing the implementation within time and budget • Risk is borne by the contractor • Not different from conventional turnkey project risks	• Relates to a change in demand of the energy service due to occupancy patterns and user behavior, intensity of use[71] • The contractor may not be able to recover its fixed costs if the demand decreases and the contract is mainly based on unit charges (EUR/kWh). • A commitment to the client to pay for a minimum amount can be included in the contract to mitigate this risk. • Additionally, the risk can be mitigated when determinants of service consumption are carefully estimated. However, uncertainty about completeness and dynamics of determinants remains to the contractor.
Energy price risk	Performance risk
• Relates to fluctuation in energy prices and commodities • The contractor is exposed to a risk because usually, the contract fixes the unit prices for energy services, which is indeed meant to protect the client from energy price risks. • In some cases the unit price will be indexed to a relevant fuel/electricity price or will be combined with a minimum (floor) price below the unit price is not allowed to fall (i.e. take-or-pay" clauses)	• Relates to the technical performance and quality level of the equipment installed. • As the contractor is interested in low operational cost, especially when unit prices are fixed, there is no strong incentive for maintenance and improvement measures if no specific contract provisions are made. Therefore quality and performance standards (e.g. lighting levels) have to be agreed upon.
Credit risk	
• Repayment risks in the case of debt financing • Credits risk is higher in private and commercial sectors compared to government entities	

[70] Bertoldi et al. 2014, IFC 2011, modified and supplemented; Deng et al. 2015, Lee et al. 2013, Lee et al. 2015

[71] And also weather conditions for energy services other than lighting, such as heating and cooling etc.

APPENDIX 5: CASE STUDIES ON COLLECTION OF LIGHTING PRODUCTS CONTINUED

APPENDIX 5: CASE STUDIES ON COLLECTION OF LIGHTING PRODUCTS CONTINUED

A5.1 Sweden

The Swedish Environmental Code (EC) states that every municipality should have a waste management directive ("Renhållningsordning") with a waste management plan and corresponding directives on management and treatment of waste not covered by the Producer's responsibility. Electronic waste has been covered by the Producers' responsibility (PR) in Sweden since 2001. In the same year the Swedish municipalities and the producers' organization El-kretsen initiated a collaboration called Elretur. A nationwide collection and recycling system for electronic goods is provided to the producers by El-kretsen. Elretur means that every municipality has the responsibility to provide and finance for recycling stations where the public can hand in their waste electronics free of charge. El-kretsen is responsible for organizing and transportation of the deposited electronics from recycling stations and to ensure that these are treated and recycled according to legal requirements. Contracted recycling companies perform the actual recycling. The municipalities are also responsible for providing information to consumers about the importance of recycling, source separation, location of recycling stations and recycling results.

A5.1.1 HÄSSLEHOLM

In Hässleholm, all household waste is taken care of by Hässleholm Miljö AB. People in apartment blocks have access to sorting rooms, but only 50 % of them have containers for light bulbs. From the villas, trash is collected on spot regularly and people have the possibility of also discharging light bulbs and batteries (Eriksson 2013). In 2016, four fraction waste bins will be introduced for villas (Öhman, Personal communication, 2015). For the apartment residents that have no fraction for light bulbs, 6 bigger recycling centers are available for hazardous waste free of charge. Analysis from 2012 show that the separation in the households does not work perfectly and this is believed to be due to laziness, ignorance or mistake.

The most common suggestion for improvement is better information. Some people think that the recycling centres are too far away, that they have too poor opening hours, that better signs on the garbage containers are needed and that fewer fractions should be used in the sorting rooms to avoid confusion. Some people want stricter control for those who doesn't comply with the waste management rules and quite a handful gave positive comments about the qualified staff at the recycling centres. The Hässleholm study also show that apartment residents' most often do their sorting in the garbage rooms, perhaps due to the fact that most of them do not own a car. Most people living in villas go to the recycling centre.

A5.1.2 'SAMLAREN' (RICHER AND KOPPEJAN 2016)

Samlaren ('The Collector') is a waste cabinet collection system that was initially designed in a project by Renova and students from Chalmers University in order to make small electronics collection more convenient and efficient. Collectors are positioned in grocery stores next to beverage packaging vending

[72] http://www.sysav.se/Privat/Produkter-och-tjanster/Inlamning-av-farligt-avfall/Samlaren/

machines (and designed to look similar, though they in fact have no moving parts). Although the collectors are more expensive than other forms of collection it has become more cost effective with time as collection effectiveness has increased. More than 60 collectors have been installed in 2014/15 in Southern Sweden. The collection project is led by municipal waste companies and (partly) financed by producers[72].

A5.2 The Netherlands

The Netherlands averaged 4.91 kg WEEE collection per capita per year from 2005 to 2013. The Nordic countries are leading with 8-20 kg per capita per year (Richter and Koppejan 2015). In the 1980's the awareness of the need for alternatives to landfills started to grow (WMW 2010). Today the Netherlands has 22 landfills and a ban on opening of new landfills (WMW 2013). Under The Dutch Packaging Covenant in 1991 Extended Producer Responsibilities (EPR) efforts commenced (OECD 1998). In 1999 the Netherlands became the first country in Europe to introduce a national system for collecting and recycling electronic equipment. The system was based on the Decree on the Removal of White and Brown Goods (NVMP 2012) which paved the way for the European-wide 2002/96/EC Directive on Waste Electric and Electronic Equipment (WEEE).

In the Netherlands the producers are responsible for all non-household WEEE collection and for collection of household WEEE from municipal drop-off centres and retailer in-store collection. The producers have organized this by the Producer Responsibility Organization (PRO) LightRec which has a service agreement with PRO WeCycle.

Each Municipality is responsible for providing a minimum of one location for private drop-off for free. When a new product is put on the market, the distributors are responsible for taking back the customers old similar products for free. Retailers with floor space of ≥400m^2 are obligated to take back small WEEE (≤25cm) and small retailers often provide the same service on a voluntary basis. It is uncertain how small and medium sized businesses dispose their collected lighting equipment, but it is assumed that they use municipal drop-off centres.

The contractual relationships are complex, the business and distributors contract directly with the national PRO "Wecycle". PRO "Wecycle" is a sister company to the lighting equipment specific PRO "Strichting LightRec". The municipalities contract with Wecycle who provide depots with containers and also contract and subcontract with other waste management companies.

In the City of Eindhoven the Municipality contract "Cure" who provide two drop-off depots and "Wecycle" who collect and transport lighting equipment WEEE under a subcontract with "Sita". "Sita" deliver the WEEE to recyclers in Belgium, "Indaver" and recyclers in Germany, "Alba". "Sita" also provide new containers to the depots. On behalf of the Municipality, "Midwaste" manages all the waste contracts. "Wecycle" controls the WEEE logistics, from the Municipal depots, to the recyclers.

The Netherlands allocates responsibility for information provision to the Producer and Distributor in terms of data provision to relevant authorities and for end-of-life take-back. The Producers are responsible for reporting all data to the Dutch Government through the Producer founded (W)EEE Register.

The Producers are also required to show the WEEE symbol on each product and also to provide information on the reuse, recycling and further treatment of the products. They are responsible to provide information about the different components and materials in the equipment and the location for any hazardous substances.

The City of Eindhoven Municipality promotes online information through the Municipal call centre, the "Chemco box". The "Chemco box" is provided for free by "Wecycle", to all households and allows householders to store spent lamps and LEDs, together with other separated small WEEE, until they are ready to drive to the drop-off depot and properly dispose the WEEE.

A5.2.1 DISTRIBUTOR TAKE-BACK

In-store take-back has been proven effective in the Netherlands. They have 10 000 collection networks operating across the country; Media Markt, Gamma and Praxis all practice Distributor responsibilities through in-store take-backs. One example is that Praxis has collaborated with Wecycle to customize a drop-off cabinet for in-store use, which has proven so attractive and easy to use that it has been implemented in other stores as well. The main Praxis driver for this commitment is corporate social responsibility.

A5.2.2 KERBSIDE COLLECTIONS

The Netherlands has several kinds of kerbside collection by purpose built vehicles for roadside pickup household waste by standardized containers. The City of Eindhoven has a call up service, but it is rarely used. The drop-off depot operators believe that this is due to the service not being widely advertised and that householders generally make an effort to bring the WEEE including lighting equipment to the drop-off depots. Though, it is important that householders who cannot physically get to the drop-off depot have other options.

A5.2.3 PERMANENT COLLECTIONS

The Netherlands has one permanent collection facility per 1,596 residents while the UK has one for every 15,755 residents. The Netherlands has one of the most dense permanent collection facility ratings in the world, even compared to Norway with an equivalent 1,889 residents per collection facility.

The PRO foundation LightRec represents all first producers and importers that introduce lighting equipment on the market. The management of the system, including the overall collection and recycling of electrical appliances, is undertaken by PROWecycle which is a non-profit organization and co-founder of the WEEE forum. LE PRO Dynamics, NTL, has the producers as the "Founding fathers" and as Board of Directors for LightRec they wield significant and direct influence on the PRO and the service level. This includes aspects that motivate producer interest and impact EPR such as pricing and lobbying. The City of Eindhoven and Wecycle appear to have a strong partnership with the Municipality, but the Municipality say that there is little understanding of where the lighting equipment go once it is removed under contract with Wecycle.

Another PRO, WEEE.NL joined in partnership with the European Recycling Platform (ERP) in 2013 to service the ICT sector take-back and challenge the monopolistic position of Wecycle. Considering that lighting equipment is becoming increasingly digitalized and recognized as a valuable for the REE, ICT PROs may become more interested in this category.

The producers in the Netherlands pay (Through membership of the PRO LightRec) for collection, treatment, recovery and environmentally sound disposal of lighting equipment from Municipal drop-off depots and B2B clients including retail in-store take-back. Producer PRO registration and annual fees are based on a proportion of their EEE market share. Wecycle compensate Municipalities for expenses related to the drop-off depots. Information about how and to what extent Municipalities are compensated is vague. In reality, Municipalities and Distributors/Retailers are contributing to end-of-life management financially e.g. with staff time for administration and facilitation of the system.

The City of Eindhoven has a "Quadruple helix" program focused on community-led city development and a higher level of community participation. Distributors are also looking beyond legislation to align with broad corporate social responsibility goals.

A5.3 United Kingdom

The UK WEEE Regulations were decreed 11 December 2006 and came into force 2 January 2007. The UK WEEE collection 2007-2013 was 5.83 kg per capita per year. There are 725 active landfill sites in the UK. 1700 landfills have ceased their operations since 2001. The UK has begun seeking alternatives as a response to land scarcity, attitudinal change and EU directives.

Hertfordshire County has a general household recycling rate of 49 % whilst the national average is 44%. Their waste is sent to landfill and energy recovery facilities within the county. The County Council has promoted recycling and held special WasteAware events focusing e.g. on WEEE take-back. The County contributed to the white paper "Extended Producer Responsibility: Stakeholder Concerns and Future Developments" in 2014 and general WEEE formed part of the discussion which focused on transparency, stakeholder engagement, improved data management and differentiated fees.

The producers are responsible for all non-householder WEEE collection and for collection of householder WEEE from municipal drop-off centers. There are three different ways for distributors to organize WEEE take-back: in-store collection, via collection Municipal DCF facilities or via facilities shared with other distributors.

The businesses contract directly to one of the Producer Compliance Schemes (PCS) for WEEE collection. There is only one specific PCS for lighting equipment, "RecoLight". PCS recycling services are contracted to "Approved Authorized Treatment Facility" (AATF. The Municipalities can either contract a PCS or retain control of certain high value WEEE streams.

The Hertfordshire Country Council contracts a waste manager "Amey" which contracts RecoLight as the PCS, which in its turn contracts "Balcan Engineering" as the AATF.

The UK allocates responsibility for data provision to relevant authorities and regarding end-of-life product take-back to the producers and distributors. For UK producers, responsibility to report all data to the national data-house for all PCS data (the "Settlement Centre") is critical. The "Settlement Centre" transfers all the data to Eurostat. The WEEE symbol has to be on products and information regarding EEE POM (the collection rate of WEEE) has to be provided to AATFs to assist with treatment and recycling options. Often through their PCS, producers register with the Environment Agency and are given a unique registration number provided to retailers selling EEE. The producers report quarterly sales to their PCS and records of sales abroad, including to other Member States. According to UK WEEE Regulations, drop-off depots or DFC are required. It is implicit that information should be provided to encourage householders to use the service, but no information obligation is stated.

The Herdfordshire County Council, as well as the City of Eindhoven Municipality, refers to websites on the most up-to-date information on lighting equipment waste management, but both of them agree that communication could be improved and diversified to make a bigger impact. This method relies on the householder to take a proactive stance on waste management. The Hertfordshire County Council advertises WEEE take-back directly at the DFC recycling site. However, despite all energy saving bulbs and LED being collected once inside the DFC, only fluorescent tubes are visibly advertised. Also in Hertfordshire the convenience factor is a key element for proper disposal. The "Chemco box" is a way to address householder convenience and education.

A5.3.1 PERMANENT COLLECTORS

The UK has 37 permanent collectors, most of them for take-back of all forms of WEEE. Two are lighting equipment specific: Lumicom and RecoLight. RecoLight is the main PCS and current contractor for Hertfordshire City Council. Hertfordshire County Council is satisfied that fluorescent tubes tonnage is provided regularly. Other light waste is not reported back to the Municipality. The PROs are not regulated by the Government and determine their own business models.

A5.3.2 KERBSIDE COLLECTION

Hertfordshire County Council does not operate kerbside collections for lighting equipment, but it is prevalent in neighbouring county Chelmsford that lists eight small WEEE items for collection (Chelmsford 2016).
The landfill taxes have increased in the UK over the years and therefore some municipalities seek to minimize their landfill. Unfortunately, lighting equipment is neither heavy nor currently valued and municipalities tend to focus on other items.

A5.3.3 DISTRIBUTOR TAKE-BACK

In the UK, IKEA offer in-store take-back in all 18 stores and they feel that it is a successful model that aligns well with corporate responsibility and community values. To impact energy efficiency gains, mitigate CO_2 emissions and increase awareness IKEA has made a strategic decision to sell LEDs only.

The recast UK WEEE regulations include a new model that changes the calculation of payment and requires the distributor to contribute and thereby effectively reduces the financial burden on the producer. The producer payments are based on a proportion of market share of EEE and relates to the household targets for WEEE. The government develops the targets based on analysis of trend data and projections of WEEE Category 13. A distributor can either join the Distributor Take-back Scheme (DTS) (an annual fee is paid to the operator Valpak Retail WEEE Services Ltd), offer in-store take back (PCS such as RecoLight are paid to ensure the lighting equipment is returned to an AATF) or offer an alternative free take-back service (shared facility amongst local distributors). Municipal DCF are funded through the Distributor Take-Back Scheme, but some significant costs e.g. staff and maintenance, are not taken into account.

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