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Accelerating the Transition towards Solid-state Lighting

Challenges for the Public Sector to Deploy Solid-state Lighting

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Abstract

The market uptake of solid-state lighting (SSL) is slow, even though it has many advantages and could deliver a variety of benefits to the society. The public sector is a large actor in the lighting market and could play an important role in accelerating SSL market penetration. Nevertheless, it faces many challenges to adopt SSL. Therefore, the main purpose of this research is to provide a better understanding of these challenges and explore potential strategies to overcome them. Sweden is selectd as a focus country as it is a leading nation in adopting SSL.

Overall, the public sector in Sweden faces several challenges to adopt SSL. The challenges and its underlying reasons are presented as below: (i) low confidence in SSL due to early technological shortcomings; (ii) risk averison due to uncertainties of product performance and benefits of SSL; (iii) conservative perspective on lighting due to limited awareness of SSL and its benefits; (iv) conservative perspective in prioritizing SSL health and well-being benefits due to limited attention; (v) difficulties in achieving inter-operation ability in innovative lighting solutions (SSL is part of the solution); (vi) high initial cost for outdoor and replacement lighting.

To accelerate the transition towards SSL, following actions could be taken: (i) product performance testing standards improvement; (ii) minimum quality requirements scheme setting and market surveillance enhancement; (iii) demonstration projects with high replication potential; (iv) improve awareness and acceptance of SSL and its benefits among different actors; (v) develop standard and norms for lighting's effect on human health and well-being; (vi) innovative public procurement to facilitate commercialization of innovative lighting solutions; (vii) strenthen SSL (and innovative lighting solution) value chain; (viii) private-public partnerships (PPP) to facilitate collaboration; (ix) product-servicing system as a new business model to facilitate solution-oriented approach; (x) increase financial support.

Keywords: Solid-state lighting (SSL), light-emitting diode (LED), innovative lighting solutions, human centric lighting

Executive Summary

This thesis examines solide-state lighting (SSL) adoption barriers in the public sector in Sweden, or more precisely in Skåne region. Compared to conventional lighting technologies, SSL is superior in various aspects, such as energy efficiency, life span, durability, digital compatibility, flexibility in shape and size, etc. (De Almeida, Santos, Paolo, & Quicheron, 2014). Deploying SSL could bring huge benefits to the society, like energy saving, CO_2 emissions reduction, productivity increasement, chronic diseases prevention, well-being improvement and so on (European Commission, 2011a; LightingEurope & ZVEI, 2013). Therefore, SSL is believed to displace all traditional lighting sources in the future (Haitz & Tsao, 2011). McKinsey & Company (2012) has predicted that light-emitting diode (LED) market share will increase from 12% in 2011 to 41% in 2015, and reach 63% in 2020. But in reality, the market adoption of SSL is slow, or not as fast as expected. For example, in EU, the market share of LED was 7% in 2012, which is much lower than the prediction (the predicted share was 15%) (Wierda, 2014a).

To achieve the benefits mentioned above, the society needs to accelerate the market uptake of SSL. The public sector is a large actor on the lighting market and could play an important role in accelerating SSL market penetration through public procurement. Nevertheless, it faces many challenges to adopt SSL (European Commission, 2011a; Valentová, Quicheron, & Bertoldi, 2012). In order to accelerate SSL market uptake, it is important to find out all the barriers and reasons behind them. Therefore, the main purpose of this research is to provide a better understanding of SSL adoption barriers in the public sector.

The research questions of the thesis are as follows:

- *What are the barriers for SSL adoption in the public sector?*
- *Why the barriers exist?*
- *Reflecting on the identified barriers, what are the potential strategies for further development of SSL?*

Sweden is selected as a focus country is because, on one hand, it is a leading country in adopting SSL, and many of its municipalities, such as Gothenburg, Malmö and Lund, have SSL practices or strong interests. So it is easy for the author to find and access actors in this field. On the other hand, by picking up one country, the effect of contextual differences (i.e., different public procurement instruments and scopes for public sector) on this study could be reduced.

The data of this thesis is collected through desktop research, interviews as well as communications in conferences. Firstly, a thorough literature analysis was performed to provide a background of this thesis and get an insight of this topic. Through the literature analysis, the author found there is few research on this topic. So interviews were performed to collect additional data. Interviewees were selected based on their knowledge and experience of SSL. The interviewees comprises of actors from the lighting industry, local municipalities, public organisations and academia. The information collected from interviewees were processed through triangulation.

Overall, the public sector in Sweden faces several challenges to adopt SSL. The challenges and its reasons are presented as below:

Low confidence in SSL due to early technological shortcomings. Early LED products have many problems (i.e., glare, flicker, and colour distortion) as the technology was

immature. These products have significantly undermined consumer's confidence in SSL. Because of low confidence, there is low trust and risk aversion among decision-makers, even though SSL has been improved enormously over these years.

Risk averison due to uncertainties of product performance and benefits of SSL. SSL is a new technology, the public sector faces many uncertainities to adopt it. One example is the uncertainty of product performance, as the market is flooded by poor products. Low quality products are flooding in the market is due to the fact that product performance testing standard is missing. Another example is the uncertainty of the potential benefits of SSL, especially the benefits for human health and well-being. This is due to on one hand, there is strong skepticism towards this topic among decision-makers, even though there is strong scientific evidence. On the other hand, as there is few experience (successful projects) available, everyone is afraid of to be the first mover, so waiting for others to start.

Conservative perspective on lighting due to limited awareness of SSL and its benefits. In general, decision-makers in the public sector have have a limited awareness of SSL and its benefits (not lighting experts), so they typically position lighting as a technical subject, even though the subject of lighting is multi-dimensional and includes important issuses other than technical, like health, comfort, productivity, well-being, etc. The fact that decision-makers have a limited awareness of SSL and its benefits is because there is knowledge gap among different departments. For example, the technology department typically has a higher knowledge level of lighting but they are not decision-makers.

Conservative perspective in prioritizing SSL health and well-being benefits due to limited attention. SSL could deliver benefits other than energy saving and cost saving benefits, such as productivity increasement, chronic diseases prevention and visual comfort (benefits for human health and well-being), which is often low priority for both consumers and the lighting sector. When consumers (i.e., the public sector) have a limited focus on energy and cost savings, it creats a business opportunity for producers to mislead. For example, manufacturers could produce LED products with high energy-efficiency but with poor performance (i.e., colour distortion, flicker and glare) to reduce their cost, and still present their products with a value enhancing label (i.e., energy efficiency) to make profits (as customers prioritise energy and cost savings, so this type of product could be still attractive to them). Then, the market could be flooded by this type of products. The reason that SSL's health and well-being benefits are not prioritized is because there is limited attention on the political agenda. When producers have a limited focus on energy and cost savings, they would lose their connections to customer. Then during the process of product development, customer desired positive functionalities of SSL could be lost or not achieved (i.e., benefits for human health and well-being), and negative effects (i.e., colour distortion, glare and flicker) could be (re)-introduced. Currently, there is a culture of focusing on energy and cost savings in European lighting sector. This is due to historically, the lighting market has been strongly influenced by energy-efficiency policies and up-front cost.

Difficulities in achieving inter-operation ability in innovative lighting solutions (SSL is part of the solution). Some of SSL's benefits are achieved by deploying innovative lighting solutions (i.e., human centric lighting, integrating SSL with other technologies, like sensors, lighting controls, ICTs, etc.). This means SSL's market penetration also relies on the development status of the whole system. So here, challenges to adopt innovative lighting solutions are presented. Three levels of inter-operation ability are required to deploy innovative lighting solutions. First, on the product level, different technical components should be compatible. One of the challenges on this level is currently there is no open standard network protocol, which has hindered the compatibility of differen products.

Secondly, after assembling different components together, the whole system should be functional and reliable. This is challenging because the add-on devices like e.g. dimmers, timers, photo-sensorr, etc., may cause current spikes, change power demand and temperature, which ultimately can damage LED emitters or alter their performance (i.e., shorten lifetime and reduce efficiency). Thirdly, on organizational level, different actors are required to cooperate, as the subject of lighting solutions is a new and multi-dimensional field. But collaboration is challenging. On one hand, manufacturers are fragmented along the value chain. On the other hand, deploying innovative lighting solutions requires a solution-oriented approach, which means manufacturers need to work closely with customers, but the lighting sector is used to a straight-forward, product-based business model.

High initial cost based upon circurmstances. For outdoor lighting, high upfront cost remains a main barrier. This is due to procuring outdoor lighting is a large and one-time investment. So the public sector are reluctant to deploy SSL in outdoor lighting widely, because the high upfront cost clashed with their tight annual budget, even though it could reduce their maintenance costs in the long term. For indoor lighting, it depends on circurmstances. If the purpose is to replace old lighting bulbs, upfront cost is a key factor for the public sector to select product, as they face budget restrictions and austerity measures. For new installation project, such as build a new school, the expense for lighting is just a small portion of the total large investment. And if the indirect benefits of SSL (i.e., productivity increasement, chronic disease prevention, visual comfort) are included (calculate the the total ownership cost of SSL), high purchasing price of SSL could be justified.

To accelerate the transition towards SSL, these barriers need to be overcome. As Sweden is a member state of EU, potential strategeies for further development of SSL are proposed at EU level. Following actions could be taken to accelerate the transition towards SSL in EU:

Product performance testing standards improvement. New standards that addressing all key features of SSL performance and ancillary components are essential to ensure a level playing field for a health and competitive market.

Minimum quality requirements scheme setting and market surveillance enhancement. A Minimum quality reuqirements scheme and efficient market surveillance scheme are key factors to guarantee customer's confidence in LED products and to accelerate the market uptake of LED.

Demonstration projects with high replication potential. A demonstration project with high replication potential could reduce risk aversion among decision-makers and grow SSL market.

Improve awareness and acceptance of SSL and its benefits among different actors. A variety of dissemination means such as training programme and dedicated communication are required to raise awareness and acceptance.

Develop standards and norms for lighting's effect on human health and well-being. By developing these standards and norms, consumer's awareness and acceptance of SSL's benefits (health and well-being benefits) could be raised.

Innovative public procurement to facilitate commercialization of innovative lighting solutions. Innovative problic procument, like Pre-Commercial Procurement (PCP) and Public Procurement of Innovative Solutions (PPI), could bringing innovative end-solutions earlier to the market.

Strenthen SSL (and innovative lighting solution) value chain, as actors are fragmented along the value chain.

Private-public partnerships (PPP) to facilitate collaboration. PPPs could bring different actors together and enhance mutual understanding.

Product-servicing system as a new business model to facilitate solution-oriented approach. Developing innovative lighting solutions needs a customer-centric approach. Product-servicing system is a functional-oriented business model so it could serve the purpose.

Increase financial support. Investment in R&D and project development.

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1 Introduction

This thesis deals with solid-state lighting (SSL), or light-emitting diode (LED). The future of lighting lies in SSL. In comparison to conventional lighting technologies, SSL is superior in various aspects, such as energy efficiency, life span, durability, digital compatibility, flexibility in shape and size, etc. (De Almeida et al., 2014). Deploying SSL could bring huge benefits to the society, like energy saving, greenhouse gases (GHG) emissions reduction, productivity increasement, chronic diseases prevention, well-being improvement and so on (European Commission, 2011a; LightingEurope & ZVEI, 2013). Therefore, SSL is believed to displace all traditional lighting sources in the future (Haitz & Tsao, 2011). McKinsey & Company (2012) has predicted that LED market share will increase from 12% in 2011 to 41% in 2015, and reach 63% in 2020. But in reality, the market adoption of SSL is slow, or not as fast as expected. For example, in EU, the market share of LED was 7% in 2012, which is much lower than the prediction (the predicted share was 15%) (Wierda, 2014a). To achieve the benefits mentioned above, the society needs to accelerate the market uptake of SSL. The public sector is a large actor in the lighting market and could play an important role in accelerating SSL market penetration through public procurement. Nevertheless, it faces many challenges to adopt SSL (European Commission, 2011a; Valentová et al., 2012). In order to accelerate SSL market uptake, it is important to find out all the barriers and reasons behind them. Therefore, the main purpose of this research is to provide a better understanding of SSL adoption barriers in the public sector.

1.1 Problem Definition

SSL is a disruptive technology, since the first commercial LED came out in 1960s, considerable improvments have been made. Compared to traditional lighting technologies (i.e., incandescent and fluorescent lamps), it has many advantages, such as energy efficiency, life span, durability, digital compatibility, flexibility in shape and size, etc. (De Almeida et al., 2014). To date, in average, a LED is ten times energy-efficient than a standard incandescent lamp and lasts 25-35 times longer (U.S. Department of Energy, 2014). Deploying SSL could deliver a variety of benefits to the society, like energy saving, GHG emissions reduction, productivity increasement, well-being improvement chronic diseases prevention, well-being improvement and so on (European Commission, 2011a; LightingEurope & ZVEI, 2013). For example, the UNEP (2014) estimated, if all inefficient lamps in the world are replaced by SSLs over night, approximately 1,464 terawatt-hours (TWh) electricity could be saved. This is about 52% of global lighting electricity consumption. And 735 million tonnes (Mt) of CO_2 emissions could be reduced. The total financial benefits are around USD 120 billion. And if SSL is combined with other technologies, like sesnsors, controls and information and communications technologies (ICTs), specific lighting solutions could be produced and installed in ways to satisfy diverse personal needs, such as improve academic performance and social behaviours in educational world (Vick et al., 2014), increase producitivty, safety and concentration in working places, prevent chronic diseases and support healing processes in elderly care, etc. (LightingEurope & ZVEI, 2013; Silvester & Konstantinou, 2010).

Therefore, SSL is believed to displace all traditional lighting sources in the future (Haitz & Tsao, 2011). And the society is on a clear transition path to SSL. To date, SSL applications has been used in different fields, such as indicator lighting, automonile taillights and backlights (Sanderson & Simons, 2014). But for the general illumination market[1], SSL remains as a

[1] General lighting/illumination market includes a residential application and six professional applications: office, hospitality, shop, industrial, architectural, and outdoor (McKinsey & Company, 2011).

newcomer. It was only after 2005 that warm-white LED (for general lighting market) gained commercial interests (Haitz & Tsao, 2011). Although it is a newcomer, it is predicted that SSL will dominate the market quickly, since it has numerous advantages and could bring many added values to the society. McKinsey & Company (2012) has predicted that global LED market share will increase from 12% in 2011 to 41% in 2015, and reach 63% in 2020. In contrast to the promising prediction, in reality the market adoption of SSL is slow, or not as fast as expected. For example, in EU, the market share of LED was 7% in 2012, which is much lower than the prediction (the predicted share was 15%) (Wierda, 2014a).

To achieve the benefits that SSL could deliver, many countries have established a number of projects to accelerate its deployment. Take the EU as an example, photonics has been selected as one of the key enabling technologies in Horizon 2020 Programme. Numerous investment has been put in SSL research, development and commercilisation (Photonics21, 2010). Among these projects, many have focused on the public sector, like innobooster[2], ENIGMA[3], PRO-LITE[4], etc. Because the public sector is a large actor in the market and could play a key role in accelerating the transition towards SSL through public procurement (Valentová et al., 2012). According to EU Green Paper "lighting in the future" (2011a), in Europe, professional lighting (non-residential lighting and street lighting) accounts for 52% of the total market revenues.

However, there are many challenges for the public sector to adopt SSL (European Commission, 2011a). For example, municipalities are unwilling to purchase LED products bcause they are much more expensive than other lighting sources, which clashes with their tight annual budget (European Commission, 2011a). Furthermore, this is a rather new technology and is not well-known by consumers. The public sector may not adopt it simply because decision-makers are not aware of the new technology and its advantages (Philips N.V., 2012). And even if they are informed of this technology and its benefits, the public sector may still take no action, because there are too many uncertainties. One example is the uncertainity of product performance. Currently the market is flooded by poor LED products, like colour distortion, flicker, glare, etc., which has discouraged their interests in deploying SSL (De Almeida et al., 2014).

To accelerate the market uptake of SSL, it is important to find out all these barriers. Though SSL is a popular research subject, the author found only one academic paper in this field (SSL adoption barriers). This paper investigated the potential and challenges of SSL deployment in Europe. But it did not define from which perspective (from the public or private sector or both) it took to identify the barriers (De Almeida et al., 2014). The perspective it took would have a significant influence on the results (barriers), since the two groups of consumer differ in various aspects (i.e., finance, institution, etc.). In addition, as SSL is developing rapidly over these years, previous conclusions could be invalid. For instance, high purchasing price of LED has long been considered as a main barrier for its market adoption. But LED retail price has declined dramatically in recent years, dropping at a rate of 13-24% per year (McKinsey & Company, 2012). It is possible that price is no longer a barrier. Thus, there is a need to do an updated research about the barriers for SSL adoption in the public sector.

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[2] Innobooster is EU funded projects with the purpose of supporting public procurers in purchasing innovative lighting and furniture solutions. Link: http://www.innobooster.eu/about-innobooster/

[3] ENIGMA is an EU FP7 project that aims to implement a joint transnational pre-commercial procurement (PCP) procedure in the field of public lighting. Link: http://www.enigma-project.eu/en/

[4] PRO-LITE is an EU funded project that focuses on the procurement of innovative lighting solutions and technologies. Link: http://www.prolitepartnership.eu/

1.2 Research Question

The main objective of this thesis is to provide a better understanding of SSL adoption barriers in the public sector. Firstly, all the challenges that the public sector is facing to deploy SSL will be mapped out. Then the author investigates why these barriers exist. Finally, reflecting on the identified barriers, the author will explore potential strategic pathways for further development of SSL. Hence, the research questions of the thesis are as follows:

- *What are the barriers for SSL adoption in the public sector?*
- *Why the barriers exist?*
- *Reflecting on the identified barriers, what are the potential strategies for further development of SSL?*

1.3 Method

The data is collected through desktop research, interviews as well as communications in conferences. Firstly, a thorough literature analysis was performed to provide a background of this thesis and get an insight of this topic. The content of the analysis includes the importance of lighting, different lighting technologies, trends in the lighting industry and market, and the potential benefits of deploying SSL.

Through the literature analysis, the author found the data from literature is limited (only one paper). And as SSL has been improved greatly over these years, it is questionable whether previous results are still valid. For example, previously high intial cost of LED has been considered as a main barrier for its market uptake. But LED retail price has declined dramtically in recent years, dropping at a rate of 13-24% per year (McKinsey & Company, 2012). It is possible that price is no longer a barrier. Therfore, interviews were performed to collect additional data.

The results of the analysis served as a starting point of the interview. The author designed the interview on the basis of current knowledge oft the potential of SSL. The interviews were conducted in a semi-structured manner, and questions were adjusted according to individual circumstances. This method was used because it allowed the interviewees to freely present their perceptions on the research topic.

Interviewees were selected based on their knowledge and experience about SSL. To ensure a good representation of current situation, input was sought from a number of actors involved or having an interest in SSL. The interviewees comprises of actors from the lighting industry, local municipalities, public organisations and academia. Initial contacts with several actors were established through the networking of International Institute for Industrial Environmental Economics (IIIEE). Later on, other actors were contacted through the help of Dr. Reine Karlsson, who is the project manager of EU SSL-erate project, and recommendations or references from the interviewees. A complete interviewee list can be found in Appendix I.

The purpose of interviews is to (i) get a general picture of SSL adoption in the public sector, (ii) find out the stakeholer's opinions on this topic (what are the barriers and why); (iii) identify what views they agree on or not (views from other stakeholders as well as literature), (iv) analyse the arguments on which their ideas are based (why agrees or disagrees). The information collected from interviewees were processed through triangulation.

In addition, some of the data was collected during the the Indoor Lighting for Health and Well-being Conference, which was held in Lund on February 5, 2015. Actors from a broad range of organisations, such as, local authorities, research institute, lighting industry, and public organisations (UNESCO), expressed their opinions on the development of SSL. During the conference, the author also had several Personal communication with some of attendees. Their input was collected and analysed as well.

1.4 Limitations and Scope

This thesis examines SSL adoption barriers in the public sector in Sweden, or more precisely in Skåne. The reason of choosing Sweden are twofold. On one hand, Sweden is a leading country in adopting SSL. For example, it is estimated Sweden will be the fastest growing country in deploying Human centric lighting[5] in Europe (LightingEurope & ZVEI, 2013). And many of its municipalities have SSL practices or strong interests. It is easy for the author to find and access actors in this field. For example, the city of Gotheburg started to use LED lighting on the street in 2006. It is also the President of Lighting Urban Community International (LUCI Association)[6]. Malmö municipality was a key partner of EU ENIGAMA project. Lund Municipality has a strong interests in applying SSL, such as Human Centric lighting (R. Karlsson, Personal communication). And Lund Univesity is a large research center in the region. It has many SSL related research projects, like SSL-erate[7]. Also there is IDEON in the region, many enterprises here are doing SSL related business. On the other hand, by picking up one country, the effect of contextual differences (i.e., different public procurement instruments and scopes for public sector) on this study could be reduced.

According to the material composition of the used semiconductors, SSLs could be categorized into three groups, namely, LEDs (inorganic compound), organic light-emitting diodes (OLEDs), and polymer light-emitting diodes (PLEDs). Currently LED is the most advanced and commercially viable (Tsao et al., 2014), so the focus of this thesis is LED.

Lighting applications are also generally classified into two catergories: indoor and outdoor lighting, because they have different features and market. So they may face different challenges for deployment. For example, characteristics like energy-efficiency and life span of SSL are important for outdoor lighting, as it can reduce maintenance costs significantly. While indoor lighting are more concerned about its performance, like features of light quality and colour tuning, as it impacts human health and mood. Currently, SSL is advanced in energy-efficiency and life expectancy, but features like colour tuning are immature. Addtionally, there are more actors involved in indoor lighting, such as building constructor, designer, installer, owner, etc. Accordingly, coordination of different stakeholders may be more challenging for indoor lighting proejects. Nevertheless, this research does not pick one of the two fields, but took a holistic scope. The reason of not choosing one of the two is twofold. On one hand, it is difficult for the author to find interviewees with experience exclusively on one field, as actors typically have experience in both field. On the other hand, during the interview, they may express their views on one field on the basis of experience in other field and not aware of it.

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[5] Human centric lighting are innovative lighting solutions that intend to promote a person's mood, health and well-being, which is achieved by integration of SSL, sensors, lighting controls and ICTs.

[6] LUCI Association is an international network bringing together cities and lighting professionals engaged in using lighting as a major tool for sustainable urban, social and economic development. Link: http://www.luciassociation.org/

[7] SSL-erate is an EU FP7 project that aims to accelerate the market adoption of SSL. Link: http://ssl-erate.eu/

In addition, SSL's potential benefits like productivity increasement, chronic diseases prevention and well-being improvement are realized through innovative/intelligent lighting solutions, which is the combination of SSL and other technologies (i.e., sensors, lighting controls and ICTs). This means SSL's market penetration also relies on the development status of other technologies. For example, it is possible that limitations of these technologies hinder the market uptake of SSL. However, these technologies are not the focus of this thesis. So mostly, the author assumes that the ancillary technologies will be making parallel and perhaps even faster progress. But in some circumstances, the author also analysed the development status of these technologies, as they may influence the market adoption of SSL. In these cases, the author were exploring barriers for adopting innovative lighting solutions (which is a broad scope), not just SSL.

A further limitation of this study is that the author conducted a limited number of interviews, and the majority of the interviewees are from one group (municipalities), which may not be a good representation. The limitation is due to various reasons, some interviews with important imformants could not be arranged. As a compensation measure, these imformants' written statements where they have expressed their views were carefully scrutinized if availble. As for the processed written information, some of them are in Swedish. In this respect, any errors or omissions in translating and interpreting information remain the responsibility of the author.

1.5 Audience

The main target audience of this thesis are actors who may have interests in SSL, like local authorities, public organisations, lighting industry, policy makers, scholars, etc. For local authorities and public organisations who are intend to have SSL practices or are actually adopting SSL, they could get an insight of the potential challenges they may face from the study, and prepare themselves to overcome the barriers. For lighting industry, both of small and medium enterprises (SMEs) and large companies, they might identify the public sector's interests on SSL from the research, and then use the information to tailor their business strategy, model or products to meet the public sector's needs. For policy makers, they might find useful information for them to design relevant policy instruments to accelerate the market uptake of SSL. For scholars, as there are only a few studies in this field, this thesis may provide a better understanding of this topic.

1.6 Disposition (Outline)

Chapter 1 presents the nature of the problem addressed in this research. Firstly, it briefly introduces the research purpose and the research objectives are defined. Further, it describes the methodology used to collect data to address the research question. The content provided also includes research limitations, a thesis outline and the target audience, for which this research may be useful.

In Chapter 2, a thorough literature analysis of the immediate field of this study is presented. The literature analysis provides a background of the thesis, it presents the importance of lighting, different lighting technologies, trends in the lighting industry and market, as well as the potential benefits of deploying SSL.

Chapter 3 presents the main findings and analysis. Here, the challenges for the public sector to deploy SSL are mapped out. Then the causes of the barriers are analysed and potential strategies for further SSL development are explored.

Chapter 4 discusses and reflects on findings, analysis and research process.

Chapter 5 summarises the main findings and lessons learned in the course of this research, highlights main research contributions and provides suggestions for further research.

2 Literature Analysis

In this chapter, the result of literature analysis is presented to provide a background of this thesis. The content provided includes the importance of lighting, different lighting technologies, trends in the lighting industry and market as well as the potential benefits of deploying SSL.

2.1 The importance of lighting

Lighting is essential for life. Since Thomas Edison created the first incandescent lamp in 1880s, electric lighting has changed our lifestyle profoundly. Nowadays electric lighting is a ubiquitous feature of modern societies, crucial to our productivity (reducing dependence on daylight and providing adequate light for work) and welfare (improving security and enabling education and housework to be taken at night).

Yet we scarely pay attention to lighting when we enter a room or walk under a lit street during the night. In fact, lighting is a great consumer of energy. It was esmitated that lighting consumed 2,815 TWh electricity in 2010, which was 15.1% of global electric power consumption. The resulting 1,471 Mt CO_2 emissions are equivalent to 27% of emissions of the U.S. (UNEP, 2014). In Europe, lighting alone accounts for 50% of municipal electricity consumption (European Commission, 2013). Furthermore, little attention has been paid on lighting's impacts on human health and well-being so far. Lighting is not neutral in terms of human health and well-being. Poor lighting could lead to various adverse effects, such as visual discomfort, disturbance of human circadiam rhythm and mood disorders. And high quality lighting has the potential to increase productivity, support healing process, stimulate moods, etc. (LightingEurope & ZVEI, 2013). Conventional lighting sources distribute light in a unidirectional and static manner, which do not offer the opportunity of controlling light. But SSL is different, it is directional, digitally compatible and has a wide range of colours. By integrating SSL with different technologies (sensors, lighting controls, ICTs), innovative lighting solutions (i.e. human centric lighting) could be produced to control the directions, colours and illuminance of light. Therefore, to date, it is possible to control lighting to improve human health and well-being.

In order to understand the significance of accelerating the deployment of SSL, it is worthwhile to take a few moments to review the importance of lighting.

2.1.1 Lighting, energy and environment

Lighting is a large and rapidly growing source of energy demand and GHG emissions. In 2005, global lighting energy consumption was 650 million tonnes of oil equivalent (Mtoe) of primary energy. The resulting 1,900 Mt CO_2 emissions was about 7% of global fuel combustion CO_2 emissions. Amid the total lighting energy consumption, on-grid lighting[8] consumed 2,650 TWh electricity, representing 19% of global electricity consumption. Figure 2-1 shows lighting electric power consumption by sector in 2005. The commercial sector was the largest user, consumed 1,133 TWh electricity (43%). The rest was distributed in the residential sector, industrial sector and outdoor stationary sector, relatively used 811 TWh

[8] On-grild lighting are lighting application connected to grid

(31%), 490 TWh (18%) and 218 TWh (8%) electric power. In addition, off-grid lighting[9] consumed 132 billion litres of fuel in 2005, equivalent to 112.7 Mtoe of primary energy. The consumed energy entailed approximately 370 Mt of CO_2 emissions, accounting for about 20% of global lighting related CO_2 emissions. (Waide & Tanishima, 2006; Aalto University, 2010)

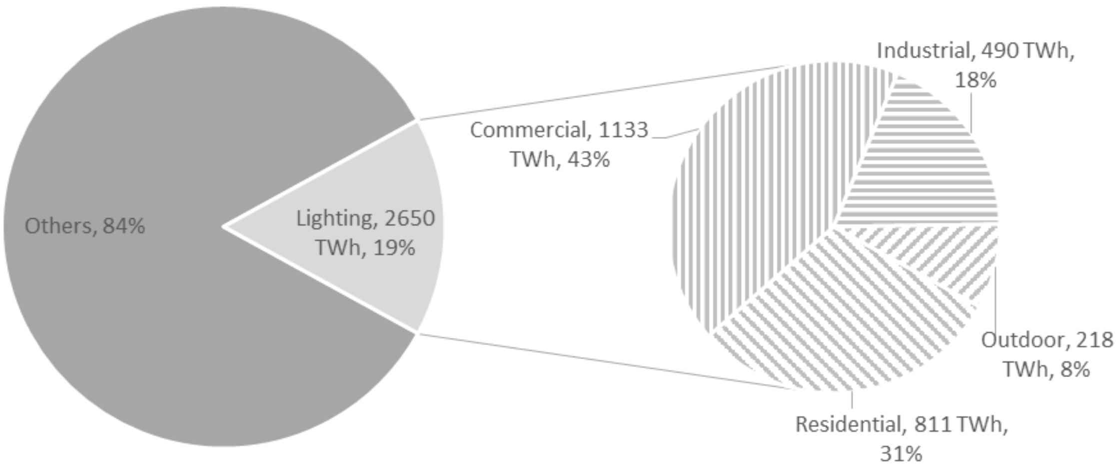

Figure 2-1 World Lighting electricity consumption by sectors in 2005

Source: (Waide & Tanishima, 2006)

And according to a recent UNEP (2014) report, global on-grid lighting energy consumption has increased to 2815 TWh in 2010, representing 15.1% of global electricity consumption (the percentage was 19% in 2005, though the percentage has decreased, the absolute number has increased). The resulted CO_2 emissions were 1,471 Mt, accounting for 5% of global GHG emissions (here both the percentage and absolute number have decreased) (en.lighten, n.d.-f). In addition, 25 billion litres of kerosene was used to power kerosene lamps (off-grid lighting). It is predicted that, if no action is taken to encourage the use of energy-efficient lighting (i.e., LED lamps), lighting electricity consumption will increase by 27% (compared to 2010), reaching 3,575 TWh in 2030 (UNEP, 2014).

In EU, the trend of lighting electricity consumption is slightly different. As presented in Figure 2-2, the annual lighting electric power consumption kept increasing from 1990 to 2007. Between 2007 and 2011, it was roughly constant, remaining around 400 TWh per year. Then, it started to decrease in the following year, reaching to 382 TWh in 2013, which is still a considerable number (Wierda, 2014b).

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9 Off0grid lighting are lightin application not connected grid, such as candles, gas lamps, kerosene lamps as well as vehicle lightings

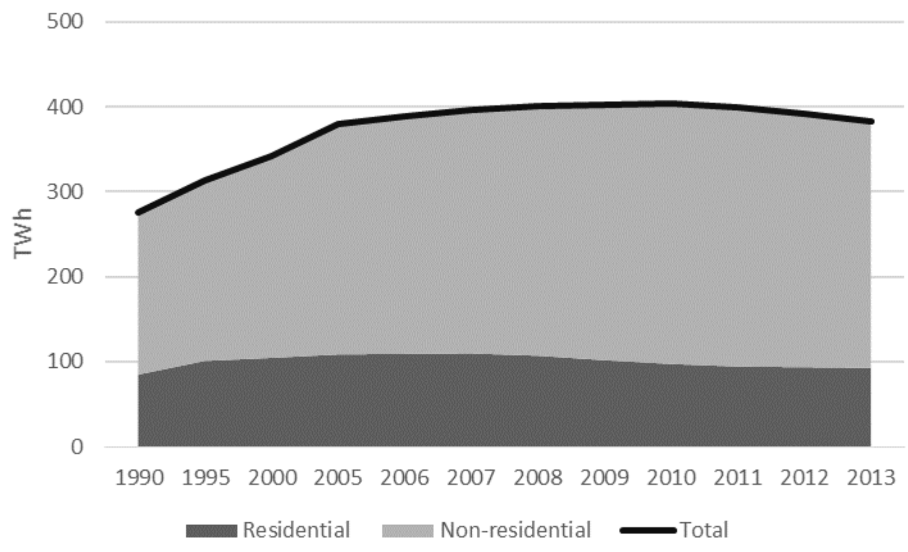


Figure 2-2 Lighting electricity consumption in EU from 1990 – 2013

Source: (Wierda, 2014b)

In 2007, lighting-related electricity consumption was around 408 TWh in EU, representing 14% of its total electricity consumption. The resulted CO_2 emissions were 180 Mt. Figure 2-3 presents lighting electric power consumption by sector. The commercial sector used the most amount of electricity (164 TWh, 40.2%), the rest were distributed in the industrial sector (24.5%), residential sector (20.6%), and outdoor stationary sector (14.7%). Overall, non-residential consumers consumed around 80% of the total lighting electricity consumption (De Almeida et al., 2014; CELMA & ELC, 2011).

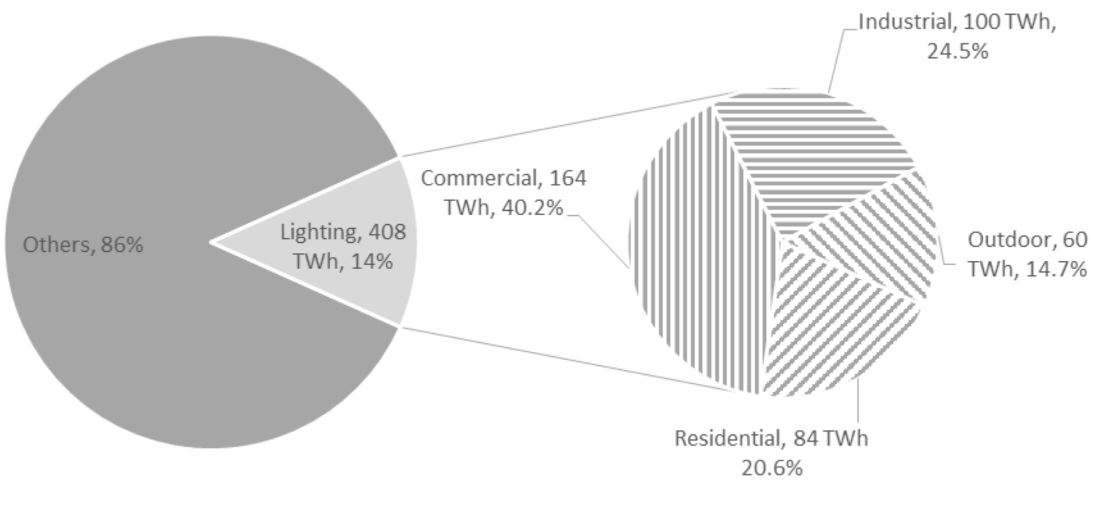


Figure 2-3 EU lighting electricity consumption in 2007

Source: (De Almeida et al., 2014)

Apart from being a large contributor of CO_2 emissions, lighting also has impacts on the environment in its other life cycle stages, such as raw material extraction, manufacturing and disposal. Among them, the disposal phase is the most concerned stage. Because many lighting sources (i.e., linear fluorescent lamps, mercury-vapour lamps, compact fluorescent lamps and so on) contain hazardous materials, lead and mercury in particular. These bulbs pose potential healthy risks on both human and the environment if disposed randomly.

In addition, to date, lighting is so pervasive that the animal and plant behaviours are strongly affected, especially in outdoor spaces. For instance, some studies have concluded that birds can be severely influenced by lighting on oil rigs when migrating on the sea (European Commission, 2011b).

Overall, it is estimated that globally 70% of total electricity for lighting is used by inefficient lamps (Aalto University, 2010). And in Europe, 60% of lamps are inefficient (CELMA & ELC, 2011). SSL is energy efficient (the most efficient lighting source), durable and has a long life time. If all inefficient lamps can be replaced by LEDs, great energy saving, climiate change mitigation and financial saving benefits can be obtained (the concrete benefits are presented in Section 2.4 – potential benefits of adopting SSL).

2.1.2 Lighting, Health and Well-being

Lighting is vital for human life, it can act as a stimulator or an inhibitor in terms of human health and well-being. As a stimulator (good lighting), it not only enables vision, safety and orientation, but also has the power to energize, mix, and enhance attention, cognitive performance and mood. In contrast, issues like glare and flicker can lead to visual discomfort and further affect a person's mood or productivity (Aalto University, 2010; LightingEurope & ZVEI, 2013).

Lighting influences human in terms of visual (physical), non-visual (psychological and biological) aspects. Firstly, many lighting-related factors may cause visual discomfort, such as uniformity of lighting in a space, colour consistency, glare and flicker. Secondly, changes of luminance level and colour spectra could have an impact on personal emotions and mood (psychological effects). Lighting also has long term effects on human health and well-being (biological effect). For example, lighting can regulate human biological clock, as it is controlled by light and darkness. Biological clock is essential to human beings because it controls most daily rhythms in physiology and behavior (Aalto University, 2010).

Existing studies have demonstrated good evidences of a correlation between lighting, and human health and well-being. Its effects rely on the intensity, spectrum, and temporal pattern of the light, as well as personal perception and exposure history of lighting (Vick et al., 2014; Silvester & Konstantinou, 2010). For example, high level of illumination may trigger feelings of alertness and vitality, which could sustain attention and promote productivity at workplaces (LightingEurope & ZVEI, 2013). Dynamic lighting (variations of intensity and spectrum) may boost students' academic performance, social behaviour, as well as their physical and mental health (Vick et al., 2014).

But too much lighting is also a problem. For example, long night time exposure to lighting can affect the timing and duration of sleep (Aalto University, 2010). And nowadays lighting is so pervasive in the night time, people can hardly see the stars, which impairs human beings' connection to the nature.

Therefore, having the right light at the right place and time is of high importance. CELMA & ELC (2011)summarised the benefits of having good lighting for human at different places:

- Enhance visibility, safety, reduce fatigue, and improve personal productivity and accuracy at working places;
- Increase the sense of safety for walking, bicycling and driving on streets and roads;
- Improve studying experiences in educational worlds, stimulate and motivate students;
- Stimulate and improve amenity, comfort and shopping experiences in the retail environment;
- Promote calm and comfort in hospitals;
- Increase social and cultural life quality, particularly in cities; and
- Beautify the visual attractiveness of architecture and landscape;

However, little attention has been paid on lighting's impacts on human health and well-being so far. Conventional lighting sources distribute light in a unidirectional and static manner, which do not offer the opportunity of controlling light. But SSL is different, it is directional, digitally compatible and has a wide range of colours. By integrating SSL with different technologies (sensors, lighting controls, ICTs), innovative lighting solutions could be produced to control the directions, colours and illuminance of light. Therefore, to date, it is possible to control lighting to improve human health and well-being.

In addition, whilst many people are concerning about having good lighting, citizens from developing countries have no access to electricity. It is estimated that more than 1.3 billion people have no access to electricity. They have to use fuel-based lighting (UNEP, 2014). Fuel-based lighting, like kerosene or paraffin, not only is expensive and inefficient, but also affects human health. It is estimated that, annually, it accounts for less than 1% of global lighting output, yet contributes 10% of global lighting CO_2 emissions. And it causes thousands of deaths from respiratory and cardiac problems every year (Waide & Tanishima, 2006). Furthermore, the light it emits is often poor, which could compromise safety, educational performance, and working productivity (Mills, 2014b). Through the combination of LED and portable batteries (i.e., like solar-photovoltaics), LED lanterns could be produced. Compared to fuel-based lighting sources, LED lanterns have many advantages. It is not only cheaper, easy to carry with and more energy-efficient, but also healthier and safer. Some developing countries, such as Lao PDR, Kenya and Brazil, have used LED lanterns and achieved encouraging results (i.e., more citizens could have affordable and better lighting, the negative healthy impacts from kerosene lamps have been reduced) (IIIEE, 2014; Mills, 2014b). Besides, there is also evidence that deploying LED lanterns could contribute to local economic development, such as create more employment opportunities (Mills, 2014a). Hence, accelerating SSL deployment could also serve as a mean of combating against poverty.

2.2 Lighting technology

From candle to incandescent lamp, human development cannot be achieved without the innovation of lighting technologies. Since Edison incandescent lamp came out in 1880s, lighting technology has evolved greatly. In this section, different kinds of lighting sources will be introduced. Further, the evolving history and trend of SSL will be briefly described.

There are three main lighting technologies, namely incandescent, gas-discharge and solid-state lighting, whilst a bundle of variants have been developed based on them (Figure 2-4). Table 2-1 summarizes the characteristics of various lighting technologies.

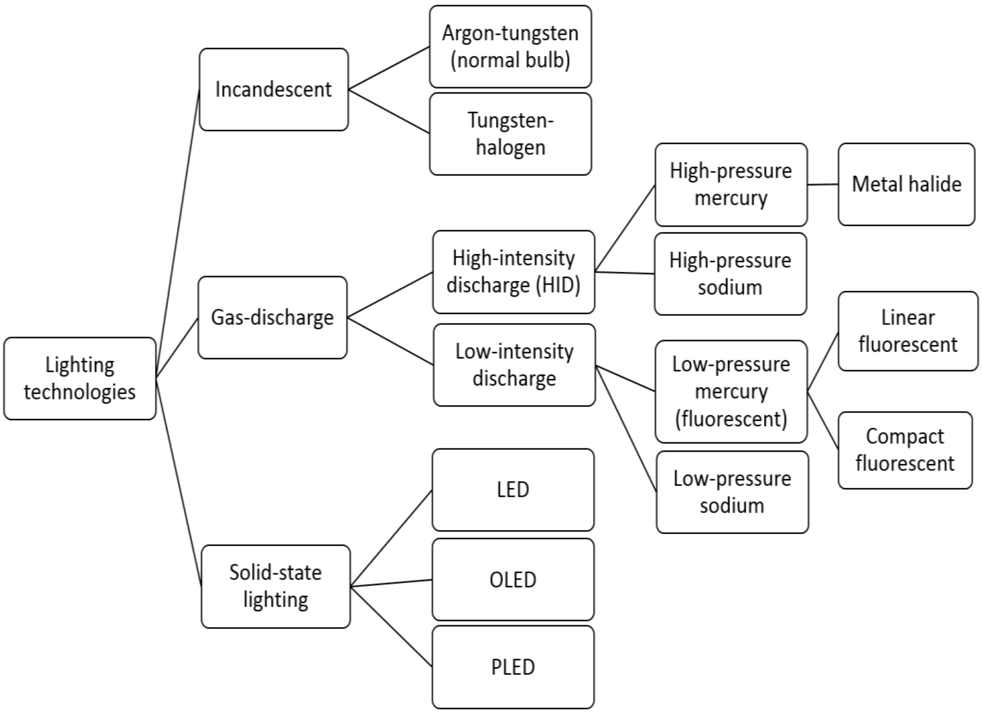


Figure 2-4 Lighting technologies

Source: Ajusted from (Waide & Tanishima, 2006)

2.2.1 Traditional lighting technologies

Incandescent lamp, or general lighting service lamp (GLS), was firstly commercialized in 1878. It is still widely used today. It produces light by heating a wire filament to a high temperature by electric currents. Incandescent lamps is very inefficient, roughly 5% of the energy it consumes is used for emitting light. The rest is wasted as heat. Its efficacy[10] is in the range of 5 – 15 lm/w. It also has a shor life span, approximately 1,000 h in average. Nevertheless, it is cheap and has good chromaticity characteristics (CCT in the range of 2400 to 3100 K) (Waide & Tanishima, 2006; Aalto University, 2010). Tungsten halogen lamps (or halogen lamps) was developed in 1958, as a higher-efficiency derivative of incandescent lamps. It entered the market in 1980s. The bulb is filled with high-pressure halogen gas that allows higher operation temperature, and restrict the evaporation of filaments. This improvement help it last longer and look whiter than GLS. In average, it has an efficacy between 12 and 35 lm/w and lasts 2000 – 4000 hours. To date, for incandescent lamps, no further great improvement has been made after halogen lamps. (Aalto University, 2010).

Fluorescent lamps was invented in 1903 and commercialized in 1937. A fluorescent lamp or tube is a low-pressure mercury lamp that uses fluorescence to produce visible light. The mercury vapor is excited by an electric current and emits ultraviolet light, which is converted into visible light by phosphor coating on the inside of the tube. Its chromaticity characteristics

[10] For lighting sources, energy efficiency is normally described by efficacy (lm/w), which is the ratio of emitted luminous flux (lumens) to power (watts).

largely depend on the type of phosphor used, CCT values can vary from 2700 to 6500 K (Aalto University, 2010). It needs a ballast to regulate the electric current. There are two groups of fluorescent lamps, one is linear fluorescent lamp (LFL), and the other is compact fluorescent lamp (CFL). LFL has an efficacy of 60 – 104 lm/w, and life expectancy from 10,000 to 16,000 hours. LFL has been improved with time, from the old, T12, passing through T8, to the present T5 lamps, not only its diameter has been reduced, but also its efficacy has increased. T5 efficacy can reach 100 lm/w (*ibid.*). CFL is a compact and short variant of fluorescent lamp. Its tube is often folded into two to six fingers or a spiral. A typical CFL has a high efficacy (40 – 65 lm/w), and long operating period (6,000 – 12,000 hours) (*ibid.*). It was considered as a direct alternative for inefficient incandescent lamps, yet because of reasons like high initial costs, the market adoption of CFL was slow (Sanderson, Simons, Walls, & Lai, 2008).

Table 2-1 Characteristics of different lighting technologies

Type	Characteristics							
	Efficacy lm/w	Lifespan Hours	Dimmability	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5-15	1,000	Excellent	Prompt	Very good	Low	Very high	General lighting
Tungsten halogen	12-35	2,000-4,000	Excellent	Prompt	Very good	Low	High	General lighting
Mercury-vapour	40-60	12,000	Not possible	2-5 min	Poor to good	Moderate	Moderate	Outdoor lighting
CFL	40-65	6,000-12,000	With special lamps	Prompt	Good	Low	Low	General lighting
LFL	50-100	10,000-16,000	Good	Prompt	Good	Low	Low	General lighting
Metal halide	50-100	6,000-12,000	Possible but not practical	5-10 min	Good	High	Low	Shopping malls, commercial buildings
High pressure sodium (standard)	80-100	12,000-16,000	Possible but not practical	2-5 min	Fair	High	Low	Outdoor, streets lighting, warehouse
High pressure sodium (colour improved)	40-60	6,000-10,000	Possible but not practical	2-6 min	Good	High	Low	Outdoor, commercial interior lighting
LED	20-120	20,000-100,000	Excellent	Prompt	Good	High	Low	All in near future

Source: (Aalto University, 2010)

High-intensity discharge lamp (HID) produces light by forming an electric arc between tungsten electrodes, which are housed inside a translucent fused quartz or alumina arc tube. The tube is filled with both gas and metal salts. The gas facilitates the arc's initial strike, and heats the metal salts to evaporate to increase the light intensity. HID lamps can be classified into mercury-vapour, high-pressure sodium and metal halide lamps, defined by the metals it uses. HID lamp has advantages when compared to incandescent and some fluorescent lamps in energy-efficiency, lifespan (12,000 hours) and temperature insensitivity. These features make it suit for certain application, such as street lighting. Mercury-vapour lamp is the oldest type of HID lamp, compared to metal halide lamp (efficacy: 50 – 100 lm/w), it has a lower efficacy (40 – 60 lm/w), but it is still widely used around the world (Waide & Tanishima, 2006).

2.2.2 Solid-state lighting – the disruptive technology

2.2.2.1 SSL Basics

An SSL is a semiconductor diode which emits light by the movement of electrons inside it. It is electroluminescent. According to the material of semiconductor used, SSLs are typically categorized in three groups, namely, LEDs (inorganic compound), organic light-emitting diodes (OLEDs), and polymer light-emitting diodes (PLEDs) (Sanderson et al., 2008). Currently, LED is the most advanced and commercial viable. Thus, this part will focus on it (Tsao et al., 2014).

Unlike incandescent or fluorescent bulbs, an LED inherently emit rather roughly monochromatic light than white light. The color of its light depends on the chemical composition of used semiconductor. Based on the color (visible spectrum) it yields, LEDs can be classified as red, orange, yellow, green, blue LEDs and so on. The characteristic of emitting sing-color light makes LED highly efficiently for colored light application, i.e., indicator lights. In order to be used as a general light source, it needs to emit white colour. However, it was only after 2005 that warm-white LED (for general lighting market) gained commercial interests (Haitz & Tsao, 2011).

For a long time, white LED is the "holy grail" of LED lighting (Sanderson & Simons, 2014). To date, there are three main approaches to produce White LED (Figure 2-5).

1. Phosphors conversion, in which a monochromatic LED (blue or UV LED) is coated by phosphors (i.e., red and green phosphors) to yield white light. This type of LED is typically called as phosphor-converted white LED (PC-LED);
2. RGB systems, in which multiple monochromatic LEDs (red, green and blue) are mixed and combined to produce white light. White LED used this technique is named as color-mixed LED (CM-LED) or RGB LED; and
3. A hybrid method, which combines one or more monochromatic LEDs with a PC-LED.

(U.S. Department of Energy, 2015)

To date, phosphor conversion is the most used approach. Because it is the most efficient and has a lower cost (Haitz & Tsao, 2011). According to its colour temperature, white LEDs can be divided into two main bands, cool or warm white LEDs. The U.S. DoE (2014) defines cool white LEDs with correlated color temperatures (CCT) from 4746K to 7040K and color rendering index (CRI) greater than 70, and warm white LED with CCT between 2580K and 3710K and CRI greater than 80.

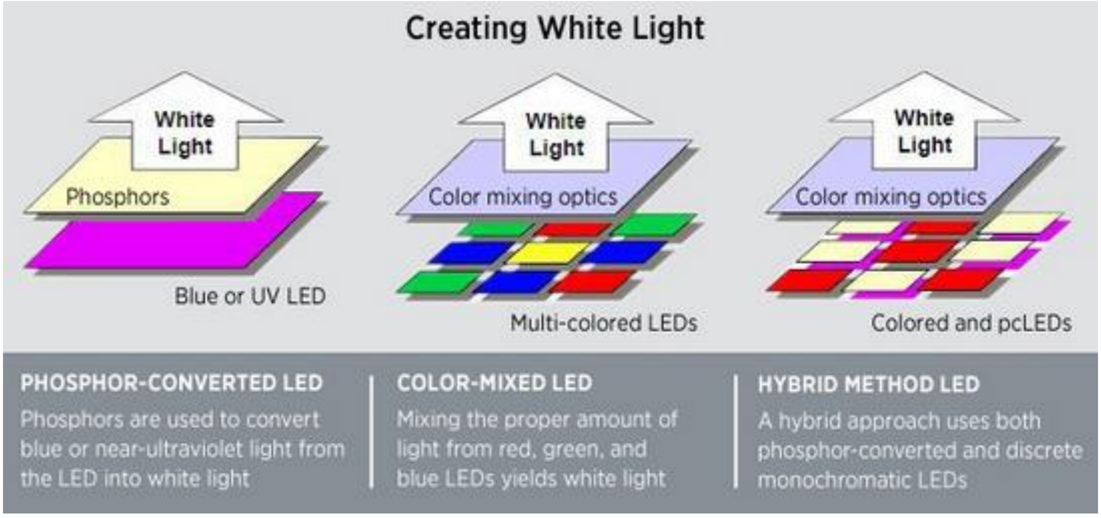


Figure 2-5 Different Approaches to produce white LED

Source: (U.S. Department of Energy, 2015)

2.2.2.2 A brief history of SSL development and its future

In 1907, H. J. Round noticed the phenomenon of semiconductor electroluminescence. After about six decades, the first red LED came out and was soon commercialized as indicator lamps. The initial efficacy of red LED was very poor, approximately 0.02 lm/w. After continuous effort of R&D, its efficacy has been improved greatly. Now it is more than 150 lm/w (Tsao et al., 2014).

Red LED is the stepping stone for LED market entry. After its success in the niche market of indicator lighting, more investments were put in R&D. Significant performance improvement were achieved. And most importantly, a variety of monochromatic LEDs came out, such as yellow, orange, and weak green and blue. The new products opened more market, like traffic lights and backlights (Sanderson & Simons, 2014).

Nevertheless, with white LED products, it could not enter the general illumination market. Bright blue LED is the key for white LED. In 1992, the first bright blue LED was developed by Shuji Nakamura. It is the second stepping stone for LED, as it opened the market of general illumination. In 1996, the first white LED based on blue LED with yellow phosphor was developed by a Japanese company, Nichia (Sanderson & Simons, 2014). Henceforth, its efficacy has increased for multiple orders of magnitude: from around 10 lm/w to more than 200 lm/w (De Almeida et al., 2014). And it was gradually adopted in street lighting and architectural lighting. But its adoption in residential sectors started very late, in 2010 (Sanderson & Simons, 2014).

For the future of SSL or LED, being smart and ultra-efficient will be the trend. Being smart means it can be integrated with ICTs, and deliver light on the basis of personal needs (intensity and colour change). To achieve smartness and ultra-efficiency, PC-LED has to give way to CM-LED. Because on one hand, for PC-LED, there is always an efficiency loss in phosphor conversion. Without considering other factors, the highest efficiency of down converting blue to red or green light is 80%. CM-LED can avoid efficiency loss, as it does not use phosphor converstion to emit white colour. On the other hand, PC-LED has limited possibilities of being smartness. For instance, it has a set chromaticity. So it is not possible to have the featue of colour tuning with PC-LED (Tsao et al., 2014).

There are many chanllenges (or uncertainties) needs to be overcome to achieve smartness and ultra-effiency. Firstly, green and yellow LED need to improve their efficiency. Untill 2013, for green LED, its power conversion efficiency was around 22%. But for blue and red LED, their efficiency were relatively 55% and 44% (U.S. Department of Energy, 2014). Secondly, blue and red LED need to maintain their effiency in different conditions. For blue LED, its efficiency peaks at moderate input power intensity then starts to decrease if power intensity increases. So the challenge is to maintain high efficiency at high input power intensity. For red LED, its efficiency drop significantly as temperature increases. So it needs to become temperature insensitive. Further, to realize smartness, LED must be better integrated with ancillary devices, such as sensors and controllers. The integrated products (innovative lighting solutions) faces many uncertainities, like reliability, functionability, and affordability (Tsao et al., 2014).

2.2.2.3 The advantages and disadvantages of SSL

2.2.2.3.1 Advantages

In comparison to its predecessors, SSL has the following advantages:

- High energy-efficiency. To date, SSL is the most energy-efficient lighting source. And it still has huge room for improvment, whilst other lighting technologies have almost reached their limits. Figure 2-6 illustrates the approximate range of efficacy of common light sources. LED efficacy is in the range from 10 lm/w to 120 lm/w. The majority is between 40 and 80 lm/w (U.S. Department of Energy, 2013). Furthermore, the US Department of Energy (DoE) (2014) projected that most LEDs would achieve an efficacy of above 200 lm/w in 2020. In fact, both Cree and Philips have developed state-of-the-art 200lm/w LED luminaires in 2013;
- Durability and long life expectancy. A typically LED can last from 25,000 to over 50,000 hours (De Almeida et al., 2014);
- A wide range of colors, dimmability and digitally compatibility. By integrating SSL with different technologies (sensors, lighting controls, ICTs), innovative lighting solutions (i.e. human centric lighting) could be produced to control the directions, colours and illuminance of light;
- Good physical robustness and compactness. SSL is more resistant to vibration or shock;
- High flexibility in shape and size. SSL could provide new design possibilities. It also can be easily integrated with ancillary components because of small size, for example, with portable batteries. LED lanterns is easy to carry with. Then people without access to electricity can use LED lanterns. This is not only more energy-effient, but also cheaper and healthier than kerosene lamps (Waide & Tanishima, 2006);
- Environmental friendly, i.e., mercury-free. Many life cycle assessments (LCAs) have concluded that LED has the least impact on environment almost in every category, such as acidification, land use and human toxicity (LightingEurope, 2013). Its advantage will become even greater in the future as it is still under rapid improvement;
- Fast response under on/off, can be applied as cycling lights;
- Directionality. SSL can reduce light pollution, especially in outdoor applications;

- No UV/IV radiation and less heat, safe to touch;

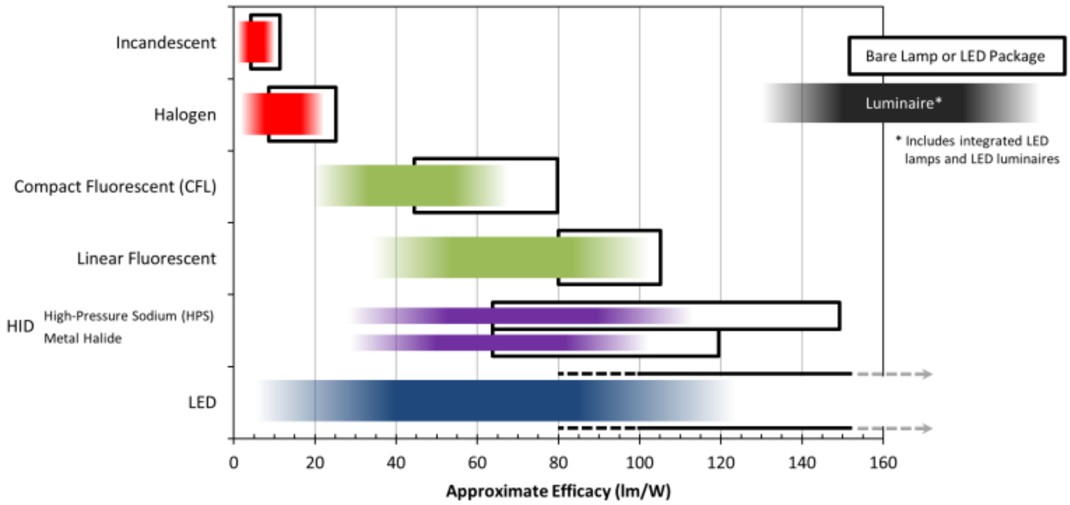


Figure 2-6 Approximate range of efficacy for common light sources. (The black boxes show the efficacy of bare conventional lamps and LED packages, which can vary based on construction, materials, wattage, or other factors. The shaded regions show luminaire efficacy, which considers the entire system, including driver, thermal, and optical losses. Of the light source technologies listed, only LED is expected to make substantial increases in efficacy in the near future).

Source: (U.S. Department of Energy, 2013)

2.2.2.3.2 Disadvantages

Nonetheless, SSL also has some disadvantages. Some of its disadvantages will be overcome or improved as it is still under rapid development. The main disadvantages are as follows:

- High initial price. SSL is usually ten times expensive than incandescent lamps. So it is not so attractive to consumers, even though it has a lower life cycle cost;
- Temperature sensitivity. Operating temperature has strong effects on LED performance. Its maximum operating temperature is called as "junction temperature". It is possible to change junction temperature by adding different drivers or controls. Junction temperature can be very high. But LED performance is very sensitive to any of its increase. For example, If LED runs at a high junction temperature, its efficiency and lifetime expectancy will be significantly undermined though its lumen output will increase. If operating under a low junction temperature, the result is opposite. A typcial LED is designed to run in a defined range of ambient temperatures (not exceeding the junction temperature). If there is a large increase in the ambient temperature, i.e., 10 ℃ increase, LED chips could be damaged serioiusly and stop functioning;
- Voltage dependence. LED works most efficiently under a low voltage (or current), and it has limited adaptability to voltage fluctuations or peaks. High voltages or current spikes can lead to an immediate failure;
- Light quality problems, such as glare and flicker. LED is directional, the light yielded by small size products could be too obtrusive;

- Color shift. For conventional lamps, there is minor color shift between different lamps. For LED, the color it emits depends on the material composition of semiconductor. Its thickness and uniformity can change the colour it emits. It is very difficult to ensure the semiconductor used in different LEDs has the same thickness and uniformity. Hence, there is always colour inconsistency in different LEDs.
- High complexity. A LED needs many components to maintain its performance, such as heat sinks to regulate its operating temperature, drivers to control voltage, optics to direct light, etc. If additional features are desired, like smartness, then more ancillary components will be added, like lighting controls, sensors and so on. It will be difficult to ensure co-functionality of all components;
- Potential environmental impacts. SSL contains many rare and hazardous metals (i.e., lead). There is uncertainty about the potential environmental impacts if SSL is disposed randomly (Lim, Kang, Ogunseitan, & Schoenung, 2013). Nevertheless, as mentioned above, according to many LCAs, LED has the least environmental impact in many aspects;
- Blue pollution. Cool-white LED with high color temperature emits more blue light than conventional lighting technologies. The emited blue light may excced the safety limit and cause more light pollution than others (European Commission, 2011a); and
- Lack of standardization. SSL is fundamentally different to conventional lighting sources. A variety of present lighting performance metrics and testing methods used today cannot be applied to SSL. New performance metrics and testing methods are needed to indicate its advantages. For example, for traditional lighting lamps, their life time could be significantly influenced by on-off cycle. But for SSL, on-ff cycles do not affect its performance. Thus, this requirement should be excluded. Furthermore, factors like operating temperature, voltage, and oritentaion could have strong impacts on its performance, so there is a need to test LED performance under different circumstances to understand its adaptability (i.e., temperature and voltage). Last but not least, existing LED standards only measure the performance of LED packages, not the final products. Yet, when LED packages are used to assemble LED luminaires or fixtures with different components, like optics, drivers, and controls, the resulted performance varied diversely.

(Cole, Clayton, & Martin, 2015; De Almeida et al., 2014)

2.3 Lighting Industry and market

The lighting industry was monopolized by big three for a long time, namely, Philips Electronics (Philips), OSRAM-Sylvania (OSRAM), and General Electric (GE). With the development of SSL, disruption of the industry structure is becoming more apparent. Many new players have entered the lighting market. These players are mainly from Asia, such as Japan, South Korean and China (Sanderson et al., 2008). They entered the market successufully for different reasons. For Janpan, it is because the first bright blue LED is created by a Japanese scientist, so they have first-mover advantage. For China, it has cheap labour and owns most rare metal ore (Sanderson & Simons, 2014).

In Europe, the lighting industry is highly fragmented along the value chain, and there are many small and medium enterprises (SMEs) (European Commission, 2011a). As the industry is redrawn, new business opportunities are also emerging. For example, the lighting control system is already fast-growing. It is predicted that the market will grow rapidly, with a rate of

20% in average during 2010 to 2020 (McKinsey & Company, 2012). And for the future, innovative lighting solutions (interating SSL with sensors, controls, ICTs, etc.) will be the trend, as it provides the opportunity to control lighting for human health and well-being (LightingEurope & ZVEI, 2013).

Mckinsey & Company (2012) estimated that there were over 14 billion units (unit: lamp) sold out in general lighting market in 2011, including new installation and replacement. Figure 2-7 presents sales of different lighting technologies. LED only accounts for 1% of the total sale. Incandescent is the single largest lighting source lamps, accounting for 58% of the total sale, including GLS and halogen lamps.The rest are 39% for fluorescent lamps (LFL and CFL), 2% for HID lamps.

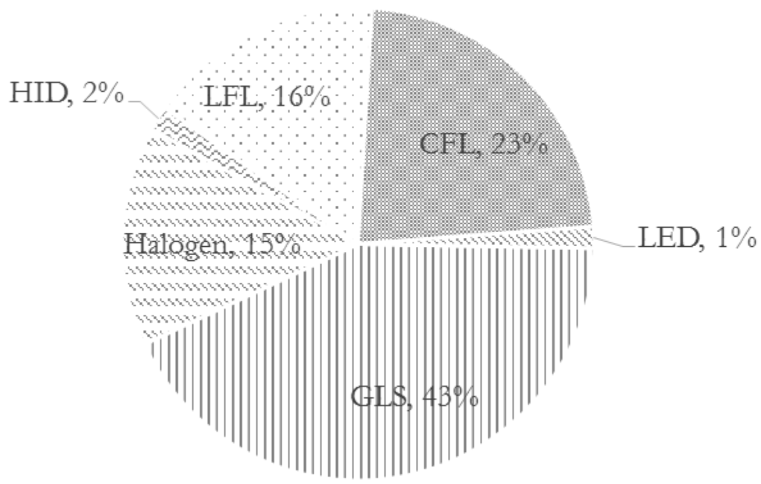


Figure 2-7 Sales of l in general lighting market by lighting technology in 2011 (unit: %)

Source: (McKinsey & Company, 2012)

In terms of market value, the LED market was EUR 9 billion in 2011 (Figure 2-8), representing about 12% of the total lighting market. But it is anticipated that it will increase to EUR 37 billion and EUR 64 billion in 2020, and its share in the total market will increase to 41% in 2016 and 63% in 2020. (McKinsey & Company, 2012)

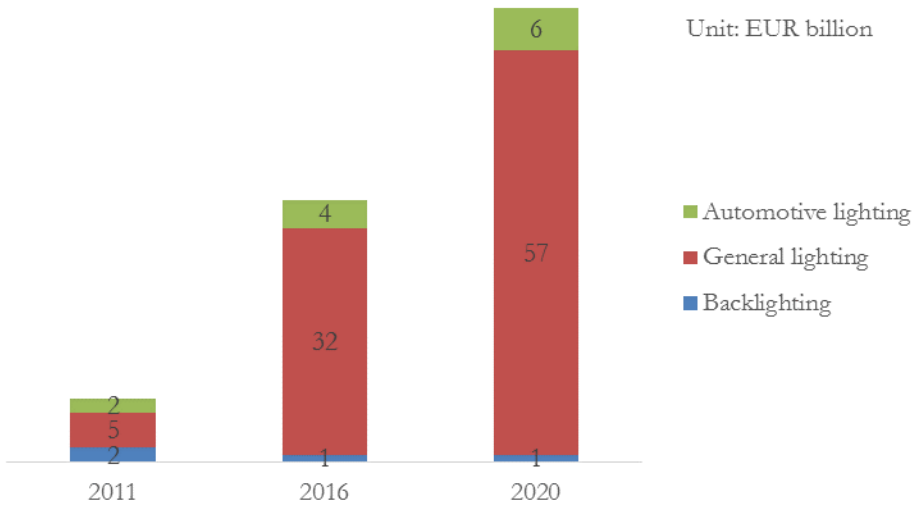


Figure 2-8 LED lighting market by sectors (unit: EUR billion)

Source: (McKinsey & Company, 2012)

Regarding to different sectors (Figure 2-9), backlighting is an early adopter of LED. In 2011, LED has accounted for 57% of its market. General lighting will be the key sector for adoption from 2011 to 2020. It is expected that LED will have 45% of general lighting market in 2015 and 70% in 2020. (McKinsey & Company, 2012)

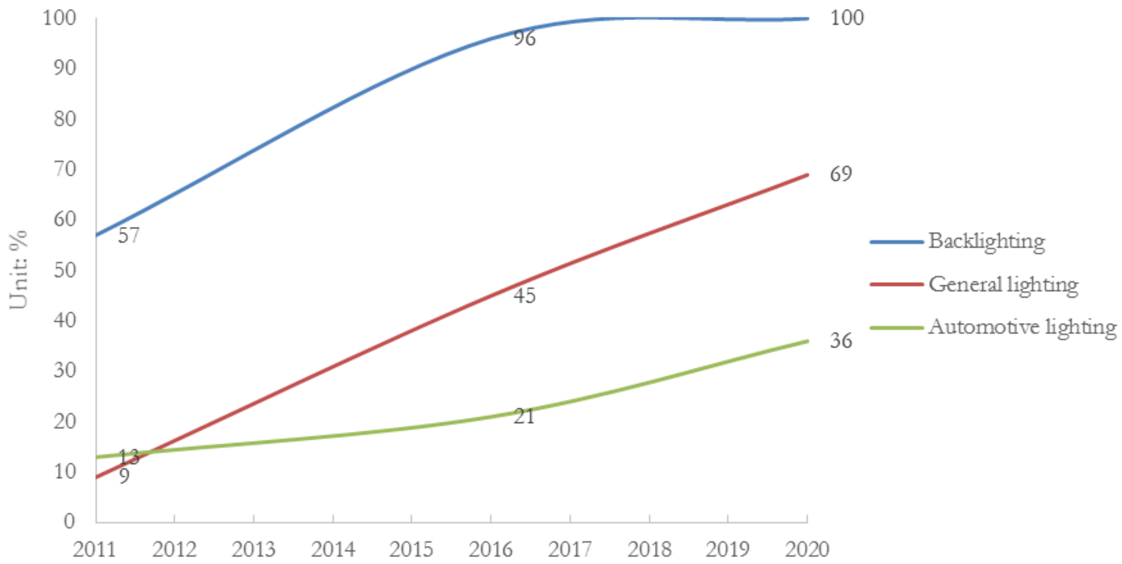


Figure 2-9 LED value-based market share by sector (unit: percent)

Source: (McKinsey & Company, 2012)

In contrast to the promising prediction, the market adopts SSL slowly. For instance, In EU, the total sales of lighting applications were around EUR 11,284 million (the residential sector: 5,781 EUR million) in 2012. The share of LED was 7% (Figure 2-10). But according to the prediction, LED should have a sale of 2,017 EUR million in 2012 in the EU, representing 15% of the market share. (Wierda, 2014a)

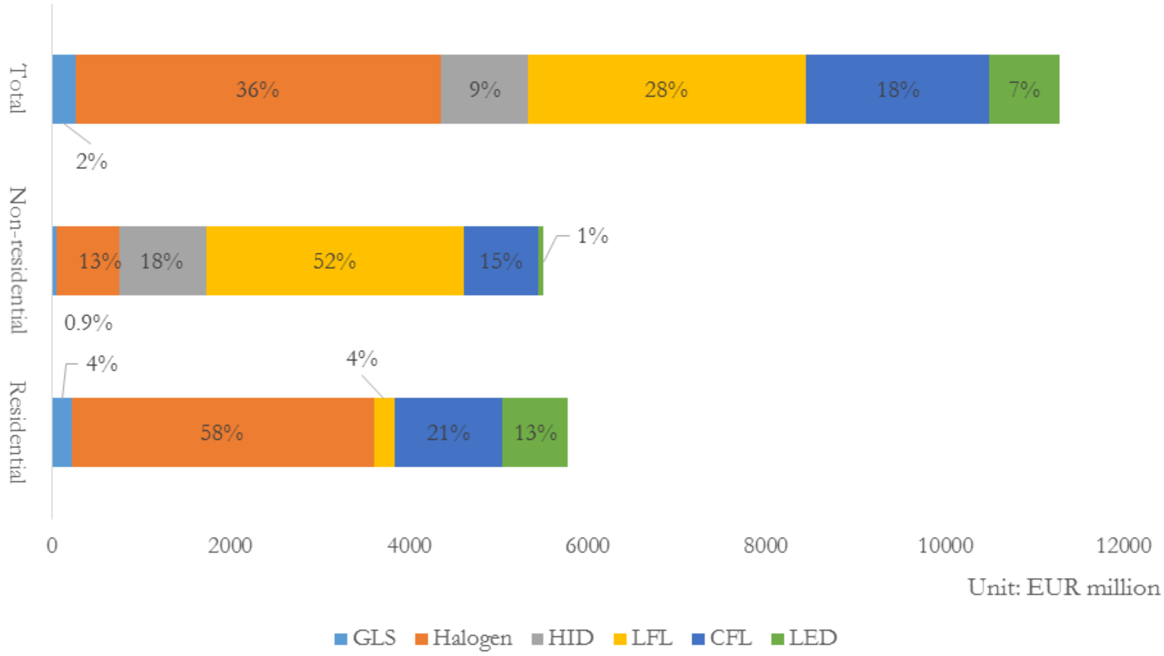


Figure 2-10 Sales of lighting applications in EU in 2013 (unit: EUR million)

Source: (Wierda, 2014a)

2.4 Potential benefits of adopting SSL

This section presents the potential and benefits of adopting SSL. That is, energy saving and climate change mitigation benefits as well as other benefits, like environmental benefits, good indoor climate, etc. Neverthelss, apart from energy saving and climate change mitigation benefits, SSL's other benefits are very less documented, or are less concerned.

2.4.1 Energy saving and climate change mitigation Benefits

Globally, there are more than 26 billion lamp units installed for general illumination use (Figure 2-11), and only 2% are LEDs. Incandescent lamps remain the dominant lighting sources, representing 49% of the total. Fluorescent lamps has a share of 47%, whilst HID only accounts for 2%. (McKinsey & Company, 2012)

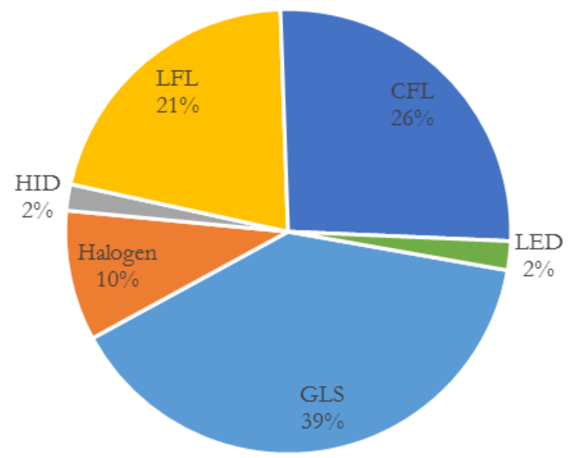


Figure 2-11 Share of total installed lighting sources (until 2011) for general illumination use (unit: %)

Source: (McKinsey & Company, 2012)

In Europe, the picture is slightly different. The number of lighting sources in use is 11 billion in 2013, among which, 6.5 billion units (59%) are for residential use. The share of different lighting soures is presented in Figure 2-12. LED has a rather low share, representing 1% of all installed lamps. Fluorescent lamps have surpassed incandescent lamps and became the primary lighting source, with a share of 61%. But Incandescent lamps still have a substantial share, accounting for 37% in total. And it is the largest lighting source in the residential sector, amounting to 53%. (Wierda, 2014a)

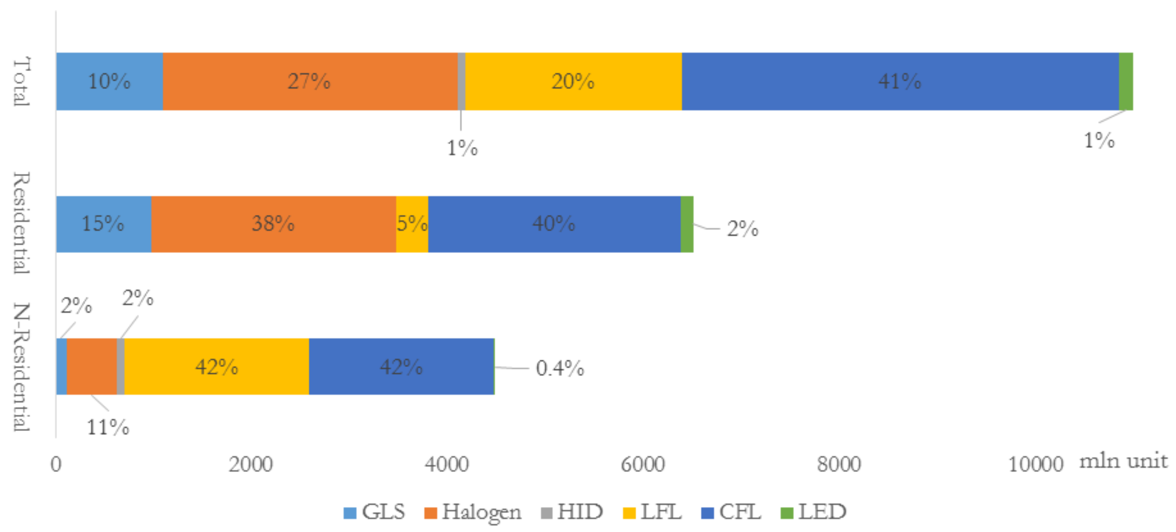


Figure 2-12 Share of different lighting sources in 2013 in the EU

Source: (Wierda, 2014a)

As presented in Figure 2-11 and 2-12, many lamps used are inefficieny lamps. Therefore, there is huge potential for energy savings. According to UNEP (2014) analysis, if all inefficient lamps are replaced by energy efficient lighting (i.e., LEDs), annually approximately 1,044 TWh electricity would be saved (Table 2-2). This is 35% of global lighting electricity consumption, and 5.6% of global electricity consumption. The saved electricity is equivalent to the annual electricity production of 280 large (500 MW) base-load coal-fired power plants. The financial benefits are approximately USD 120 billion. Moreover, the annual reduction of CO_2 emissions would reach 624 Mt, 530 Mt from on-grid lighting and 90 Mt from off-grid lighting. This is the annual emissions of more than 150 million mid-size cars (en.lighten, n.d.-a).

For Europe (Table 2-2), switch to energy-efficient lightings could save more than 200 TWh electricity annually, and reduce around 70 million tonnes of CO_2 emissions. The annual savings is approximately USD 35.8 billion.(en.lighten, n.d.-b).

Table 2-2 Energy aving and climate change mitigation benefits of adopting energy-efficient lighting sources.

Benefits	Financial benefits/ USD billion	Energy saving benefits		Climate change mitigation benefits		
		Savings / TWh	Equivalent to number of 500MW power plants	On-grid Savings / Mt	Off-grid Savings / Mt	Equivalent to number of mid-size cars /mln
Global	120	1044	280	534	90	150
Europe	35.8	203.1	55	69.8	N/A	17

Source: (UNEP, 2014; en.lighten, n.d.-c)

If all lighting sources are replaced by LED, even higher energy saving benefits could be achieved. UNEP (2014) estimated that global lighting electricity consumption would be reduced more than 52%, and avoid 735 Mt of CO_2 emissions. Philips (2012) reached a similar conclusion. The average achievable energy saving are 40% of the total lighting electric power consumption, which is about 1284 TWh electricity (Table 2-3).

Table 2-3 Energy saving and climate change mitigation benefits of adopting SSL by region.

Benefits	Financial benefits/ EUR billion	Energy saving benefits/ TWh	Climate change mitigation benefits / Mt
Global	128	1,284	670
Europe	28	282	98
North America	40	396	210
Latin American incl.	9	92	24

Mexico			
Asia Pacific	36	362	236
Middle East and Africa	15	152	102

Source: (Philips N.V., 2012)

2.4.2 Other benefits

SSL not only is superior in energy efficiency and life span, but also is more environment-fridendly. The Country Lighting Assessment project assessed that if all lamps swichted to LED overnight in Europe, six tonnes of mercury could be reduced (Table 2-4). Further, 356 kiltonnes SO_X as well as 193 kilotonnes of NO_X emission reduction could be achieved.

Table 2-4 Envrionmental benefits of adopting SSL in Europe

Environmental benefits	Mercury / tonnes	SO_x / kilotonnes	NO_x / kilotonnes
Europe	6.0	356.6	193.1

Source: (en.lighten, n.d.-c)

As mentioned above, light is essential for life. And existing studies have demonstrated light intensity, spectrum and temporal patten could have impacts on human health and well-being, which were not well-known before (Vick et al., 2014; Silvester & Konstantinou, 2010). Conventional lighting sources distribute light in a unidirectional and static manner, which do not offer the opportunity of controlling light. But SSL is different, it is directional, digitally compatible and has a wide range of colours. By integrating SSL with different technologies (sensors, lighting controls, ICTs), innovative lighting solutions could be produced to control the directions, colours and illuminance of light. Therefore, to date, it is possible to control lighting to improve human health and well-being.

SSL also could reduce light pollution, particularly in outdoor space. Conventional lighting sources are not directional, so the light emited is dispersed to all directions. This not only wastes energy but also leads to light pollution. Nowadays light pollution is so pervasive that we can hardly see the sky and stars. Too much light could also affect our health as well as animal and plant behavior. For example, long night time exposure to light can affect the timing and duration of sleep (Aalto University, 2010).

Furthermore, SSL is highly flexible in shape and size, which would provide more room for design. And it could be very small. Then it would be easily integrated with ancillary components, such as portale batteries. LED lanterns is easy to carry with. Then people without access to electricity can use LED lanterns. This is not only more energy-effient, but also cheaper and healthier than kerosene lamps (Waide & Tanishima, 2006).

It is estimated that more than 1.3 billion people have no access to electricity. They have to use fuel-based lighting (UNEP, 2014). Fuel-based lighting, like kerosene or paraffin, not only is expensive and inefficient, but also affects human health. Annually, it accounts for less than 1% of global lighting output, yet contribute 10% of global lighting CO_2 emissions. And it causes thousands of deaths from respiratory and cardiac problems every year (Waide & Tanishima, 2006). Furthermore, the light it emits is often poor, compromising education performance, safety and working productivity (Mills, 2014b). If all kerosene lamps are replaced by LED lanterns, annually 25 billion litres of fuel could be saved, as well as 90 Mt CO_2 emissions (en.lighten, n.d.-a, n.d.-d). And the expense they consumed for koresene could be saved, the financial savings are around 25 – 33 USD billion (en.lighten, n.d.-e).

Some developing countries, such as Lao PDR, Kenya and Brazil, have used LED lanterns and achieved encouraging results (i.e., more citizens could have affordable and better lighting, the negative healthy impacts from kerosene lamps have been reduced) (IIIEE, 2014; Mills, 2014b). Besides, there is also evidence that deploying LED lanterns could contribute to local economic development, such as create more employment opportunities (Mills, 2014a). Hence, accelerating SSL deployment could also serve as a mean of combating against poverty.

3 Findings & Analysis

3.1 Challenges

3.1.1 Low confidence in SSL due to early technological shortcomings

When SSL enetered general lighting market, it was immature and had many shortcomings, such as glare, flicker, poor luminous efficacy, short life time, and colour inconsistency. Early LED products with these problems have significantly undermined consumer's confidence in the new technology (SSL) (Sandahl, Cort, & Gordon, 2013).

With years of development, early technological shortcomings have been gradually improved or overcome. For example, the luminous efficacy of warm white LED has increased by more than 10 times, from sigial digit to above 150 lm/w. But because of low confidence, there is low trust and risk aversion among the potential users/investors (I. Johansson, Personal communication). For example, Lund minucipality tried LED lamps in early years. Some of them stoped functioning within one year (supposed to last three years). This negative experience impaired their confidence on SSL. It took them a long time to rebuild their trust. It was not only after years did they retry LED lightings (H. Nygren, Personal communication).

3.1.2 Risk averison due to uncertainties of product performance and benefits of SSL

Risk aversion is another main barrier. SSL is a new technology, the public sector faces many uncertainties to adopt it (I. Johansson, Personal communication). When facing uncertainties, it is much easier for the decision-makers to follow what has been done last time. By doing so, they would not been blamed if it goes wrong. But if they do it differently, they have to bear the risk of failure.

3.1.2.1 Uncertanities of product Performance

One example is the uncertainity of product performance. After years of development, SSL has been improved significantly, yet there are still lots of low quality products (i.e., low efficacy, short life time, colour distortion) in the market, which has prevented potential users (the public sector) to adopt it (P. Kisch, Personal communication; R. Karlsson, Personal communication). And compared to conventional lighting sources, there is huge quality difference among LED products. This fact has increased the difficulties and costs for the public sector to select products (P. Kisch, Personal communication). For example, as showed in Figure 3-1, the luminous efficacy range of LED products are much larger than other lighting sources (U.S. Department of Energy, 2013).

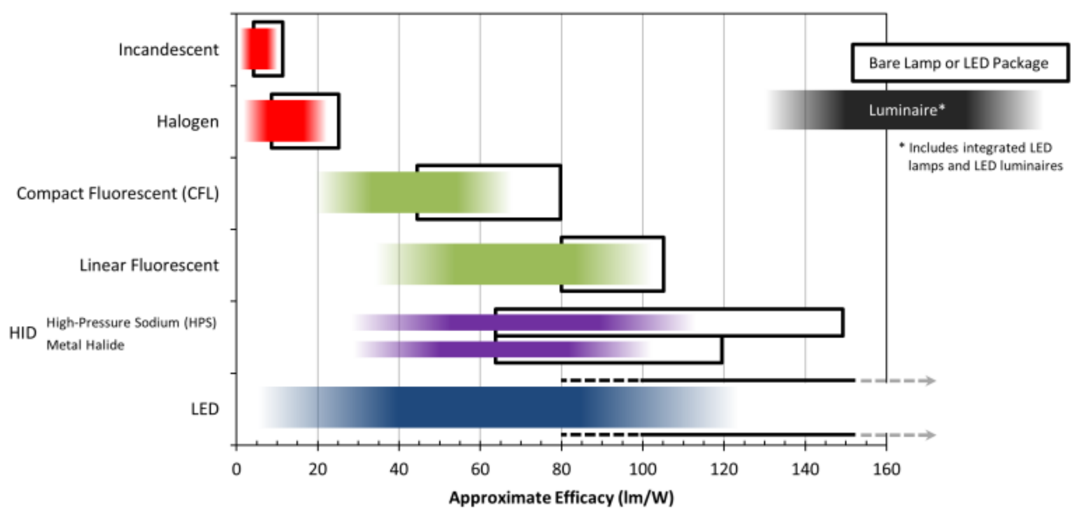


Figure 3-1 Approximate range of efficacy for common light sources. (The black boxes show the efficacy of bare conventional lamps and LED packages, which can vary based on construction, materials, wattage, or other factors. The shaded regions show luminaire efficacy, which considers the entire system, including driver, thermal, and optical losses. Of the light source technologies listed, only LED is expected to make substantial increases in efficacy in the near future).

Source: (U.S. Department of Energy, 2013)

Why the market are flooded by poor products? – Lack of standard testing specifications for product performance

Poor products are flooding in the market is due to the fact that product performance testing standard is missing (De Almeida et al., 2014; European Commission, 2011a). Previously, the lighting industry was monopolized by Philips, OSRAM and GE. But SSL has redrawn the lighting industry structure, many new players has entered the market (new players are mainly from Asian countries, like South Korea, Japan and China) (Sanderson & Simons, 2014; Sanderson et al., 2008). Currently, the market has too many players. When the standard is missing, market players could take advantage of it. They could produce poor products to reduce costs, and providing exaggerated or misleading information to make profits (R. Karlsson, Personal Communication, P. Kisch, Personal communication).

Developing a good LED performance testing standard is challenging. The reasons are multifold. Firstly, LED is improving rapidly (its efficacy doubles in the lab every 1-2 years), it is difficult to set requirements (European Commission, 2011a; Valentová et al., 2012). Secondly, LED is a different technology, some existing testing methods cannot be applied to it. For example, for traditional lighting lamps, producers could use relative photometry[11] to calculate photometric values of a lamp based on "standard lamps" with the same light center lengths (LCL)[12]. The results are highly accurate and this approach could reduce testing costs. Nonetheless, this method cannot be applied to LED. Because there are too many variations

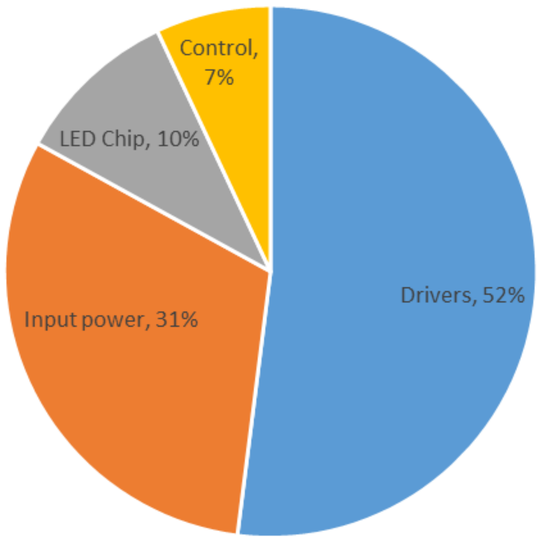
[11] Relative photometry: for instance, there are five High Pressure Sodium (HPS) lamps, 35 W, 50 W, 70 W and 100 W. If they have the same LCL. A manufacture only needs to perform photometric testing on one lamp. For the rest, their photometric results could be calculate with simple algebra. This method is called as relative photometry.

[12] Light center lengths (LCL): the distance between the center of the light-generating element of a lamp (e.g., the filament of an incandescent lamp) and an arbitrary point on the lamp base; for each type of lamp base, the reference point is defined by convention.

among LED products. For example, if a manfacuturer wants to apply this approach to LEDs, they have to ensure these products use identical chips and drivers, and have the some replacement or angle of optics, heat sink, etc., which is almost impossible (Cole et al., 2015).

Thirdly, some existing lighting performance metrics also cannot be applied to LED. This means new performance requirements are required for LED. For instance, for traditional lighting lamps, their life time could be significantly influenced by on-off cycles. However, for LED, this does not affect its life span. Thus, this requirement should be excluded for LED. Another example is there is minor colour inconsistency among conventional lighting lamps. But this is a problem for LED. Because the color it emits depends on the semiconductor's material composition, like its thickness and uniformity. It is very difficult to ensure the semiconductors used in different LEDs are identical. Therefore, colour shift among different LEDs is more apparent. A standard performance requirement on colour quality is needed as it could mitigate noticeable colour variations among different brands of LEDs (Cole et al., 2015). Further, unlike conventional lighting technologies, factors like operating temperature, voltage, and oritentaion have considerable impacts on LED performance. For example, high ambient temperature could increase LED light output, but its life time and efficiency would be undermined. And LED is also voltage sensitive. When conntected to grid, LED could be damaged by voltage fluctuation and peaks. So there is a need to test LED performance under different circumstances to understand its adaptability (i.e., temperature and voltage) (Cole et al., 2015).

Last but not least, exisiting LED standards only measure the performance of LED packages[13], standards for components (like optics, drivers, and controls) used to assemble LED fixtures or luminaires (the final products) are missing. Yet, these components have significant impact on LED performance. For example, it is estimated that 52% of LED failures come from drivers (Figure 3-2). (Cole et al., 2015). This is because LED chips ususally could last for a long time, like ten years. But other components, such as drivers, may only last one year. Therefore, to ensure its functionality, LED specifications should also cover other componets (Valentová et al., 2012; R. Holm, Personal communication).



[13] An LED package is the building block of most LED products (U.S. Department of Energy, 2013).

Figure 3-2 Sources of LED fixture failure

Source: (Cole et al., 2015)

3.1.2.2 Uncertainties of benefits of SSL

A second uncertainty is about the potential benefits of SSL, especially the benefits for human health and well-being, such as concentration improvement, productiticy increasement, and chronic diseases prevention (LightingEurope & ZVEI, 2013), which could be attained by deploying innovative lighting solutions (the integrated system of SSL, ICTs, sensors, controls, etc.). Even though existing studies have demonstrated good evidences of a correlation between lighting, and human health and well-being, the public sector still holds a skeptical attitude on this topic (P. Kisch, Personal communication). Also, the economic effects of innovate lighting solutions, such as total cost of ownership or returns on investment are doubted. Because it is difficult to convert lighing's indirect effects (benefits/costs on human health and well-being) into monetary values. In addition, Skepticism from the public could also prevent decision-makers from deploying innovative lighting solutions. For example, it could be regarded as manipulation or productivity measures, which conflicts with the interests of people (LightingEurope & ZVEI, 2013). And as there is few experience (successful projects) available, everyone is afraid of to be the first mover, so waiting for others to start.

3.1.3 Conservative perspective on lighting due to limited awareness of SSL and its benefits

One of the main barriers for SSL adoption in the public sector is decisions-makers generally have a conservative perspective on lighting, as they have limited awareness of SSL and its benefits. SSL is a new and much more flexible technology than the old ones, so it provides more possibilities, such as productivity increasement, chronic diseases prevention and concentration improvement (LightingEurope & ZVEI, 2013). But in general, the decision-makers in the public sector position lighting as a pure technical subject and consider it as technology officer's[14] responsibility (P. Kisch, Personal communication) This is because typically they are not lighting experts, so they may not be aware of the new technology and its benefits (De Almeida et al., 2014; Philips N.V., 2012).. During the indoor lighting for health and well-being conference (held in Lund on February, 5, 2015), it was mostly technology officer presented (which indicates decision-makers hold a conservative perspective on lighting). However, the subject of lighting is multi-dimensional and includes important issuses other than technical, like health, comfort, productivity, well-being, etc.

The fact that decision-makers have a limited awareness of SSL and its benefits is due to the knowledge gap among different departments (actors) in the public sector (H. Nygren, Personal communication). Figure 3-3 presents the partial governance structure of a typical Swedish municipality and the decision-making procedures for a new building project (lighting is part of it). Departments like education, elderly & handicapped care, and health care unit are the decision makers, they have the power to decide what lighting products are needed for the new buildings. The procurement unit is responsible for purchasing the needed lighting applications. And the technology and service unit is in charge of installation and maintenance.

[14] Technology officer is responsible for technology and serice management, such as lighting application installation and maintenance, not the decision-makers

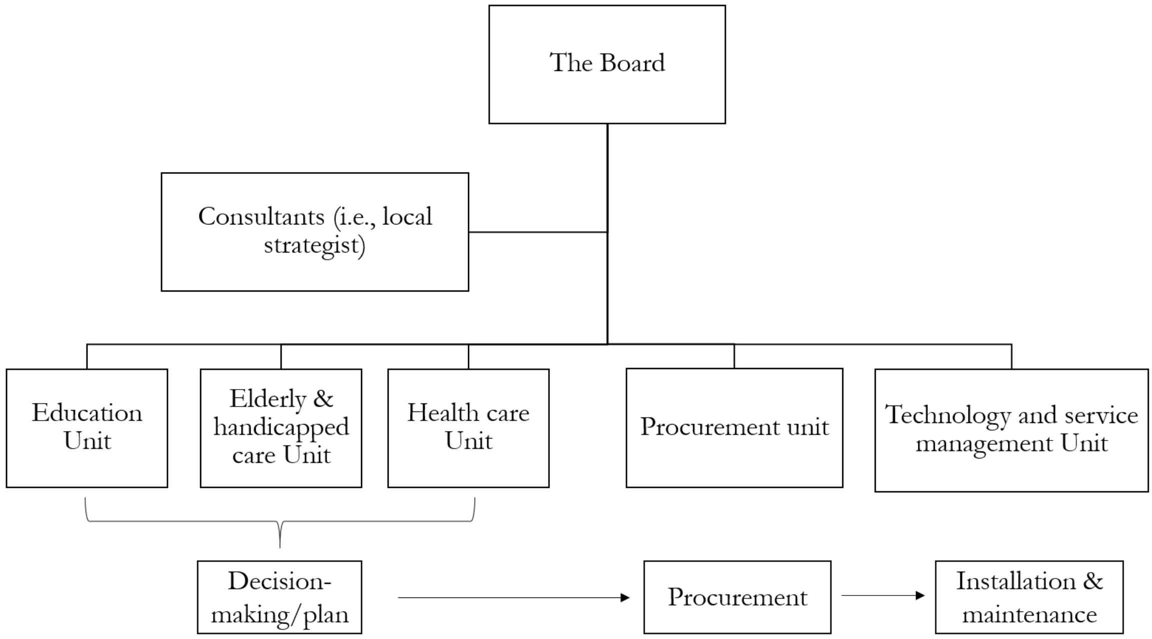


Figure 3-3 Part of a typical Swedish municipal governance structure and decision-making process for a new building project

Source: (H.Nygren, Personal communication)

Unlike the decision-making process, the knowledge of lighting transferred in another way. Figure 3-4 shows a conceptual model of the knowledge gap among different actors (actors who are interested in adopting SSL in the public sector). For instance, a municipality plans to build a new school. The technology officer may know from lighting designers that by integrating SSL with sensors, ICTs and controls, dynamic lighting (variation of light intensity and colour) could be produced, which could boost student academic performance, increase concentration and improve social behaviours. But they are not the decision-makers. In this case, the education unit is responsible for deciding the needed lighting products. In general, officers from this department normally position lighting as a technical subject, because they have a limited understanding of lighting, particularly its effects on human health and well-being (H. Nygren, Personal communication).

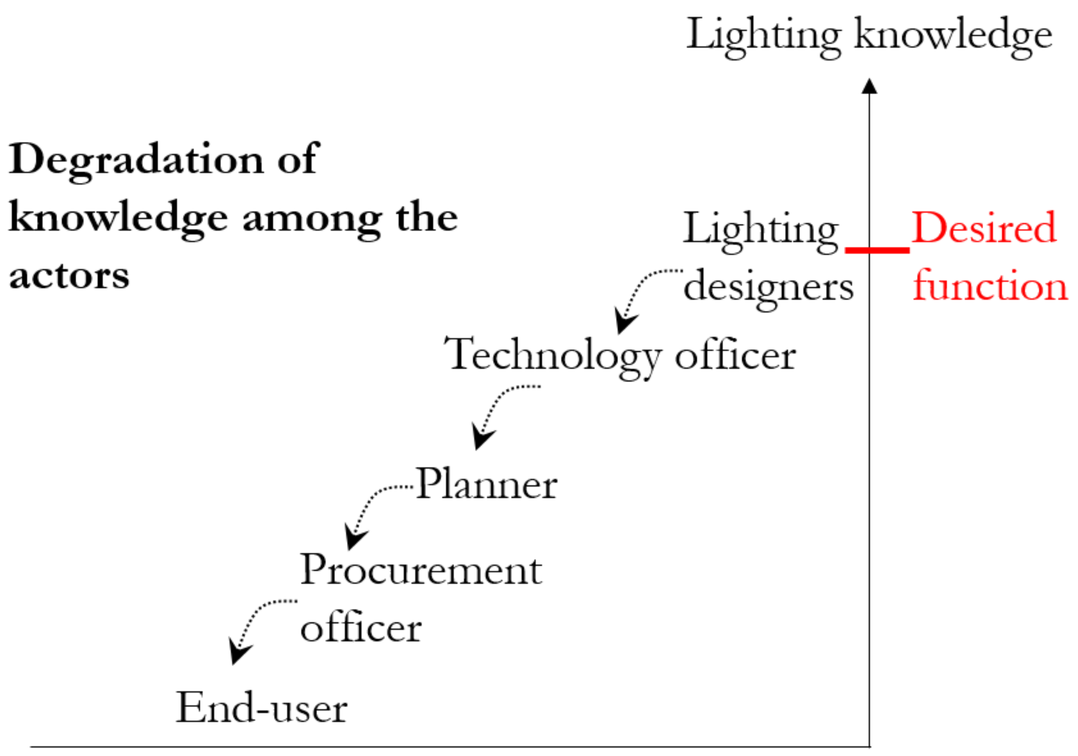


Figure 3-4 The author's conceptual model of knowledge gap among different actors

Source: (R. Karlssson, Personal communication; H. Nygren, Personal communication)

3.1.4 Conservative perspective in prioritizing SSL health and well-being benefits due to limited attention

The benefits SSL could deliver are huge, including energy savings, cost (maintenance) savings, climate mitigation benefits as well as health and well-being benefits. Among these benefits, energy and cost savings are the most concerned on the political agenda (LightingEurope & ZVEI, 2013). Energy saving and cost savings are important. But if the focus is limited on it, SSL development could be undermined (R. Karlsson, Personal communication).Currently, both the consumers and the lighting sector have a limited focus on energy and cost saving.

Figure 3-5 presents the risk of having a limited focus on energy and cost savings (from customer's perspective). Conventional lighting sources distribute light in a unidirectional and static manner, which do not offer the opportunity of controlling light (Figure 4-5). But SSL is different, it is directional, digitally compatible and has a wide range of colours. By integrating SSL with different technologies (sensors, lighting controls, ICTs), innovative lighting solutions could be produced to deliver dynamic lighting (variations of light directions, colours and illuminance), just like the light in nature, and even better (SSL-erate, 2014; R. Karlsson, Personal communication). Therefore, to date, it is possible to control lighting to improve human health and well-being. But little attention has been paid in this field (LightingEurope & ZVEI, 2013).

When the consumer (i.e., public users) are more concerned about cost and energy savings, it provides a business opportunity for suppliers to mislead/cheat (Figure 4-5). Suppliers could make use of the large technical freedom of action to reduce their cost and still present their products with a value enhancing label (i.e., energy efficiency). For instance, suppliers could produce LED products with high energy efficiency, but has problems like color distortion, glare or flicker. These products could reduce their costs and still could get the market attention, as energy and cost savings are their focus (SSL-erate, 2014; R. Karlsson, Personal communication). Then, the market could be flooded by this type of products.

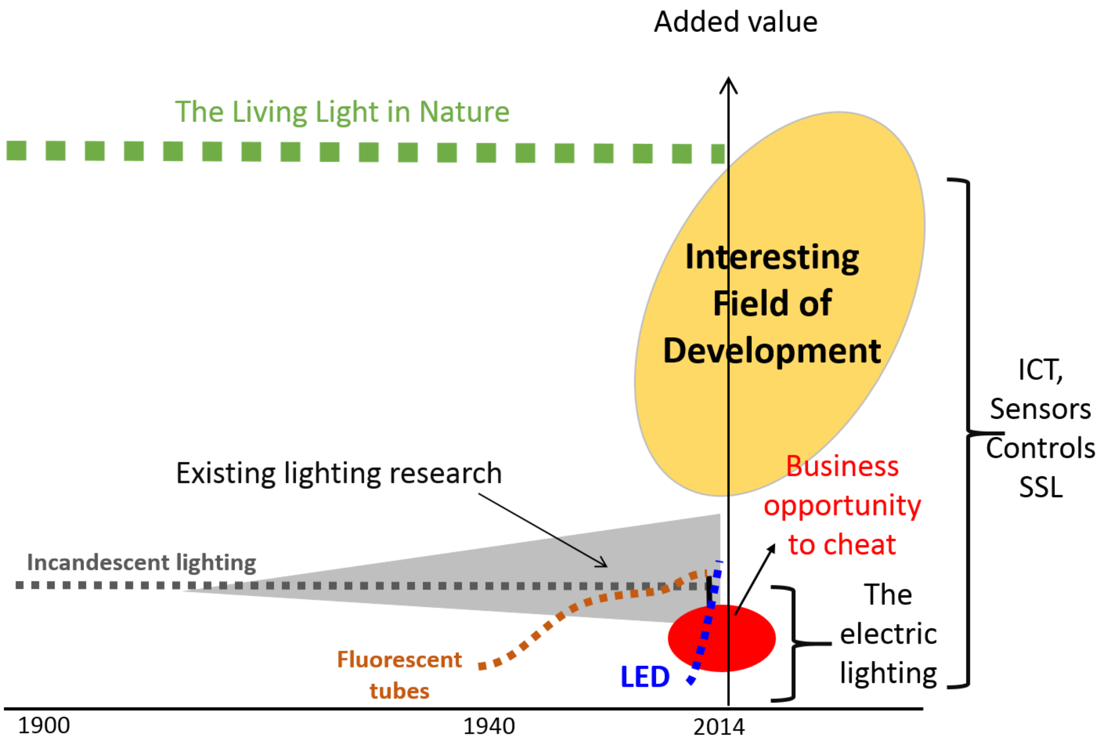


Figure 3-5 Conceptual model of risks of having a limited focus on energy and cost savings

Source: (SSL-erate, 2014)

The reason that SSL's health and well-being benefits are not prioritized is because there is limited attention on the political agenda. The economic crisis has lead to a number of budget restrictions and austerity measures, which affect the public sector's investment interests in SSL. And if there are other urgent issues, they would rather invest in these issues, such as improve IT infrastructure. And so far, regulations about lighting sector have been focused on energy-effiency so far. Therefore, limited attention is paid on lighting's effects on human health and well-being {Citation}.

Figure 3-6 presents risks of having a limited focus on energy and cost savings (from supplier's perspective). For a normal customer value enhancing product development process, positive functionailities will be increased and negative effects will be reduced gradually over time (Figure 3-6 (a)). But with a limited focus on energy and cost savings, manufactuers may lose connections to their customers. Then, during the process of product development, positive functionalities of SSL could be lost or not achieved (i.e., benefits for human health and well-being), and negative effects (i.e., colour distortion, glare and flicker) could be (re)-introduced, as the manufactueres lose its connection to customers (Figure 3-6 (b)) (SSL-erate, 2014).

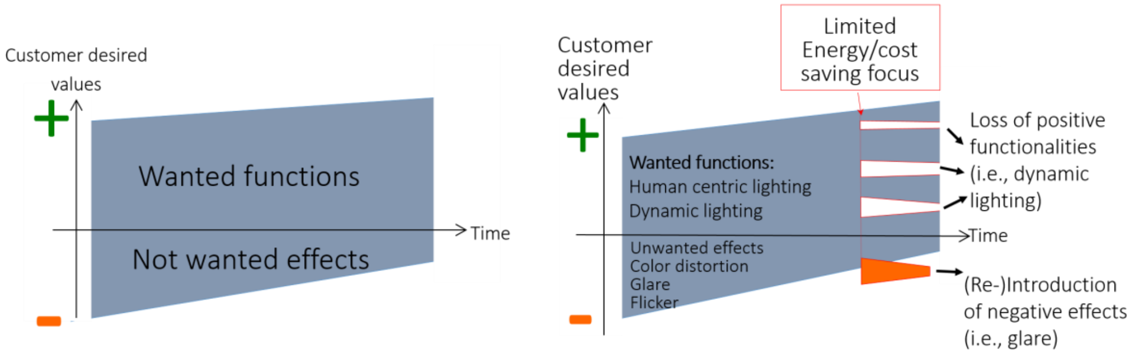


Figure 3-6 Conceptual model of risks of limited focus on energy and cost savings in product development. Left (a) Normal customer value enhancing product development; Right (b) A limited focus on energy and cost savings

Source: (SSL-erate, 2014; R. Karlsson, Peronsal communication)

In Sweden, nowadays advertising energy efficiency alone is not so attractive. Because on one hand, electricity is relatively cheap. On the other hand, concerns about lighting's added values on human health and well-bings have been gradually raised P. Kisch, Personal communication; H. Nygren, Personal communication). Unfortunately, there is a culture of focusing on energy savings in European lighting sector (R. Karlsson, Personal communication). The fact is due to historically, the lighting market has been strongly influenced by energy-efficiency policies and up-front costs.

3.1.5 Difficulities in achieving inter-operation ability in innovative lighting solutions (SSL is part of the solution)

Some of SSL's benefits are achieved by deploying innovative lighting solutions (integrating SSL with other technologies, like sensors, lighting controls, ICTs, etc.). This means SSL's market penetration also relies on the development status of the whole system. In the future, deploying lighting ssolutions rather than lamps alone will be the trend (P. Kisch, Personal communication; R. Karlsson, Personal communication). Here, some challenges to adopt innovative lighting solutions are presented. But as this is not the focus of this thesis, the author did not explore in-depth.

To deploy innovative ligting solutions, three levels of inter-operationability need to be achieved (Figure 3-7) (SSL-erate, 2014; R. Karlsson, Personal communication).

Figure 3-7 Inter-operationability

Source: (SSL-erate, 2014; R. Karlssion, Personal communication)

Firstly, the interoperability must be achieved on product level, that is different technical components should be compatible. Previously, lighting controls could not be added to LED because it was not dimmable. This fact has hindered the deployment of controls for these applications. Currently, LED is able to dim. But there is a problem of upgrading early products (Sandahl et al., 2013). There is also a problem about data network protocols. Nowadays there are too many protocols in the market, and most of them cannot communicate with each other, which has impeded the compatibility of different products. An open protocol could be condusive for LED market penetration (T. Wingren, Personal communication).

Secondly, after different components being connected together, the whole system should be functional and reliable. A LED can typically last for years, but after adding other components, its life time could be impaired. For example, LED is temperature sensitive. Under high operating temperature, LED increases output, but its life time and efficiency would be undermined. The added components could increase its operating temperature and then increase the rates of failure (i.e., short life time) (Cole et al., 2015; De Almeida et al., 2014). Also, LED is voltage sensitive. LED based light solutions must be flexible enough to accommodate add-on light controls. If lighting systems are designed without such flexibility, the add-on devices like e.g. dimmers, timers, photo-sensors, passive infrared sensor (PIRs), etc., may cause current spikes, change power demand, which ultimately can damage LED emitters or alter their performance and shorten lifetime (Cole et al., 2015; P. Andrius, Personal communication).

Thirdly, different organisations and actors (lighting industry, lighting designers, and the authorities) need to cooperate. Because the subject of lighting solutions is a new and multi-dimensional field, including important issuses other than technical, like health, comfort, productivity, well-being, etc. Collaboration could enhance mutual understanding of each actor, and bridge the knowledge gap among them, as each actor has its own interests/priority and possess limited knowledge of the whole system (R. Karlsson, Personal communication). But collaboration is challenging. On one hand, manufacturers (including electronics, smart home, and software engineering) are fragmented along the value chain. On the other hand hand, this is a solution-oriented approach, so the lighting industry should work closely with customers. Nevertheless, the lighting sector is used to a straight-forward, product-based business model (LightingEurope & ZVEI, 2013).

3.1.6 Is High initial cost still a barrier?

High upfront cost was reckoned as a main barrier for SSL adoption by previous studies, because historically the lighting sector has been greatly affected by initial purchasing price. (European Commission, 2011a; De Almeida et al., 2014; Philips N.V., 2012). Haitz and Tsao (2011) argued that to compete with fluorescent lamps (high-power lamps, 1,000 lm), the retail lamp cost of warm white LED needs to be reduced by a factor of 10.

For outdoor lighting, high upfront cost remains a main barrier. In general, outdoor lighting procurement project is a large and one-time investment. And the public sector are reluctant to deploy SSL in outdoor lighting widely, because the high upfront costs clashed with their tight annual budget, even though it could reduce their maintenance costs in the long term (European Commission, 2011a; I. Johansson, Personal communication).

For indoor lighting, it depends upon circumstances. If the purpose is to replace old lighting bulbs, upfront cost is a key factor for the public sector to select products, as decision-makers face budget restrictions and austerity measures (R. Holm, Personal communication; P. Carlberg, Personal communication). For new installation projects, such as build a new school, investment in indoor lighting applications is much more flexible than outdoor lighting. Because the expense for lighting is just a small portion of the total large investment. (H. Nygren, Personal communication). And if the indirect benefits of SSL are included (calculate the the total ownership cost of SSL), such as increase producticity, improve concentration, prevent chronic diseases, etc., high purchasing price of SSL could be justified (P. Kisch, Personal communication).

3.2 Potential strategies for further development of SSL

To accelerate the transition towards SSL, these barriers need to be overcome. As Sweden is a member state of EU, this section presents potential strategeies for further development of SSL in the EU level. Following actions could be taken to accelerate the transition towards SSL in EU.

- **Product performance testing standards improvement**. When standard product performance testing methods are missing, market players could publish exaggerated and misleading information, which could undermined customer's confidence on SSL. To ensure a level playing field for a health and competitive market, new standards that addressing all key features (i.e., luminous efficacy, colour quality, lifetime, etc.) of SSL performance and ancillary components (such as drivers, lighting controls, sensors, etc.) are required (European Commission, 2011a; De Almeida et al., 2014; Cole et al., 2015);

- **Minimum quality requirements scheme setting and market surveillance enhancement**. One of the main barriers for the public sector to adopt SSL is that the market is flooded by poor products. A Minimum quality reuqirements scheme and efficient market surveillance scheme are key factors to guarantee customer's confidence in LED products and to accelerate the market uptake of LED (De Almeida et al., 2014; European Commission, 2011a);

- **Demonstration projects with high replication potential**. There is strong skepticism towards SSL and its benefits (especially its health and well-being benefits) in the public sector as well as private customers, as there is little experience available. A demonstration project with high replication potential could reduce risk aversion among consumers and grow SSL market (R. Karlsson, Personal communication);

- **Improve awareness and acceptance of SSL and its benefits among different actors**. SSL is a new and much more flexible technology than the old ones, so it provides more possibilities, such as productivity increasement, chronic diseases prevention and concentration improvement. But unfamiliarities of the technology and its benefits exists in all levels of actors (i.e., lighting designers, policy makers, suppliers, customers, etc.). A variety of dissemination means such as training programme and dedicated communication are required to raise awareness and acceptance (LightingEurope & ZVEI, 2013);

- **Develop standard and norms for lighting's effect on human health and well-being**. In building certification schemes or occupational safety and health standards, there is little requirement concerned about lighting's effect on human health and we-being. By developing these standard and norms, consumer's awareness and acceptance of SSL's benefits (health and well-being benefits) could be raised (LightingEurope & ZVEI, 2013);

- **Innovative Public procurement to facilitate commercialization of innovative lighting solutions**. SSL's benefits such as productivity increasement, chronic diseases prevention and concentration improvement are new fields, there is few practical products available on the market. Innovative problic procument, like Pre-Commercial Procurement (PCP)[15] and Public Procurement of Innovative Solutions (PPI), could bring innovative commercial end-solutions earlier to the market;

- **Strenthen SSL (and innovative lighting solution) value chain**. In European lighting industry, actors (including lighting designers, wholesale and retail, smart home, lighting service companies, electronics software engineering, etc.) are fragmented along the value chain;

- **Private-public partnerships (PPP) to facilitate collaboration**[16]. Deploying innovative lighting solutions requires requires different actors (i.e., manufacturer, lighting designers, decision-makers) collaborate together. PPPs could bring them together and enhance their mutual understanding;

- **Product-servicing system as a new business model to facilitate solution-oriented approach**. Developing innovative lighting solutions need a customer-centric approach, so the lighting industry are required to work closely with customers. Product-servicing system is a functional-oriented business model, which could accelerate the deployment of innovative lighting solutions (LightingEurope & ZVEI, 2013); and

- **Increase financial support**. Investment in R&D and project development.

[15] Example: EU ENIGMA project: http://www.enigma-project.eu/en/

[16] Example: Danish outdoor lighting lab (DOLL): http://www.lightinglab.dk/UK/

4 Discussion

4.1.1 Legitimacy of research questions

The starting point of this thesis is that the public sector faces challenges to deploy SSL. This conclusion was drawn from the author's literature analysis. It should be noticed that the literature analysis were performed from a global (and European) perspective. But the scope of this thesis is Sweden, or more precisely Skåne region, which is a smaller scale than the literature analysis. This means the conclusion drawn from literature may not be applied to Sweden. So it is questionable whether the public sector in Sweden encounter obstacles to deploy SSL. As there is little information in literature about SSL adoption status in Sweden, the author had resort to interviews.

The views from the interviewees are mixed. The majority agree that they are facing challenges do adopt SSL. But a few interviewees hold a different view. For example, one interviewee mentioned their municipality have no problems in adopting SSL, and they have used LED lightings in quite a few places (C. Jonsson, Personal communication). In these cases, the author had to adjust the research objective from identifiying the barriers to identifying the key drivers to their success, as the author assumed their successful factors could be barriers for other municipalities. For instance, the city of Gothenburg started to use LED lighting on street in 2006. According to the interviewee, two factors were essential for their success. One is the decision maker was aware of SSL and its benefits. The other is there was a special funding could cover their expense (Klimp – climate investment programme). Based on these two points, the author speculated that limited awareness of SSL and high initial cost could be barriers. But drivers and barriers are not totally interchangeable. It might be necessary to outline both the challenges and the barriers (I. Johansson, Personal communication). Nevertheless, due to various reasons, the author could not explore more successful cases. Therefore, in this research, the author only presents challenges. For future studies, it might be interesting to do a case study on these successful projects, and identify the key drivers.

4.1.2 Legitimacy of scope

This thesis examines the barriers for adopting **SSL**, but in some circustances, the author expanded or narrowed down the scope. This is because SSL has a wide range of applications.

For example, lighting applications are generally classified into two catergories: **indoor and outdoor lighting**, because they have different features and market. This means they could face different challenges for deployment. This point of view has been mentioned by several interviewees. For example, for outdoor lighting, high upfront cost remains a strong barrier, whilst indoor lighting is much more flexible (I. Johanssion, Personal Communication; P. Kisch, Personal communication). But this thesis did not pick one over another, even though the author did ajust the scope on the basis of interviewee's experience on relevant field. For example, if the interviewee has more knowledge and experience about indoor lighting, the author would focus on barriers for adopting SSL indoor lighting.

In addition, SSL applications could be categorized into **replacement or new installation** products. Some interviewees mentioned barriers for these two types of products are also different. One example is, for replace market, SSL applications has limited flexibility, as it has to acommote to existing fixtures. So the functions/benefits it could deliver could be restrained (i.e. colour change) (R. Karlsson, Personal communication). But same as above, the author did make a choice between the two.

Lastly, SSL's potential benefits like productivity increasement, chronic diseases prevention and well-being improvement are realized through innovative/intelligent lighting solutions, which is the combination of SSL and other technologies (i.e., sensors, lighting controls and ICTs). This means SSL's market penetration also relies on the development status of other technologies. For example, it is possible that limitations of these technologies hinder the market uptake of SSL. However, these technologies are not the focus of this thesis. So mostly, the author assumes that the ancillary technologies will be making parallel and perhaps even faster progress. But in some circumstances, the author also analysed the development status of these technologies, as they may influence the market adoption of SSL. In these cases, the author were exploring barriers for adopting **innovative lighting solutions** (which is a broad scope), not just **SSL**.

Generally speaking, the author adapted the scope of this thesis on the basis of the knowledge and experience of the interviewees. In the future, it might be interesting to look into one of these fields.

4.1.3 Generalisability of results

Initially, this thesis aimed to find out SSL adoption barriers in the public sector in Sweden, with a strong focus on Skåne region. This means the conclusion of the thesis may not be applied to other nations or regions, as there is context difference. Nevertheless, based on the data collected, the author reckons the results of thesis could be applied to a broad region (Europe), especially for Section 3.2, the potential strategies for further SSL development are proposed at EU level. The reasons are threefold. Firstly, desktop research are performed at EU level, as there is little research about SSL adoption status in Sweden. Secondly, the author conducted a limited number of interviews, and the majority of the interviewees are from one group of actors (municipalities). This is due to various reasons, some interviews with important informants could not be arranged. So the information collected from the interviewees might be insufficient for analysing Sweden. Thirdly, during the interviews, the author noticed some interviewees discussed the topic in a broad scale (Europe), because they have involved in several EU projects. So the data collected has a slightly large scope than initial plans. This means it is possible apply this study's results to EU scale.

5 Conclusions

This chapter summarises the main findings and lessons learned in the course of this research, primarily by answering the stated research questions in section 1.2, and provides suggestions for further research.

5.1 Revisiting the research question

This thesis examines SSL adoption barriers in the public sector in Sweden, or more precisely in Skåne region. Compared to conventional lighting technologies, SSL is superior in various aspects, such as energy efficiency, life span, durability, digital compatibility, flexibility in shape and size, etc. Deploying SSL could bring huge benefits to the society, like energy saving, CO_2 emissions reduction, productivity increasement, chronic diseases prevention, well-being improvement and so on. Therefore, SSL is believed to displace all traditional lighting sources in the future. McKinsey & Company (2012) has predicted that LED market share will increase from 12% in 2011 to 41% in 2015, and reach 63% in 2020. But in reality, the market adoption of SSL is slow, or not as fast as expected. For example, in EU, the market share of LED was 7% in 2012, which is much lower than the prediction (the predicted share was 15%) (Wierda, 2014a).

To achieve the benefits mentioned above, the society needs to accelerate the market uptake of SSL. The public sector is a large actor on the lighting market and could play an important role in accelerating SSL market penetration through public procurement. Nevertheless, it faces many challenges to adopt SSL. In order to accelerate SSL market uptake, it is important to find out all the barriers and reasons behind them. Therefore, the main purpose of this research is to provide a better understanding of SSL adoption barriers in the public sector.

The research questions of the thesis are as follows:

- *What are the barriers for SSL adoption in the public sector?*
- *Why the barriers exist?*
- *Reflecting on the identified barriers, what are the potential strategies for further development of SSL?*

And Sweden is selected as a focus country is because, on one hand, it is a leading country in adopting SSL, and many of its municipalities, such as Gothenburg, Malmö and Lund, have SSL practices or strong interests. So it is easy for the author to find and access actors in this field. On the other hand, by picking up one country, the effect of contextual differences (i.e., different public procurement instruments and scopes for public sector) on this study could be reduced.

5.2 Main findings and conclusions

5.2.1 Challenges

Overall, the public sector in Sweden faces several challenges to adopt SSL. The challenges and its reasons are presented as below:

- **Low confidence in SSL due to early technological shortcomings**. Early LED products have many problems (i.e., glare, flicker, and colour distortion) as the technology was immature. These products have significantly undermined consumer's confidence in SSL. Because of low confidence, there is low trust and risk aversion among decision-makers, even though SSL has been improved enormously over these years;

- **Risk averison due to uncertainties of product performance and benefits of SSL**. SSL is a new technology, the public sector faces many uncertainities to adopt it. One example is the uncertainty of product performance, as the market is flooded by poor products. Low quality products are flooding in the market is due to the fact that product performance testing standard is missing. Another example is the uncertainty of the potential benefits of SSL, especially the benefits for human health and well-being. This is due to on one hand, there is strong skepticism towards this topic among decision-makers, even though there is strong scientific evidence. On the other hand, as there is few experience (successful projects) available, everyone is afraid of to be the first mover, so waiting for others to start;

- **Conservative perspective on lighting due to limited awareness of SSL and its benefits**. In general, decision-makers in the public sector have have a limited awareness of SSL and its benefits (not lighting experts), so they typically position lighting as a technical subject, even though the subject of lighting is multi-dimensional and includes important issuses other than technical, like health, comfort, productivity, well-being, etc. The fact that decision-makers have a limited awareness of SSL and its benefits is because there is knowledge gap among different departments. For example, the technology department typically has a higher knowledge level of lighting but they are not decision-makers;

- **Conservative perspective in prioritizing SSL health and well-being benefits due to limited attention.** SSL could deliver benefits other than energy saving and cost saving benefits, such as productivity increasement, chronic diseases prevention and visual comfort (benefits for human health and well-being), which is often low priority for both consumers and the lighting sector. When consumers (i.e., the public sector) have a limited focus on energy and cost savings, it creats a business opportunity for producers to mislead. For example, manufacturers could produce LED products with high energy-efficiency but with poor performance (i.e., colour distortion, flicker and glare) to reduce their cost, and still present their products with a value enhancing label (i.e., energy efficiency) to make profits (as customers prioritise energy and cost savings, so this type of product could be still attractive to them). Then, the market could be flooded by this type of products. The reason that SSL's health and well-being benefits are not prioritized is because there is limited attention on the political agenda. When producers have a limited focus on energy and cost savings, they would lose their connections to customer. Then during the process of product development, customer desired positive functionalities of SSL could be lost or not achieved (i.e., benefits for human health and well-being), and negative effects (i.e., colour distortion, glare and flicker) could be (re)-introduced. Currently, there is a culture of focusing on energy and cost savings in European lighting sector. This is due to historically, the lighting market has been strongly influenced by energy-efficiency policies and up-front cost;

- **Difficulities in achieving inter-operation ability in innovative lighting solutions (SSL is part of the solution).** Some of SSL's benefits are achieved by deploying innovative lighting solutions (i.e., human centric lighting, integrating SSL with other technologies, like sensors, lighting controls, ICTs, etc.). This means SSL's market penetration also relies on the development status of the whole system. So here, challenges to adopt innovative lighting solutions are presented. Three levels of inter-operation ability are required to deploy innovative lighting solutions. First, on the product level, different technical components should be compatible. One of the challenges on this level is currently there is no open standard network protocol, which has hindered the compatibility of differen products. Secondly, after assembling different components together, the whole system should be functional and reliable. This is challenging because the add-on devices like e.g. dimmers, timers, photo-sensorr, etc., may cause current spikes, change power demand and temperature, which ultimately can damage LED emitters or alter their performance (i.e., shorten lifetime and reduce efficiency). Thirdly, on organizational level, different actors are required to cooperate, as the subject of lighting solutions is a new and multi-dimensional field. But collaboration is challenging. On one hand, manufacturers are fragmented along the value chain. On the other hand, deploying innovative lighting solutions requires a solution-oriented approach, which means manufacturers need to work closely with customers, but the lighting sector is used to a straight-forward, product-based business model; and

- **High initial cost based upon circurmstances**. For outdoor lighting, high upfront cost remains a main barrier. This is due to procuring outdoor lighting is a large and one-time investment. So the public sector are reluctant to deploy SSL in outdoor lighting widely, because the high upfront cost clashed with their tight annual budget, even though it could reduce their maintenance costs in the long term. For indoor lighting, it depends on circurmstances. If the purpose is to replace old lighting bulbs, upfront cost is a key factor for the public sector to select product, as they face budget restrictions and austerity measures. For new installation project, such as build a new school, the expense for lighting is just a small portion of the total large investment. And if the indirect benefits of SSL (i.e., productivity increasement, chronic disease prevention, visual comfort) are included (calculate the the total ownership cost of SSL), high purchasing price of SSL could be justified.

5.2.2 Potential strategies for further development of SSL

To accelerate the transition towards SSL, these barriers need to be overcome. As Sweden is a member state of EU, potential strategeies for further development of SSL are proposed at EU level. Following actions could be taken to accelerate the transition towards SSL in EU:

- **Product performance testing standards improvement**. New standards that addressing all key features of SSL performance and ancillary components are essential to ensure a level playing field for a health and competitive market;

- **Minimum quality requirements scheme setting and market surveillance enhancement**. A Minimum quality reuqirements scheme and efficient market surveillance scheme are key factors to guarantee customer's confidence in LED products and to accelerate the market uptake of LED;

- **Demonstration projects with high replication potential**. A demonstration project with high replication potential could reduce risk aversion among decision-makers and grow SSL market;

- **Improve awareness and acceptance of SSL and its benefits among different actors**. A variety of dissemination means such as training programme and dedicated communication are required to raise awareness and acceptance;

- **Develop standards and norms for lighting's effect on human health and well-being**. By developing these standards and norms, consumer's awareness and acceptance of SSL's benefits (health and well-being benefits) could be raised;

- **Innovative public procurement to facilitate commercialization of innovative lighting solutions**. Innovative problic procument, like Pre-Commercial Procurement (PCP) and Public Procurement of Innovative Solutions (PPI), could bringing innovative end-solutions earlier to the market;

- **Strenthen SSL (and innovative lighting solution) value chain**, as actors are fragmented along the value chain;

- **Private-public partnerships (PPP) to facilitate collaboration**. PPPs could bring different actors together and enhance mutual understanding;

- **Product-servicing system as a new business model to facilitate solution-oriented approach**. Developing innovative lighting solutions needs a customer-centric approach. Product-servicing system is a functional-oriented business model so it could serve the purpose; and

- **Increase financial support**. Investment in R&D and project development.

5.3 Suggestions for future researches

For future researches, the following four areas are interesting to explore. Firstly, indoor lighting vs. outdoor lighting. This two group of lighting applications have different markets, so it is possible that they would face different market uptake challenges. This fact has been reflected by several interviewees. For example, for outdoor lighting, high upfront cost remains a strong barrier, whilst indoor lighting is much more flexible. But this thesis do not choose one over another, future studies could focus one field and investigate the barriers

Secondly, replacement vs. new installation. Some interviewees mentioned barriers replacement and new installation market are also different. For example, for replace market, SSL applications has limited flexibility, as it has to acommote to existing fixtures. So the functions/benefits it could deliver might be restrained (i.e. colour change).Therefore, future researches could pick one area and explore its market adoption barriers.

Thirdly, SSL vs. innovative lighting solutions. Some of SSL's potential benefits like productivity increasement, chronic diseases prevention and well-being improvement are realized through innovative/intelligent lighting solutions, which is the combination of SSL and other technologies (i.e., sensors, lighting controls and ICTs). This means SSL's market penetration also relies on the development status of the whole system. So in thesis, the author also explore challenges to adopt innovative lighting solutions. But as this is not the focus of this thesis, the author did not investigate in-depth. In the future, deploying lighting ssolutions rather than lamps alone will be the trend, so probably more researches are needed.

Lastly, some municipalities (i.e., Gothenburg, Landskrona) have several successful initiatves in deploying SSL. It might be interesting to perform a case study to find out the key drivers of their success.

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Appendix I

A list of interviewees

Person and position	Organization	Date
Christer Jonsson – Head of building technology	Landskrona Municipality	May 12, 2015 – Email communication
Ingemar Johansson – Head of street lighting	Gothenburg Municipality	May 12, 2015 – Email communication
Peter Kisch – Project Lead / Consultant	Future by Lund / Lund Municipality	May 13, 2015 – Personal meeting
Reine Karlsson – Project Lead	Lund University open innovation center	May 6, 2015 – Personal meeting
Henrik Nygren – local strategist	Lund Municipality	May 12, 2015 – Personal meeting
Tord Wingren – Vice president	Lund R&D center	February 5, 2015 – discussion
Lennart Svensson – Management & Co-founder	PhotonicsSweden	February 5, 2015 – discussion
Rune Holm - Founder	Holm Energy	April 30, 2015 – Skype meeting