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Lighting transition: Overcoming barriers to eco-innovation in the LED sector

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Outline

1. Introduction

This paper analyses the barriers to the ecological transition of lighting, notably the ones faced by European firms, notably SMEs, when trying to produce ecodesigned LED systems that can substantially reduce the ecological impacts of lighting. The multilevel perspective (MLP) is used to analyse these barriers and their interactions, as well as to suggest strategies and policies to overcome them. The ecological impacts of lighting technologies concern pollutions, the exhaustion of resources, and global environmental changes, and occur at each phase of the lifecycle. For example, in the production phase chemicals are used and upstream mining activities lead to the exhaustion of metals such as Gallium or Indium used in light emitting diodes (LED). During the use phase most impacts derive from the energy consumed and thus depend on the local energy mix, which in most countries is carbon-intensive. The end-of-life (EOL) phase of lighting solutions generates hazardous waste contained in lighting products (e.g. compact fluorescent lights (CFL) and other energy saving bulbs contain hazardous substances), but can also offset part of its impacts if valuable materials are recovered from "urban mines". New lighting solutions such as ecodesigned LED can contribute to overcome these ecological challenges by reducing the use of energy and other raw materials as well as lighting wastes. They can also help overcome societal challenges by creating jobs in a cleaner economic sector and by reducing the lighting gap, as evidenced by the diffusion of LED systems fuelled by renewables in developing countries (Adkins et al. (2010), Harish et al. (2013)). As Hall et al. (2014: 5) underline, "approximately two billion people currently do not have access to electricity and have to rely on candles and kerosene-based lighting, a dangerous, unhealthy, expensive and poor quality alternative".

Besides providing strategy and policy recommendations to European LED firms and policy makers, from an academic perspective this study is the first of its kind to study barriers to eco-innovation in the LED sector. Eco-innovation in the lighting sector is an emerging topic. In a review of the literature on green technology and low carbon technology innovation from 1994 to 2010, Shi and Lai (2013) do not mention lighting. This paper also brings out specific features of the LED sector by contrasting it with other sectors for which barriers to eco-innovation have been analysed. Finally, it also constitutes a first attempt to construct solutions to overcome barriers to eco-innovation by using the multilevel perspective.

In order to identify the obstacles to be overcome to facilitate the ecological transition of the current lighting regime, this paper proceeds in four steps. After providing an introduction to the lighting sector in general and to the LED sector in particular, section 3 presents the methods and data used to identify barriers to LED eco-innovation and find solutions to overcome them. Section 4 presents the results of the case studies and survey, while section 5 discusses the solutions that can be found to overcome these barriers at each of the three levels of the multilevel perspective.

2. Background: The evolution of the lighting regime

The history of human-made lighting is thousands of years old. It emerged from flame-based lighting, moved to electricity-based lighting, and is currently switching to ecodesigned solid state lighting. This is section explains the challenges that had to be overcome to reach the current lighting regime, and underlines the remaining ones on the way to a sustainable lighting regime.

2.1 From flame-based lighting…

For thousands of years, fuel combustion has dominated the history of human-made lighting. According to DiLaura (2008: 23):

> "The first records of fire-making appear in the Neolithic period, about 10,000 years ago. In 1991, scientists discovered a Neolithic man, dubbed "Otzi," who was preserved in an Alpine glacier. Otzi carried on his belt a fire-making kit: flints, pyrite for striking sparks, a dry powdery fungus for tinder, and embers of cedar that had been wrapped in leaves."

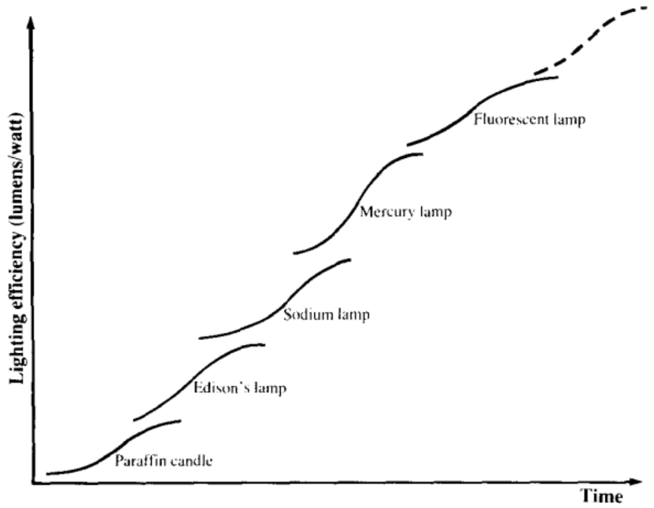
More than 4,500 years ago, in modern day Iraq oil lamps were used to burn oils made from olives and seeds. In Northern Europe and colonial America, animal oils from fish and whales have commonly been used (animal grease was used in controlled fires 250,000 years ago). DiLaura (2008: 23) also explains that "Lascaux cave paintings produced in France 15,000 years ago were likely created using illumination from burning animal grease in lamps". The first candles appeared 2000 years ago in Rome, but were too expensive for being used for ordinary lighting. According to Bowers (1980), it was only in 19th c. that chemical advances using stearine and especially paraffin in the 1860s replaced animal and vegetable oils and enabled improvements of more elaborated lamps like the one developed by Ami Argand in 1784. The next important technological change appeared at the same period with the development of gas lighting (first using coal), which enabled the large illumination of cities.[1] At the end of the century, gas mantle burners using rare earth elements further improved luminous efficiency.

Lighting technologies also had a huge impact on social behaviour. For example, lighting in cities was initially provided to deter crime, and much later for other safety purpose such as the prevention of road accidents. As Holmes (1997: 25) recalls: But people did not like this civic duty, and centuries later besides moral and medical grounds, gas lights were even protested on theological grounds: "Night is appointed to be darkness only broken at certain times by the Moon" (p. 26). This suggests that new lighting technologies have required not only technological changes but also cultural ones, whose changes do not happen in a wink. In turn, lighting innovations had enormous impacts on modern societies. For example, Freeberg (2013) claims that public lighting enabled the expansion of nightlife in urban cores, encouraging young people to leave their small towns and farms to settle down in cities. Offices and factories could operate longer hours and doctors benefit from better operating conditions. As for households, the diffusion of lighting changed their living patterns, since family members no longer had to chat around a dim lamp but could go to read in their own rooms.

The following graph underlines that the history of lighting "is not one of smooth, linear, upward progression, but rather one of relatively short periods of linear progress punctuated by instances of discontinuous leaps" (Wissema (1982)). Following Dosi (1982), we know that technological developments occur through paradigm shifts following patterns of Schumpeterian creative destructions. Across the 19th c., flame-based lighting was overtaken by a much more efficient technology generating less smoke and smell and much more lumens per unit of energy consumed: electricity-based lighting.

[1] The first public demonstration took place in London on 4th June 1807, and the first gasworks was established in 1816 in Freiburg by the German mineralogist W.A. Lampadius.

Figure 1. Successive waves of lighting technologies



Source: Wissema (1982), quoted in Olleros (1986: 7).

2.2 … to electricity-based lighting

Gas mantle burners became the most efficient flame-based lighting technology, and it remains in use in some cities across the world, such an in Berlin where they are part of the city's history (Schulte-Römer (2014)). But it was challenged in the 19th c. by the introduction of a new source of lighting: electric arc and incandescent lighting.[2]

Early work on incandescent lamps dates from about 1840, and following works by Joseph Swan, Thomas Edison showed in 1879-1880 the importance of deep vacuum, and in October 1879 he built and tested what he called a "filament" lamp. But the inventor did not stop there and by 1881, "Edison's company was manufacturing complete systems consisting of a dynamo, wiring, switches, sockets and lamps" (Bowers (1980: 27)). Besides, notices Freeberg (2013), thanks to his reputation (phonograph, moving pictures, telegraph, ...) he was connected to key stakeholders of the technological regime (in the patent office, in the media, ...), and knew how to stir desire for his product through press announcements.

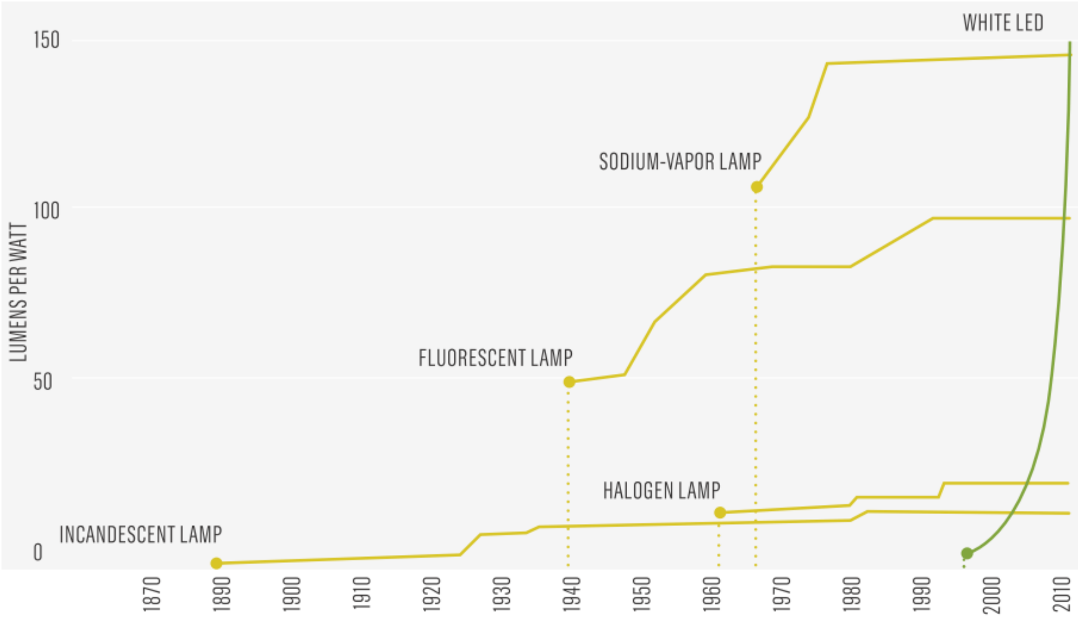
In 19th c., lighting innovations evolved to the point of triggering a "quantitative lighting" fashion, by which streets and other public spaces or buildings were flooded with light (Ganslandt and Hofmann (1992)). But glare problems and harsh shadows led to new lighting concerns, such as aesthetics ones, which led to seek the control of excessive amounts of light (Clear (2013), Hickcox et al. (2013). Lighting did not only require light sources anymore, but also whole infrastructures having their own dynamics and trajectories. Besides, more electronics were incorporated into lighting technologies to control current or latter with LEDs to generate light itself (the dotted line in Figure 1). After the problems caused by mercury or sodium used in discharge lamps (GEC in 1932), SSL created a new type of environmental problems in the form of electronic waste, besides the consumption of exhaustible resources such as precious metals.

We can see that technological improvements do not necessarily equally generate environmental improvements. If an ecological lighting regime is to be based on LEDs, substantial improvements are to be expected in terms of ecodesign for example in order to

[2] The first successful demonstration of electric street lighting took place in Paris in 1878, avenue de l'Opéra.

substantially reduce the consumption of energy in the use phase.[3] Today, lighting represents almost 20% of global electricity consumption (similar to the amount of electricity generated by nuclear power).[4] For Holmes (1997: 28), "the overall process of obtaining light from a basic energy source, via electricity, is very inefficient". According to Kavehrad (2010), in the field of photonics white LEDs hold the potential "to be as transformational as the transistor was in electronics". The following figure shows the superiority of LED lamps compared to other lighting technologies.

Figure 2. The efficiency of LED lamps compared to other lighting technologies



Source: The Climate Group (2012).

A positive side effect of this efficiency is for example that applying LED lighting systems in the EU could lead to energy savings of about 209 TWh, preventing the emission of some 77 Mt of CO_2 (De Almeida et al. (2014: 46)). Compared to other lamps, LEDs are made from non-toxic materials, could be recycled (Qiu (2007)), and attract insects less (Bessho and Shimizu (2012)). According to the The Climate Group (2012), the deployment of LEDs in cities could enable them to save 60% energy. As for Bloom (2012), she argues that in the city of Glen Cove (NY) a state of the art LED lighting upgrade led to 77% energy saving and an investment recouped in a year time. Finally, benefit could extend beyond industrialised economies by helping bridge the "lighting gap" between North and South (Harish et al. (2013), Huang et al. (2010), Chun and Jiang (2013)).

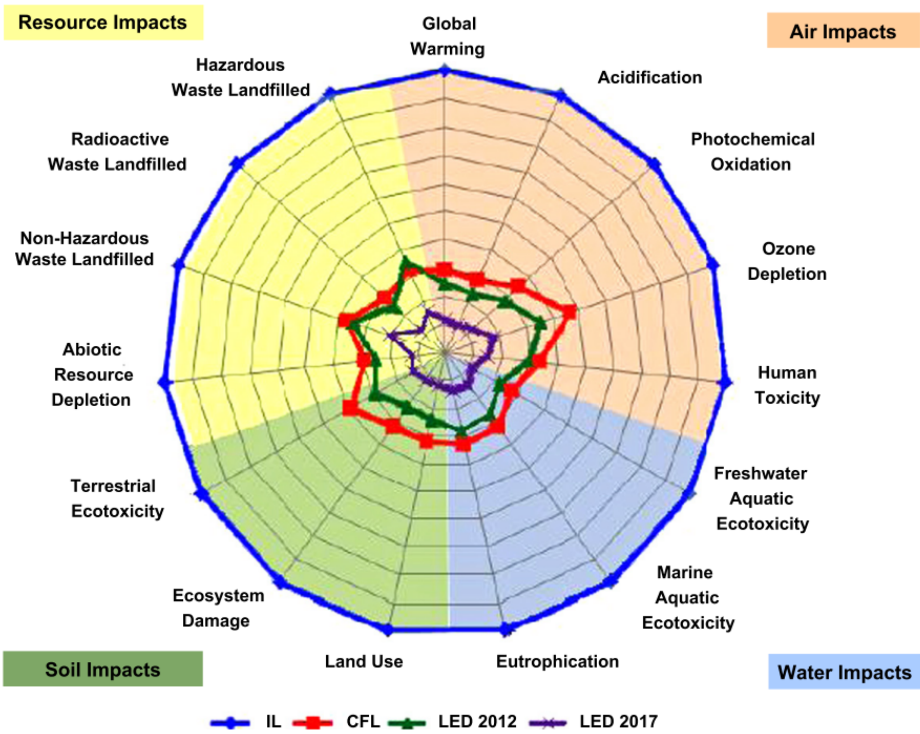
But lighting also generates direct environmental impacts (energy-related ones or toxics) and indirect environmental impacts (e.g. rebound effects, see Chitnis et al. (2013), Hicks and Theis (2014), Saunders and Tsao (2012)). Tsao and al. (2010: 15), who analysed lighting consumption patterns over the last three hundred years in six continents, found that "the result of increases in luminous efficacy has been an increase in demand for energy used for lighting that nearly exactly offsets the efficiency gains – essentially a 100% rebound in energy use'

[3] The use phase of incandescent, compact fluorescent and LED lamps represents the 90% of total life-cycle energy use on average (Aman et al. (2013: 489)).

[4] Source: http://www.iea.org/topics/energyefficiency/subtopics/lighting/. Accessed on 5 August 2016.

because ‘there is a massive potential for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light”. De Almeida et al. (2014) underline that lighting consumes one fifth of the electricity used in the world, and accounts for 650 Mt of primary energy consumption as well as 1 900 Mt of CO_2 emissions (i.e. 70% of the emissions of the world’s passenger vehicles, three times more aviation emissions). Besides, a great amount of energy is being wasted, not only by inefficient lamps but also by lighting and electricity infrastructures fuelled by large, centralised and mostly thermal power stations connected to a high-voltage transmission grid. According to Chappin and Afman (2013: 17), “over 98% of the electricity used in converted into heat and not light”. Before distributed gas lighting solutions, the light source was close to the energy source (candles, oil lamps, ...). As explained in Section 2, there is now a whole network of electric utilities companies, manufacturers and suppliers, investors, and customers that is involved in the evolution of lighting technologies. The following figure suggests that future generations of LED lamps might be able to deliver these environmental promises. This is provided that producers manage to overcome their barriers to eco-innovation.

Figure 3. Life-cycle assessment impacts of IL-CFL and LED lamps



Across its history, lighting technologies have overcome many technological challenges, which have required behavioural changes as in the case of the public requirement to fix lanterns on house doors. But these changes were not driven by environmental objectives, which is a new feature of the LED lighting transition.[5] We can also notice that radical changes occurred with the use of different types of innovations as in the case of Edison (technological innovation in various fields but also innovation in infrastructures and in marketing).

[5] Environmental improvements were sometimes achieved as side effects of efficiency-driven technical changes, as in the case of smoke e.g. eliminated with the switch to gas lighting.

3. Methods and data

The analysis of barriers to eco-innovation in the cycLED project consisted in two phases. Phase 1 focused on the four cycLED SMEs in charge of developing a demonstrator, and used face-to-face interviews. Phase 2 broadened the analysis to European LED firms, by using an online survey. The results of phase 1 enabled us to provide recommendations to cycLED SMEs so that they can overcome barriers to eco-innovation, especially when developing their demonstrator, which consisted in an ecodesigned LED product or service. These results were also used to prepare the online survey of phase 2, whose results were analysed by using the multilevel perspective (MLP), introduced in section 4.3.

3.1 The methodology used in phase 1

The methodology used in this first phase was based on face-to-face interviews with senior managers and engineers of the four cycLED SMEs in charge of developing a demonstrator. To do so, an interview guideline was developed,[6] based on the review of the literature presented in section 3, and on an ad hoc workshop of the cycLED project during which all partners contributed to its content and eventually validated the guideline. The final version of the latter contained 144 barriers to eco-innovation in the LED sector. These barriers were both internal (technological resources, financial resources, human resources, …) and external (public policies, LED market, financial market, …) to LED firms.

The four cycLED SMEs interviewed were located in Germany for two of them, in Spain, and in Netherlands. They provide LED lighting solutions for warehouses, municipalities, hotels and parking lots. They were asked to discuss each barrier and to evaluate its importance from its own perspective, by using four different levels:

- 2 (Major barrier to eco-innovation for my organisation).
- 1 (Relevant barrier to eco-innovation for my organisation)
- 0 (Irrelevant barrier to eco-innovation for my organisation)
- -1 (Not a barrier but rather a support to eco-innovation)

They were also asked to suggest solutions to overcome the most important of their barriers to eco-innovation, and cycLED partners helped them during an ad hoc workshop to find solutions to do so. Since each SME provided one evaluation per barrier, a total of 576 evaluations were obtained. The results are presented in section 5.1, they focus on major and minor barriers to LED eco-innovation.[7]

3.2 The methodology used in phase 2

The methodology used in this second phase consisted in an online survey directed to European manufacturers of LED products. The survey was based on the results of phase 1, on comments collected from cycLED partners, and on the Community Innovation Survey (CIS). The survey consisted in a maximum number of 35 questions (some questions were conditional), and was divided into four parts:

1. Information about the firm (name, address, capital structure, market, active in LED production or not);

[6] The interview guideline of phase 1 was reproduced in the appendix n°2 of the deliverable 8.1 of the cycLED project, available for download at https://gossart.wp.mines-telecom.fr/cycled/.
[7] The full results of phase 1 are presented in the deliverables 8.1 and 8.2 of the WP8 of the cycLED project, available for download at https://gossart.wp.mines-telecom.fr/cycled/.

2. Eco-innovation activities;
3. Barriers to eco-innovation (finance, knowledge, market, other factors);
4. Other information about the firm (revenues, patents, patent licence).

Surveyed firms were asked to provide an evaluation of their motivations to eco-innovate and of the importance of eco-innovation barriers by using the following scale: High, Medium, Low, Not appropriate (N/A), Void.[8]

Data obtained through surveys represent an important input to understand innovation activities. As pointed out by Kemp and Pearson (2007), it is difficult for data obtained in surveys to be linked to different databases or other survey data. Kemp and Arundel (2009) argue that surveys should contain relevant questions to obtain data on determinants and control variables to measure eco-innovation:

- Inputs: financial and human resources, R&D expenditure supporting the technological capabilities of a firm;
- Environmental policy framework (e.g. regulatory stringency, different environmental policy instruments such as technology-based standards, emission taxes or liability for environmental damages);
- Existence of environmental management systems, practices and tools;
- Demand pull hypothesis: expected market demand, profit situation in the past;
- Appropriation problem: competition situation (e.g. number of competitors, concentration of the market), innovation cooperation;
- Influence of stakeholders and motivations for environmental innovation (e.g. public authorities, pressure groups such as industry or trade associations);
- Availability of risk capital;
- Availability of high-skilled labour force.

They also suggest using the following control variables:

- Firm-level attributes (sector, size, stock market listing, employment, value of shipments);
- Commercial conditions (scope of the firms' markets, competition, sales, profitability);
- Environmental impacts of the facilities' products and production processes by different environmental fields (importance of each impact and change in impacts during the last three years).

As Kemp and Pearson (2007) point out, adding questions related to eco-innovation to the Community Innovation Surveys enables us to gain a greater knowledge about eco-innovation activities in Europe. Therefore, we adapted the CIS survey with questions aiming to better understand eco-innovation activities in the European LED sector. Our survey integrates the suggestions made by Kemp and Pearson (2007) as well as the ones of Kemp and Arundel

[8] The full results of phase 2 are presented in the deliverables 8.1 and 8.2 of the WP8 of the cycLED project, available for download at https://gossart.wp.mines-telecom.fr/cycled/.

(2009: 25) regarding the formulation of questions, e.g. suggesting to ask questions in a simple manner and if possible with binary answers: “In many cases, ordinal or nominal questions can provide higher quality results”. Finally, we also used the control variables suggested by Kemp and Arundel (2009: 33-34): “Firm-level attributes (sector, employment, sales or other output measure) [and] Commercial conditions (scope of the firms’ markets (where and what it sells), level of competition, and if possible, profitability)”.

The online questionnaire was translated into German and French to increase the number and quality of responses. In order to increase the number of responses to our email and telephone queries, we have also given the questionnaire during professional fairs where many firms are physically present (LED Forum, Smart Lighting conference, …). Professional associations also helped us diffuse information about the survey on their website, such as the French Cluster Lumière.[9]

38 firms outside the cycLED project completed the on-line survey. Their capital structure shows that they are in majority privately owned (87%). 56% of them carry out research on or are involved in the manufacturing of LED products, but 37% of them are also dealing with other lighting technologies (only 13% are not involved in LED technologies and operate in other lighting activities). The majority of the surveyed firms are active at local and national levels (82%). 76% are active in the EU, 45% in Asia, 39% in Africa, 34% in North America, and 31% in Australia. 68% of surveyed firms own granted patents.

Regarding the types of activities carried out by eco-innovative firms, over the past four years 33% of surveyed firms eco-innovated to reduce their energy consumption during the manufacturing phase. 84% did it to reduce the energy consumption of their products in the use phase, 45% to reduce the use of hazardous materials in products or during production, and 32% to reduce air, water or soil emissions. Finally, 42% of surveyed firms claimed to eco-innovate to generate less waste during the production process. We can see that the main driver of eco-innovation of surveyed firms is the reduction of energy consumption, probably because energy savings tend to reduce production costs during the production phase as well as during the use phase. Indeed, displaying highly energy efficient LED products is a source of comparative advantage for LED manufacturers.

The scope of eco-innovations developed in-house is an important aspect to examine, since the market potential of these eco-innovations will not be the same if they are new to the firm only or if they are new to the whole world. Our results reveal that 24% of surveyed firms consider that their eco-innovation activities are a novelty for the world and 24% a novelty for Europe, which suggests that these firms have a robust innovation potential.

Only the responses having been deemed of high or medium importance by at least 25% of the surveyed firms were taken into account in the results of phase 2 discussed in section 5.2.

3.3 The multilevel perspective

The MLP enables us to analyse transitions of human societies, which can be defined as “long-term fundamental changes (irreversible, non-linear, multi-levelled and systemic) in the cultures (mental maps, perceptions), structures (formal institutions, and infrasystems) and practices (use of resources) of a societal system” (Loorbach et al. (2010: 1195)). Various

[9] See http://www.clusterlumiere.com/enquete-sur-les-barrieres-a-leco-innovation-dans-le-secteur-de-leclairage/. Accessed on 5 August 2016.

models or representations have been developed by transition scholars to shed light on how sociotechnical systems change over time and co-evolve with their natural environments. Those systems are not easy to capture because (p. 1196):

1. They are open and embedded in an outside environment with which they co-evolve,
2. There is a changing outside environment that influences the system,
3. The system itself exhibits non- linear behaviour in order to adapt to its environment.

These internal and external changes occur at various levels of society, which based on Kemp et al. (2001: 277) transition scholars have divided into landscapes, regimes, and niches. The landscape level concerns external and slow societal trends; societal regimes include the interwoven fabric of institutions, technologies, routines and other rules; while emerging innovations take place at the niche level. The combination of the multilevel and dynamic perspectives provides an analytical approach that has permitted many scholars to decipher the factors having led to past transitions. But they can also shed light on factors blocking a current transition, in our case on barriers to eco-innovation in the LED sector.

Several sociotechnical systems have been analysed[10] as in the cases of energy (Raven and Verbong (2007), Verbong and Geels (2007)), waste (Raven (2007) or water (Geels (2005)). Concerning lighting, research has seldom focused on lighting despite its wide-ranging economic, societal and environmental impacts. For example, when discussing the challenges of the transition to a low carbon future, Hammond and Pearson (2013) does not even mention lighting. Only Holtz (2011) quotes two PhD theses, which analyse the consequences of the EU ban on the consumption of incandescent lamps and conclude that the ban will increase energy efficiency in the sector (Chappin and Afman (2013)).

In this paper, the MLP is used to provide a systemic approach to formulate managerial and policy recommendations based on the results of phase 2. In the case of the ecological transition of the lighting sector, we have used the following MLP categories to analyse barriers to eco-innovation:

- Landscape level (macro): no major or minor barrier to eco-innovation was brought forward by the surveyed LED firms, this level will therefore not appear in our analysis.
- Regime level (meso): four dimensions appeared to be relevant for the lighting regime:
  - Financial market
  - LED market
  - LED Technology
  - Public policies
- Niche level (micro): two dimensions appeared to be relevant for the lighting regime:
  - Financial resources
  - Human resources

4. Results

4.1 The case of cycLED SMEs

As explained earlier, cycLED SMEs provided 576 evaluations about how serious were to them the 144 eco-innovation barriers. As shown in the following table, 3% of those evaluations corresponded to major barriers to LED eco-innovation. 60% were irrelevant to the

[10] See the list of relevant transition reference list produced by the Sustainability Transitions Research Network (STRN): http://www.transitionsnetwork.org/files/Reference%20list%20to%20transition%20publications.pdf.

interviewed firms, which could be explained by the fact that many barriers were collected from the eco-innovation literature that was not specific to SMEs of the LED sector.

Table 1. Distribution of SMEs' evaluations per level of barrier

Levels		Regulatory barriers	Barriers to ecodesign	Total number of evaluations	Total number of evaluations (%)
2	Major barrier	8	7	15	3%
1	Relevant	47	143	190	33%
0	Irrelevant	121	225	346	60%
-1	Not a barrier	12	13	25	4%
TOTAL		**188**	**388**	**576**	**100%**

The 15 "major barrier" evaluations concern 14 different barriers to eco-innovation, which are listed below per MLP level and category of barrier.[11]

Table 2. Major barriers to eco-innovation according to cycLED SMEs

Barrier #	Level	Category	Title
1	Meso	Financial market	Lack of private funding to support SMEs' ecoinnovation
2	Meso	Labour market	Lack of skilled people to repair used LED products
3	Meso	Labour market	Educational institutions do not provide enough people well trained to develop eco-innovations
4	Meso	LED market	Increasing & unfair competition from non-European firms
5	Meso	LED market	Existence of litigations between LED firms
6	Meso	LED market	Lack of modularity between radical lighting innovations
7	Meso	Public policies	Lack of certification mechanisms to check out the technical specifications of LED products put on the market
8	Meso	Public policies	National policies do not provide adequate support to eco-innovation and/or emerging LED technologies
9	Micro	Financial resources	Lack of in-house sources of finance
10	Micro	Financial resources	The gross intrinsic value of the LED product is too low, which discourages innovation in recycling technologies
11	Micro	Financial resources	Eco-innovation costs are too difficult to control
12	Micro	Human resources	Lack of technical personnel to eco-innovate
13	Micro	Technological resources	Information systems are sources of rigidity that discourage eco-innovation
14	Micro	Technological resources	LED drivers are barriers to ecoinnovation

These 14 barriers need to be given priority in order to support the development of ecodesigned LEDs. The solutions to overcome these barriers are discussed in section 6, and ad hoc reports were provided to each SME with solutions to help them overcome their barriers to eco-innovation. These barriers have been placed in MLP representation of the barriers to the ecological transition of the LED sector.

[11] The full list of barriers is provided in the appendix n°3 of the deliverable 8.1 of the cycLED project, available for download at https://gossart.wp.mines-telecom.fr/cycled/.

4.2 The case of European LED firms

The answers provided by European LED firms to our online survey have enabled us to identify 18 major barriers to LED eco-innovation. Major barriers are the main causes for the stability of the dominant lighting system that needs an ecological transition.

Table 3. Barriers to eco-innovation according to European LED firms

Barrier #	Level	Category	Title
1	Meso	Financial market	Lack of private funding sources to support eco-innovation
2	Meso	LED market	Consumers lack knowledge about eco-innovative products
3	Meso	LED market	Future standards in the LED sector are uncertain
4	Meso	LED market	Consumers are not willing to spend on eco-innovations
5	Meso	LED market	Established firms prevent entering eco-innovation markets
6	Meso	LED market	Lack of standardisation in the LED sector
7	Meso	LED market	Lack of cooperation between firms of your sector on eco-innovation
8	Meso	Public policies	Lack of EU policies supporting eco-innovation
9	Meso	Public policies	Difficulties to access EU instruments supporting eco-innovations
10	Meso	Public policies	Lack of public funding sources to support eco-innovation
11	Meso	Public policies	Lack of financial support for SMEs
12	Meso	Public policies	To comply with legal obligations
13	Meso	Technological resources	Lack of information on LED markets for eco-innovations
14	Meso	Technological resources	Lack of information on recent technological developments related to eco-innovation
15	Micro	Financial resources	Lack of funds within your enterprise or group to develop eco-innovations
16	Micro	Financial resources	Eco-innovation costs are too high for my company
17	Micro	Human resources	Lack of qualified personnel to eco-innovate
18	Micro	Human resources	Difficulty to find complementary expertise to eco-innovate

Our survey also enabled us to understand why LED firms engaged in eco-innovation. The following table shows that for 58% of them, the most important reason to eco-innovate was to increase sales on existing markets. Other strong motivations to eco-innovate included reducing costs (53%), entering new markets or improving product quality (45%), increasing product range (39%), and meeting standards and labelling requirements (32%). Another motivation to eco-innovate was outperforming regulatory requirements (32%).

Table 4. Reasons to eco-innovate

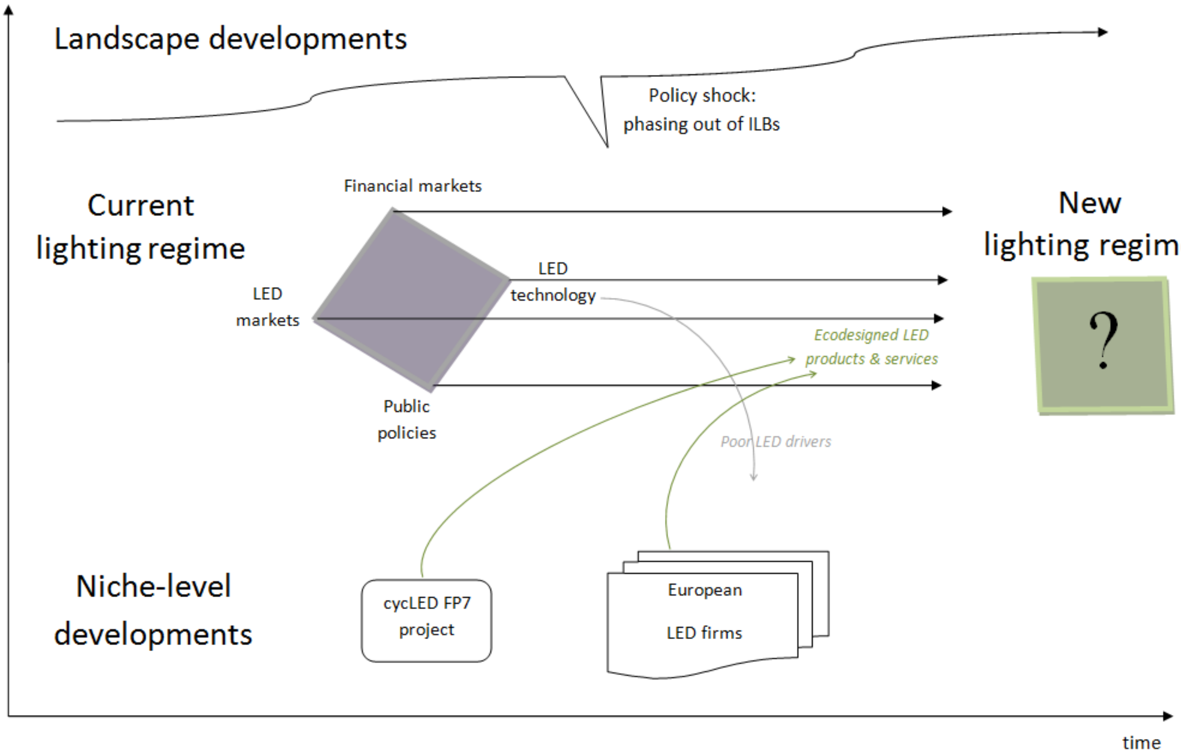
	HIGH	MEDIUM	LOW	N/A	V	SUM
To increase sales on existing markets	58%	11%	11%	8%	12%	**100%**
To reduce cost	53%	18%	11%	5%	13%	**100%**
To enter new markets	45%	24%	11%	8%	12%	**100%**
To improve product quality	45%	24%	11%	8%	12%	**100%**
To increase product range	39%	29%	5%	13%	14%	**100%**
To meet standards and labelling requirements	32%	18%	18%	18%	14%	**100%**
To outperform regulatory requirements	18%	32%	18%	18%	14%	**100%**
To comply with legal obligations	26%	29%	16%	16%	13%	**100%**
To improve compatibility with other products on the market	23%	11%	37%	15%	14%	**100%**
To improve reputation	21%	11%	8%	47%	13%	**100%**

In their analysis of barriers to energy efficiency, Cagno et al. (2013) also take into account internal (Economic, Behavioural, Organisational, Competences, Awareness) and external (Market, Government/politics, Technology/services suppliers, Designers and manufacturers, Energy suppliers, Capital suppliers) barriers, and associate each barrier with an actor. They suggest distinguishing perceived barriers from real barriers, since “it is apparent that every barrier is associated with the perception of the decision-maker and the value that he/she attributes to this perception” (p. 300). In this paper, our methodology only enables us to analyse the barriers perceived by individual firms. However, this paper focuses on major barriers in the LED sector, which have been deemed as such by many firms and thus can reduce the bias of the individual perception of a barrier by a single firm.

5. A multi-level perspective on barriers to LED eco-innovation

In this section, we discuss barriers to eco-innovation which inhibit the ecological transition of the LED sector, at each level of the MLP. To do so, we use the results presented in the previous section, and suggest ways to overcome the identified barriers to LED eco-innovation. The MLP has never been used to elaborate solutions to overcome barriers to eco-innovation. In a study of the barriers to open government data, Martin (2014) explains why the MLP approach can help bring out barriers and envisage solutions. As for Nilsson and Nykvist (2016), they combine the MLP and scenarios methods to analyse the electric vehicle (EV) transition. The latter paper shows how the MLP can help foster the ecological transition of a high-tech sector, including the LED one, which also relies on the same key resource (electricity). The following figure proposes a graphical representation of the possible ecological transition of the lighting sector. In appendix, this representation is used to position the barriers and discuss their interactions and solutions.

Table 5. The ecological transition of the lighting regime



5.1 The landscape of the lighting transition

According to Geels and Schot (2007), in the MLP landscape refers to the overall setting in which processes of change occur (social values, policy beliefs, worldviews, macro-economic & macro-political developments, etc.). It is the most difficult element to change and strongly constraints transitions. As evidenced in the tables presenting the LED barriers to eco-innovation in the previous section, no major barrier was indentified at macro level. The decision taken by many countries in Europe,[12] by the US,[13] or by Australia[14] to phase out incandescent light bulbs (ILBs) could represent a shock in the lighting landscape, just like the decision taken in 1838 by the British government to subsidise steamships to transport its mail (Geels and Schot (2007: 410)). The rarefaction of natural resources such as precious metals and rare earth elements are also landscape-level factors that are affecting the lighting regime, since future LEDs will have to be ecodesigned to limit the use of these metals to limit the EU's dependency from non-EU suppliers. For Germany, a landscape-level shock is the long term decision to change its energy mix by phasing out nuclear energy, which puts extra pressure on the country to save energy and deploy efficient lighting solutions.

What pertains to each level of the MLP is no clear-cut evidence. It is therefore interesting to examine what Nilsson and Nykvist (2016) have included in the landscape level of their EVs study. For example, they mentioned the public policy concern for climate change, as well as changes in technological infrastructures (IT for traffic management), the reduction of the ICE/BEV cost differential (internal combustion engine/battery electric vehicle), and the need to send strong policy signals favourable to EVs. In a similar way, increased climate change

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[12] See Trigg (2015).
[13] See http://energyblog.nationalgeographic.com/2013/12/31/u-s-phase-out-of-incandescent-light-bulbs-continues-in-2014-with-40-60-watt-varieties/. Accessed on 5 August 2016.
[14] See http://www.energyrating.gov.au/products/lighting/phaseout. Accessed on 5 August 2016.

concerns play a role in the switch to ecodesign LED solutions, as do electrical infrastructures supporting direct current.[15] Also, if digital infrastructures support the diffusion of smart lighting systems, and strong policy signals favourable to ecodesigned lighting solutions are lacking in Europe, except at local level in some pioneering municipalities such as Lyons, as evidenced by Schulte-Römer (2015). Hodson and Marvin (2010) have also suggested that cities can play an important role in shaping socio-technical transitions. Nilsson and Nykvist (2016) suggest that technological roadmaps could help change the EV policy landscape. The Optoelectronics Industry Development Association has produced such a "Solid State Lighting Efficacy Roadmap" in 2011, but it is an efficacy roadmap, i.e. only setting 10 years targets on the increase in lumens per watt without any ecological commitment (De Almeida et al. (2014: 35)). During the interviews carried out during the phase 1 of cycLED's Work Package 8 (WP8), several firms and experts highlighted that the low price of nuclear electricity in France was a strong disincentive for ecodesign LED products to penetrate the French market. This efficiency-driven strategy is not surprising since the current European lighting landscape is dominated by an economic crisis, which explains that the political priority for many countries is to support the net creation of jobs, including in the lighting sector. This is combined with an irreversible increase in the long run of the prices of raw materials, not only concerning energy but also precious metals used in new lighting technologies such as rare earth elements, which have been classified as "critical materials" by the US and the EU.[16]

5.2 The lighting regime

A socio-technical regime is the core constituent a technological trajectory which ensures its stability. It is therefore of key importance for ecological transitions, and is composed of several key dimensions that contribute to this stability, such as: Technology, Markets, Industry, Policy, Science, or Culture (Geels (2002)). Most of the barriers to eco-innovation of the LED sector pertain to this level, and some are of a similar nature to the ones observed in other sectors. For example, in the EV case Nilsson and Nykvist (2016) bring forward three main regime-level barriers: difficulties to change user norms and cognition, to reform car industries by shifting away from ICE, and obstacles to develop battery charging infrastructures. In the case of LEDs, users need to be more aware of the economic and ecological advantages of ecodesigned LEDs. The sector should stop selling inefficient lighting technologies such as ILBs, and electrical infrastructures should be changed to better suit LED products and systems. The five following dimensions of the current lighting regime enable us to bring out the main regime-level barriers that prevent the lighting sector to achieve an ecological transition:

- Financial market
- Labour market
- LED market
- Public policies
- Technological resources

Before examining these barriers and their solutions for each of these dimensions, an overview of what these dimensions correspond to is provided as an introduction.

[15] According to experts, "DC-power grids offer the potential of even greater energy efficiency when combined with LED-based lighting", see http://www.ledsmagazine.com/articles/print/volume-10/issue-6/features/lighting-industry-progresses-on-dc-power-grids-that-pair-well-with-leds-magazine.html. Accessed on 5 August 2016.
[16] See https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en for the EU, and for the US: http://energy.gov/eere/amo/critical-materials-hub. Accessed on 5 August 2016.

5.2.1 Financial market

For cycLED SMEs and other European LED firms, the **lack of private funding to support eco-innovation, especially by SMEs**, is a major barrier to eco-innovation. Financial resources are an important ingredient for innovations in general and eco-innovations in particular. They are a prerequisite for R&D investments, which are one of the four critical success factors for environmentally sustainable product innovation.[17] The importance of financial constraints for the development of eco-innovations has been highlighted in other countries and sectors. For example, Liu (2014: 416) finds in a case study of the barriers to the adoption of low carbon production in Chinese industrial firms, one of the two most frequently mentioned barriers was the "lack of financial incentives to stimulate low carbon innovation". The importance of in-house sources of finance for SMEs' eco-innovation is corroborated by several studies on SMEs.[18] To overcome that obstacle to eco-innovation by SMEs, authors suggest to "to reduce the financial constraints for SMEs in order to incentivize eco-innovation".[19] The magnitude of this barrier will vary on the location of the firm, since for example "SMEs located in provinces where the local banking system is functionally distant are less inclined to introduce process and product innovations".[20]

In order to overcome financial barriers to eco-innovation in the LED sector, cycLED firms and experts advised to increase knowledge about funding sources and how to access them. Especially SMEs do not have access to this knowledge, and making alliances with other LED firms could help them search for eco-innovation funding. Besides seeking funds from financial markets, industry associations could also be used to request more funding sources from governments and the EU. Difficulties in financing eco-innovation in the LED sector have direct consequences on the niche level, where most of the identified barriers pertain to the category of financial resources (see next section). Financial issues are therefore a major source of lock-in of the current lighting regime.

5.2.2 Labour market

cycLED SMEs mentioned two eco-innovation barriers related to their labour market (cf. Table 3). The first one concerns the **lack of skilled people to repair used LED products**. Not being able to hire technicians capable of repairing LED products is a strong disincentive to invest in design for recycling. This has a direct impact on the niche level where LED firms have difficulties finding expertise to eco-innovate (see appendix 1). This barrier could be overcome by promoting the repair training curricula and the culture of recycling, repair and reuse. The latter practices are adopted by a minority of producers and consumers, since the dominant ones tend to support a "design for the dump" model. A long legal warranty for all LED products, including LED drivers, could weaken this obsolescence-driven business model, as well as strategies in line with product service systems and a circular economy (using cradle-to-cradle design rules e.g.). The second labour market-related eco-innovation barrier concerns **educational institutions**, which **do not train enough people to develop eco-innovations**. A study of the drivers of different types of eco-innovations in European SMEs found that "those entrepreneurs who give importance to collaboration with research institutes, agencies and universities, and to the increase of market demand for green products

[17] Source: Klewitz and Hansen (2014).
[18] On barriers to innovation among Spanish manufacturing SMEs, see Madrid-Guijarro et al. (2009).
[19] Source: Cuerva et al. (2014).
[20] Source: Alessandrini et al. (2010).

are more active in all types of eco-innovations."[21] Increased collaboration on LED eco-innovation between research institutes, SMEs and universities could therefore help overcome this barrier.[22]

5.2.3 LED market

A major change in lighting markets is the switch from incandescent to LED technologies (Qiu (2007), Pimputkar et al. (2009)). The diffusion of LED technologies is facilitated by their ubiquity, since they are used in indoor lighting (for individuals or organisations), outdoor lighting (streets, roads, monuments), backlighting (mobile electronic devices, LCDs for televisions and computers), signals (traffic, billboards, hoardings and advertising signs, exit and emergency signs), and vehicles lighting, but also for non-lighting designs (e.g. wave shapers in audio circuits), and invisible light (e.g. remote controls using infra-red LEDs). Because of its fast growth and a changing regulatory environment, the LED market is highly dynamic (McKinsey & Company (2012)). In 2010, the global market for lighting products was estimated to €80 billion, of which a very small, but fast growing, fraction corresponded to LED systems (De Almeida et al. (2014)). Sales on the global lighting market will amount to more than 100 billion Euros in 2020 (80% for general lighting), which makes it the most promising technology in terms of commercial viability by 2020, ahead of electric vehicles (McKinsey & Company (2012)). Europe is not the largest lighting market, since it accounts for 22% of this market in 2020 (Asia takes the largest share -47%- followed by North America -18%-). Regarding the LED lighting market, it is anticipated to grow by 45% a year until 2019 (from $4.8 billion in 2012 to $42 billion in 2019).[23]Value is moving downstream (from backlighting to general lighting). Some countries like Korea has selected the LED industry as a new growth engine for the 21st century and is geared to become one of the world's top three LED manufacturers in 2012 (Jang (2010)). As a consequence, the LED share in general lighting should reach 45% in 2016 and 70% in 2020 (ibid.), facilitated by standardisation efforts in the industry concerning high performance heat sinks or long lasting drivers. With the rise of LED lighting solutions, economic value in the lighting sector will shift to fixtures and lighting systems, changing the balance of power among the actors of the lighting regime. New business opportunities will be created such as control systems for LED lighting, especially in offices, leaving space for new business models incorporating ecodesign strategies. Major players include Asian firms such as Nichia or Samsung.[24] As we shall see below, competition from these firms raises a number of problems for the ecological transition of the current lighting regime.

cycLED SMEs brought forward three barriers related to LED markets. The first one concerns **increasing & unfair competition from non-European firms**. Indeed, many Asian products do not deliver the performances required by the European norms they display. To overcome this barrier, environmental requirements of LED products put on the EU market should be strengthened and strictly enforced. A more protective European regulation could take the form of certification mechanisms to reduce unfair competition. Such regulatory measures could

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[21] Source: Triguero et al. (2013).
[22] See the action carried out by the Cluster Lumière in Lyon (France) on sustainable public lighting: http://www.clusterlumiere.com/projets/dedra/. Accessed 5 August 2016.
[23] Source: Report "LED Lighting: Market Shares, Strategies, and Forecasts, Worldwide, 2013 to 2019", http://www.reportsnreports.com/reports/269046-led-lighting-market-shares-strategies-and-forecasts-worldwide-2013-to-2019.html. Accessed on 5 August 2016.
[24] Source: http://www.ledsmagazine.com/articles/2014/02/strategies-unlimited-projects-packaged-led-market-to-hit-25-9b-in-2018.html. Accessed on 5 August 2016.

also strengthen the standards of LEDs that are put on the EU market, for example by only authorising the ones that achieve a certain level of environmental performance. The second barrier related to LED markets concerns the existence of **litigations between LED firms**. Indeed, some incumbent firms threaten to sue smaller firms for patent infringement. This threat discourages eco-innovation by small firms because they cannot afford a law suit. Adopting Fair Reasonable and Non-Discriminatory (FRAND) licensing regimes to LED products could help solve this problem.[25] The third barrier related to LED markets concerns the **lack of modularity** between radical lighting innovations. One way to overcome this barrier is to improve the standardisation of LED products and components. The ZHAGA consortium could help further standardise electrical and mechanical of LED components and drivers.[26]

As for other European LED firms, on the demand side they underline that **consumers lack knowledge about eco-innovative products**, which slows down the diffusion of their products and increases the risks of eco-innovation since outlets are more uncertain. Promoting a European label on LED products and services exhibiting high environmental performances, and supporting advertising campaigns to raise the awareness of consumers (both B2B and C2C ones) about the multiple benefits of ecodesigned LED products and services could help overcome that barrier. One consequence of this lack of knowledge is that **consumers are not willing to spend on eco-innovations**, a barrier that could be overcome by investing in awareness raising campaigns promoting the ecological and economic benefits of ecodesigned LED products and services. More specific economic instruments could also be used to increase the diffusion of ecodesigned LED products and services such as vouchers, subsidies, tax rebates, lower interest rate loans, or green public procurement. On the supply side, there are also information problems related to the **lack of information on LED markets for eco-innovations** and to the **lack of information on recent technological developments related to eco-innovation**. The following measures can help overcome these barriers to LED eco-innovation: encourage European LED SMEs to attend national and international lighting fairs (the Chinese government finances the participation of Chinese firms to these fairs), allocate human resources to market and technology watch, improve information flows with internal and external sales forces, for example by using an efficient ERP enabling any employee to feed in new knowledge about eco-innovative technologies and markets. But the sector also suffers from a **lack of cooperation between LED firms on eco-innovation**. Launching publicly funded research programmes fostering intra-sectoral firm collaboration as well as encouraging staff exchanges in the European LED sector could help the LED sector overcome this barrier to its ecological transition. This lack of cooperation is evidenced by the fact that **incumbent firms prevent entering eco-innovation markets**, which can take the form of the aforementioned barrier related to the existence of litigation cases between LED firms. Besides the promotion of FRAND license schemes in the sector, SMEs should be provided with cheap or free legal support to deals with threats of law suits by incumbent firms. Ideally, collaboration between small and large firms should be promoted, e.g. through publicly funded research programmes, as it happened in the case of the cycLED project whose industry partners were both SMEs and large firms. It also appears that **future standards in the LED sector are uncertain**, which increases the risks associated with eco-innovation. Existing LED-related standards should be properly enforced by all actors, especially by Asian firms present on European LED markets. Intra-sectoral collaboration on eco-friendly industry standards should also be reinforced, for example under the leadership of industry associations

[25] The extent to which patents can be used to deter eco-innovation in the LED sector is examined in another paper in which data from the EPO is used in conjunction with data on LED-related infringement procedures.
[26] See http://www.zhagastandard.org/specifications/certification.html. Accessed on 5 August 2016.

such as Lighting Europe. This sector-level barrier has a direct impact on another barrier regarding the **lack of standardisation in the LED sector**, which reinforce the aforementioned lack of modularity in the sector.

5.2.4 Public policies

According to cycLED SMEs, a very strong obstacle to their capacity to eco-innovate is the **lack of certification mechanisms to verify the technical specifications of LED products put on the European market**. In the USA, the "LED Lighting Facts" programme of the Department of Energy aims "to assure decision makers that the performance of solid-state lighting (SSL) products is represented accurately as products reach the market".[27] A similar programme should be launched at European level. In an official letter, the cycLED consortium encouraged Lighting Europe to launch a similar initiative in Europe. In March 2015, this European industry association launched a "Compliant Lighting Initiative", to ensure that all the players of the EU market are on the same level playing field.[28] Furthermore, it was also felt that **national policies did not provide adequate support to eco-innovation and/or emerging LED technologies**. Sectoral organisations such as AGORIA as well as national governments could provide funding for end users with low energy consumption, for example in the form of financial support schemes rewarding consumers who adopt ecodesigned LED products, in a similar fashion to what California did with its "Efficiency and Conservation Block Grant Program" (EECBG). This policy granted USD 37.3 million to 40 small cities and counties to develop LED street and parking area retrofit projects.[29] In the case of EVs, Nilsson and Nykvist (2016) argue that public procurement can help eco-innovations taking off, since "Fleets ease cognitive barriers in general and range anxiety in particular". They also suggest promoting "leasing to lower upfront cost", which could also be useful in the case of LED products, which usually required upfront investment in LED panels for example.

As for other European LED firms, they felt in general that it was difficult to **comply with legal obligations**, especially since in their opinion there is a **lack of public funding sources to support eco-innovation, especially for SMEs**. They also felt that there was a **lack of EU policies supporting eco-innovation**, as well as **difficulties to access EU instruments supporting eco-innovations**. Solutions to overcome these barriers include maintaining and increasing the place of eco-innovation in European RTD programmes, raise firms' awareness about these programmes and their instruments at European, national, and regional levels, and lobbying national governments and EC to increase these sources of support for eco-innovation in the LED sector.[30]

[27] See http://www.lightingfacts.com/About. Accessed on 5 August 2016.
[28] See http://www.lightingeurope.org/uploads/files/LightingEurope_Press_Release_Compliant_Lighting_Initiative_March_2015.pdf. Accessed on 5 August 2016.
[29] Source: The Climate Group (2012).
[30] Policy recommendations targeting regulatory barriers have been summarised in a Policy Brief (D8.4) available online, which has been presented and discussed in a Policy Workshop (D10.4). See http://gossart.wp.mines-telecom.fr/cycled/.

5.3 The niche level

The niche level corresponds to micro level protective spaces where innovations originate from, such as firms, research labs, or publicly funded research projects such as the cycLED one financed by the 7th framework programme of the EU. The innovations developed at this level can break into the main regime and contribute to change it. The four demonstrators developed in the cycLED project sought to contribute to change the current unsustainable lighting socio-technical regime. Menanteau and Lefebvre (2000) point out the importance of public programmes to create initial niche markets. It is precisely the objective of the cycLED project, which aims to optimise the flows of resources over all life-cycle phases of LED products.[31] To support the success of cycLED niche demonstrators and the micro level success of eco-innovative European LED firms, their barriers to eco-innovation need to be analysed. The three following dimensions of the current lighting regime enable us to bring out the main barriers that deter the ecological transition of the lighting sector:

- Financial resources
- Human resources
- Technological resources

5.3.1 Financial resources

According to cycLED SMEs, a major barrier to eco-innovation is the **lack of in-house sources of finance**. This is partly caused by the regime-level barrier related to the lack of funding for SMEs' eco-innovation. Therefore, policies seeking to support LED eco-innovation should focus on providing financial resources to SMEs. Financial constraints are a key barrier for SMEs to eco-innovate. Financial resources are an important ingredient for innovations in general and eco-innovations in particular. They are a prerequisite for R&D investments, which are one of the four critical success factors for environmentally sustainable product innovation.[32] The importance of in-house sources of finance for SMEs' eco-innovation is corroborated by several studies on SMEs.[33] Authors stress that financial barriers depend on SMEs' location, since "SMEs located in provinces where the local banking system is functionally distant are less inclined to introduce process and product innovations".[34] Financial constraints are also important barriers to innovation for low-tech SMEs. Hence, other authors suggest to "to reduce the financial constraints for SMEs in order to incentivize eco-innovation".[35] As we shall see below, our findings also suggest that public policies do not provide enough incentives for SMEs to eco-innovate. A second perceived disincentive to eco-innovation is the fact that **the gross intrinsic value of LED products is too low**, which discourages innovation in recycling technologies since the benefit firms get out of it is too low, assuming that they manage to get back their used products, which is feasible with a product service system (PSS). Otherwise, if the value that can be recovered from collected used LED products is too low, an alternative strategy is to prioritise reuse over recycling, in order to maintain a relatively high value of the used equipment. But this implies to invest in design for recycling so that LED products can be easily repaired and reused. This would be easier within a PSS business model since the producer would be in charge of the reuse of its products. This barrier also impacts the costs of LED eco-innovation, and therefore has a direct impact on a

[31] See http://www.cyc-led.eu.
[32] Source: Klewitz and Hansen (2014).
[33] On barriers to innovation among Spanish manufacturing SMEs, see Madrid-Guijarro et al. (2009).
[34] Source: Alessandrini et al. (2010).
[35] Source: Cuerva et al. (2014).

third barrier concerning the fact that **eco-innovation costs are too difficult to control**. This is also related to regime-level barriers concerning risks of patent litigations with incumbent firms who tend to raise barriers to entry on the LED eco-innovation market.

Other European LED firms also share similar problems with eco-innovation costs, since a major barrier for them is the fact that **eco-innovation costs are too high for their company**. Reducing the energy consumption of their LED products, a main driver of eco-innovation for surveyed firms, could help overcome this barrier since it reduces the return on LED investments for their customers. A more substantial change would be to adopt a different business model based on product service system, which stabilises income while favouring longer lifetime and recycling performances. All these solutions imply convincing consumers that the quality of eco-innovative LED products is worth paying for it, either because there is an economic value (acceptable ROI) or a societal value (CSR) of reducing the ecological impacts of lighting. These high costs of eco-innovation imply a high level of financial commitment from the firm itself, especially given the aforementioned lack of regime-level sources of funding for LED eco-innovation. as a consequence, European LED firms suffer from a **lack of funds within the firm or group to develop eco-innovations**. Looking for funds on financial markets could be an option but as said earlier at regime-level financial markets are not very supportive of LED eco-innovation. other alternative solutions to overcome this major barrier is to make alliances with other firms and to carry out joint research projects, with European funds as in the case of cycLED or by pulling joint human, technological and financial resources.

5.3.2 Human resources

For cycLED SMEs, a major barrier to eco-innovation is that it is difficult for them to **find technical personnel to eco-innovate**. Given that at regime-level there seems to be a lack of eco-innovation skills available to the European sector, staff exchange between firms (especially with large firms) could be encouraged, eco-innovation training courses could be given to personnel, and partnerships with local training and technology institutes could be developed. As Hansen et al. (2002) suggest, "policy to support SME's adoption of environmental innovations has to take an integrated form, i.e. addressing and developing competence, networks and strategic orientation of SMEs simultaneously whilst remaining systemic and context sensitive".[36] In their analysis of barriers to energy efficiency gains in the Italian primary metal manufacturing SMEs, Trianni et al. (2013) underline the importance of knowledge-related barriers. To overcome them, they suggest "creating and supporting a local network of knowledge and competences able to inform enterprises, technology-suppliers and installers about existing opportunities" (p. 438). Such networks should be developed in various European lighting clusters, as in the case of the Cluster Lumière in the region of Lyons.

Other European LED firms also suffer from a **lack of qualified personnel to eco-innovate**. Joint research project could foster knowledge exchange between industry and academic partners, and staff eco-innovation and ecodesign training could also make use of MOOCs if financial resources are lacking to invest in face to face training. Otherwise, it is best to hire new staff well trained in ecodesign and eco-innovation. But the overall picture we get from surveyed European LED firms is that they have **difficulty finding complementary expertise to eco-innovate**, so this related to the regime-level barrier related to the lack of eco-

[36] Source: Hansen et al. (2002).

innovation expertise in the sector as a whole, which can be solved by the sector itself and by national and European pro-eco-innovation training policies. As in the case of cycLED SMEs, collaborating with other companies and research institutions though joint projects and promoting staff exchange programmes with other firms and with research centres can also help overcome this barrier.

5.3.3 Technological resources

Two major barriers related to LED technologies were mentioned by cycLED SMEs, the main one being that **LED drivers are barriers to eco-innovation**, because their lifetime (usually between 3 to 7 years) is much lower than the possible lifetime of the rest of an LED product. Why spending a lot of efforts in ecodesigning LED products that will last long if the driver fails after 3 years? This barrier relates to the fact that LED drivers are often the weakest point of the LED product and fail well before the light bulb, especially when they are cheap and not subjected to stringent quality controls. The weakness of LED drivers is an obstacle to ecodesign because firms are discouraged to eco-innovate if they know that their product will fail because of the driver: why should they invest in designing long-lasting products with a high environmental performance if the driver purchased from its Asian supplier fails after 2 or 3 years? This is a strong barrier because usually LED firms do not manufacture LED drivers but purchase them from electronics firms, and thus they can hardly improve the driver in-house. This barrier is directly relevant for demonstrators, and was deemed major or relevant by three cycLED SMEs (the fourth one had decided manufacture its own drivers). Apart from changing supplier or using custom-made drivers, other in-house solutions include training technician about how to select reliable drivers, which implies not only to take into account the cost of the equipment but also to integrate environmental criteria such as the longevity of the driver or its replaceability. Public policies solutions to this problem include working with driver suppliers to increase quality and reliability, but according to cycLED partners it takes a lot of time and effort and the outcome remains uncertain. Therefore, standardisation and better quality control procedures should be implemented in Europe to improve drivers' quality (including their environmental performance in terms e.g. of energy consumption and recyclability), led by the European Commission and Lighting Europe. Such standards should include the replaceability of drivers as well as their modularity, in order to ensure that LED products designed for a certain driver do not need to be replaced when this driver gets out of the market. An industry-wide effort could be made to help small companies select reliable drivers; while black-listing the least reliable drivers could help level the playing field. Extending the duration of the legal warranty would force driver manufacturers to improve quality. This measure can also be requested by firms themselves, but small ones may have difficulty imposing their requests to large foreign electronics firms on which they cannot exert much pressure since the size of their orders is rather small. Finally, one cycLED SME argued that **information systems can discourage eco-innovation**. In-house solutions include the development and deployment of a new ERP System, but small firms might not be capable to do so. The latter could be given external support to carry out technology watch activities, develop information systems for eco-innovation, and recruit eco-innovation and ecodesign specialists. An EU pool of experts could be developed in association with national employment agencies and educational institutions to match needs and available skills on the European labour market.

6. Conclusion

This paper has provided an analysis of barriers to eco-innovation in the LED sector, as well as strategy and policy recommendations to support the ecological transition of the European lighting sector. We believe that the latter can lead by example and lead this sustainability transition. Our research is based on a European FP7 project called cycLED, for which we conducted case studies of SMEs and a survey of European LED firms, in order identify the most important barriers to LED eco-innovation. The multilevel perspective has enabled us to position these barriers and envisage ways to remove them so that a new and greener lighting regime can be put in place.

Some of the barriers identified are common to other sectors such as the lack of in-house financial resources to carry out eco-innovation activities, the unfair competition from Asian firms, the lack of eco-innovation skills and robust eco-friendly standards, or the role of incumbent firms to deter LED eco-innovation by using aggressive IPR strategies for example.[37] Others are specific to the LED sector, such as the role of drivers in the early obsolescence of LED products, or the lack of enforced mechanisms to check the eco-efficiency of LED products (e.g. in terms of actual lumens per watt).

Our results have enabled us to identify key barriers to eco-innovation at regime and firm levels. As the level of the lighting regime, the suggested solutions include:

1. Financial support to LED SMEs in order to carry out ecodesign activities (subsidies, vouchers, ...);
2. Knowledge support to LED SMEs in order to carry out ecodesign activities (training, partnerships, IPR management, ...);
3. Normative support to LED SMEs in order to carry out ecodesign activities (standards, regulations, ...).

At the level of LED niches, key solutions include:

1) Increasing in-house sources of finance to conduct eco-innovation activities (increase capital, loans, apply to research projects, …).
2) Adopting a product service system business model, which requires training personnel to develop it (e.g. regarding its financial prerequisites).
3) Adopting measures to get access to better LED drivers in order to extend LED products' lifetime (train personnel to identify these drivers, support industry-wide efforts to standardise them, …).
4) Training personnel on eco-innovation issues and ecodesign techniques (in-house training programmes, staff exchanges with universities, research labs, or other (e.g. larger) LED firms, …).
5) Putting in place efficient information systems in order to keep up with the fast pace of eco-innovation in the LED sector.

[37] The role of LED patents as barriers to eco-innovation has been examined in another paper co-written by the two authors of this paper.

Finally, policy recommendations contain both market pull and demand push solutions to support the sustainability transition of the European LED industry and suggest to:

1. Protect European firms from unfair competition;
2. Provide support to ecoinnovative LED technologies;
3. Support ecoinnovation training and education.

7. References

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Appendix 1. A graphical representation of the barriers to eco-innovation in the LED sector

Forthcoming.