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# Understanding LED technology as a lighting opportunity. A cognitive perspective on the efficiency dynamics in the U.S. LED market.

**Simone Franceschini**
DTU
Management Engineering
sifr@dtu.dk

Abstract

The LED technology has been widely defined as a relevant environmental friendly innovation, due to its tremendous energy efficiency performance. Born as a technology for computer and alphanumeric displays´ markets, it has turned into a relevant lighting technology only recently, attracting the interest of users, firms and policy makers, interested in reducing the environmental impacts of lighting, primarily through the increase of energy efficiency, and in exploiting new technological opportunities in terms of lighting quality, color control, miniaturization and customization.

In the new Millennium, new players, coming from several different sectors, entered the general lighting market. This has provided a new set of capabilities for the new LED lighting market. As expected by the life-cycle literature, a first era of ferment is characterized by a high degree of technical variation, before a process of convergence towards a dominant design may happen. Hence, it is expected that a similar pattern may be found in the LED lighting sector. In order to explore such process of variation, this paper draws its theoretical background over the resource base view literature, with a specific focus on the technological cognitive evolutionary economics literature, which considers product development diversity as the results of heterogeneous capabilities among different players. The LED lighting market represents an interesting case for applying such perspective, with heterogeneous players and different market development drivers in the competitive arena. The paper explores how firms? prior knowledge backgrounds and technological frameworks are related, and how this leads to different product development patterns in terms of lighting performance. This is being currently performed through an analysis of 6,000 LED lamp features and a survey among the 400 firms that are entered in the U.S. lighting market in the period 2009-2012. Preliminary findings show that efficiency is a key market driver in almost all the marketing segments. Thus, it is expected that firms with similar backgrounds show similar LED product development features. This result, whether confirmed, will give valuable findings in terms of industry evolution understanding, since the emersion of future dominant design and the variety of product features in the first stage of a new industry is related to the diversity of newcomers? prior knowledge base.

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# Understanding the LED technology as a green lighting opportunity. A cognitive perspective on the efficiency dynamics in LED lamps development.

Simone Franceschini – DTU Management Engineering

P.h.D. student since October 2011

## Abstract

The LED technology is widely recognized an eco-friendly innovation, due to its tremendous energy efficiency performance. Born as a technology for computer and alphanumeric displays´ markets, it has turned into a relevant lighting technology only recently, attracting the interest of users, firms and policy makers, interested in reducing the environmental impacts of lighting, primarily through the increase of energy efficiency, and in exploiting new technological opportunities in terms of lighting quality, color control, miniaturization and customization.

In the new Millennium new players, coming from several different sectors, entered the general lighting market providing a new set of capabilities in the LED lighting market. Using an evolutionary perspective, the paper analyses the process of diversity and convergence among different players. This paper draws its theoretical background over the resource base view literature, with a specific focus on the technological cognitive evolutionary economics literature, which considers product development diversity as the results of heterogeneous cognitive capabilities. The paper explores how firms' prior knowledge backgrounds and cognitive perspectives are related, and how this leads to different product development patterns in terms of LED lamp performances. This is analyzed over a part of the 6,000 LED lamp features and the 400 firms that joined the U.S. lightingfacts program in the period 2009-2012. Preliminary findings show that efficiency is a key market driver in almost all the marketing segments. Thus, it is expected that firms with similar backgrounds show similar LED product development features. This result, whether confirmed, will give valuable findings in terms of industry evolution understanding, since the emersion of future dominant design and the variety of product features in the first stage of a new industry is related to the diversity of newcomers' prior knowledge base.

## Introduction

First Lighting Emitting Diodes (LEDs) applications have been developed since the 60s for the electronic market. Born as a technology for computer and alphanumeric display markets[1], the LED has gradually attracted the interest of other sectors, as the lighting one, after two decades of development, based on the improvement of lighting efficiency and quality, and the reduction of production costs. The first LED applications for visual lighting effects have been developed in the 80s, and in the 90s the creation of high-brightness LEDs created the basic condition for the use of LED as a general lighting technology. With the new millennium, first commercial applications have been made available and new players with LED technological capabilities entered the general lighting market, providing new innovative dynamics in this sector.

The LED lighting market represents an interesting case for understanding technological dynamics in a competitive and heterogeneous context, driven by pull-market and push-technological drivers. On one side, the technological evolution has allowed the development of high-quality LEDs in term of lighting power, efficiency, miniaturization and customization, with further technological breakthrough, based on the Organic LED (OLED) technology, already under development. Thus, high LEDs lifetime is expected to have relevant impacts of the market dynamics as known today, since it is expected a dramatically decrease in the annual volume of sold LED lamps from 14.000 units of 2009, to 8.000 of 2020 as soon as this technology will become dominant (European Commission, 2011a). Besides that, the process of miniaturization and customization has opened new opportunities for high-tailored solutions and the integration of the lighting sources with others, e.g. textile, domotics, design, construction. On the other side, the lighting sector has attracted the interest of users and policy makers, interested in reducing the environmental impacts of lighting, primarily through the increase of lighting energy efficiency. In this context, the LED lighting dynamics represent a paradigmatic example of the new green growth perspective (OECD, 2011), in which firms play the role of eco-innovators (M. M. Andersen, 2010), driven by an institutional context that aims at fostering at the same time, innovation, competitiveness and sustainability (European Commission, 2011b).

An evolutionary perspective can provide relevant understanding of the LED lighting industrial and market dynamics. As the industry life-cycle literature expects, a first era of ferment is characterized by a high degree of technical variation, before a process of convergence towards a dominant design might happen. Evolutionary thinking understands such dynamics in terms of processes of variation, selection and replications, through innovation and imitation, among a heterogeneous population of firms. In order to explore such processes  this paper draws its theoretical background over the resource base view (RBV) literature, with a specific focus on the evolutionary economics literature about technological cognitive framework (Kaplan & Tripsas, 2008) (Benner & Tripsas, 2012), considered as the results of heterogeneous capabilities among different players. In the case of LED lighting sector, players show relevant different knowledge

[1] Excluding the military applications

backgrounds, carrying heterogeneous capabilities. New players coming from the semi-conductor industries, as well as the energy sector and others, entered the market in competition with the traditional lighting players.

In the face of such technological changes and societal pressures, it is likely to expect that such different knowledge backgrounds may lead firms in evolving different conceptualization of the LED lighting value (Kaplan & Tripsas, 2008), providing a micro-foundation of the LED lamps product differentiations and future technological developments. Thus, it is expected that the so-called green growth paradigm may influence the ongoing technological dynamics, increasing efforts towards energy efficiency in new lighting solutions.

The "lightingfacts database" for the U.S. market includes almost 7,000 LED lamps have registered in the period 2009-2012, creating a valuable data-set for the analysis of product differentiations. Starting from this data, the aim of the paper is to shed lights on whether different firms´ technological frameworks may explain the product development variations, and how these frameworks are related to the prior firms´ knowledge background.

The contribution of this working paper is threefold. First it investigates the relations between firms' prior knowledge background, technological frames and product developments, in order to explain how firms´ variety and sectorial patterns can explain different patterns of innovations, in terms of product diversification. Then the paper seeks to understand the impacts of energy efficiency on firms' behaviors and routines, giving a micro-foundation of the actual green growth perspective in terms of changing patterns of product development, under the condition of an increasing pressure towards efficiency. Last, the paper proposes a methodological contribution through the use of triangulation techniques in order to test inter-rater survey reliability, something somewhat neglected that can have deep impact on the quality of the answers.

## A cognitive evolutionary perspective for the lighting market

### Evolutionary thinking and the lighting dynamics

Evolutionary thinking understands dynamics of economy as a process of evolution of an heterogeneous population of firms and actors, through mechanisms of variation, selection and replication (Safarzyńska, Frenken, & Van den Bergh, 2012). The interrelations among those mechanisms explain the process through which heterogeneity or diversity varies in a population of firms. Schumepeterian innovation, imitation and the institutional setting represent the mechanisms through which those mechanisms actually work. The heterogeneity characteristic of the firms in a market represents one of the most relevant understanding of the evolutionary thinking, respect to the traditional neoclassic perspective, in which the focus shifts on the firm, as representative of the whole population (Jacobides & Winter, 2007). In a context of routine-based bounded rationality, heterogeneity explains the different market dynamics in which processes of innovations, institutionalizations and imitations take place. The concept of heterogeneity can be understood through the variety, balance and disparity characteristics of a population (Stirling, 2010) (Safarzyńska et al., 2012). Variety regards the different factors embodied in a population of firm. Greater number of factors represents higher variety in the population. Variety itself does not mean heterogeneity, since variety can be different balanced among firms. For instance it is possible to have a great variety of characteristics at any time in the markets, but with a leading dominant configuration, represented by the un-even balance of the distribution of factors, that gives high stability. On the other side, it is possible to have only few different configurations, low variety, but highly balanced, hence the market does not show any dominant design. The third dimension, the disparity indicates to what extent such configurations differ. The processes of selection and replication happen through imitation, in which specific varieties of configurations already in the market develop and spread among the actors, reducing heterogeneity.

The dynamics of the variety and diversity can be understood at the level of product developments through the S-diffusion curve of innovation. The diffusion of an innovation is represented by stereotypic phases: a first stage of fermentation or pre-development, in which market experiences several niches, a lack of a dominant design and in which high variety is expected; a second phase of development and diffusion, in which the innovation takes off, diversity is reduced and the diffusion pace increases; a third phase in which an acceleration phase usually happens and incremental changes take place, with relevant network effects and economies of scales. During this phase, usually diversity is reduced and/or the distribution of different characteristics among the firms shows a process of consolidation among one or few dominant configurations. The last phase shows a stabilization pattern based on incremental developments, and a dynamic equilibrium seems to appear. At the very base of the dynamics of diffusion, there is the fundamental idea that the nature and the trajectory of a technology is rarely known in advance (Nightingale, 2004). Predictability is a process of sense-construction that happens during the research and development process. This explains why in the early stage of an innovation high diversity is present and innovation does not diffuse widely, since firms and users need to make sense about how use a technology, which configurations prevail, how this impacts producers and users' behaviors, and which kind of benefits will emerge.

The lighting market has showed diffusion dynamics similar to what expected. The Bass model is a kind of s-diffusion curve model, known for forecasting the diffusion of new technologies as the results between the interactions of users and potential users (Navigant Consulting Inc., 2012a). This model has been successfully used to describe the diffusion model of new lighting technologies, with the only exception of compact fluorescent lighting (CFL) technology. The model is based on the idea that a contagious process may happen between users and potential users; hence, when the number of users increase, the number of potential users that will adopt such technology increases too, due to the contagious effects among them. The contagious effect takes place since the increase number of users can increase reliability among the potential users, reducing manufacturing production costs and creating new opportunities for distribution. The final effect is that economies of scale emerge, generating positive effects on the diffusion rate. Following this dynamics, the cumulative probability of adoption follows the classic S-shape diffusion curve as expected by literature.

## A resource-based perspective on cognitive models

In this section, I sketch how heterogeneity can be represented, proposing a micro-based interpretation of the evolutionary process in terms of firm's cognitive framework. The resource base view (RBV) represents the theoretical evolutionary economics perspective of this paper. The RBV is essentially based on the idea that firm´s performance depends on the bundle of internal resources and capabilities, and that different firms´ behaviors depends on the heterogeneous distribution of capabilities (Barreto, 2009; Teece, Pisano, & Shuen, 1997; Zander & Zander, 2005) (M. M. Andersen, 2011), subject to organizational routines (Nelson & Sidney, 1973).

The main competence considered is the management´s cognitive ability to understand and make sense of new technologies (P. H. Andersen, 2012) that influence firm´s strategies (Kaplan & Tripsas, 2008) (Benner & Tripsas, 2012). When a firm makes sense of a new technology, it tries defining what it is and how it could be used to create value; hence firm performs more or less explicitly a process of sense-making in which a technology is assed and specific performance criteria defined. The process of making sense becomes a process of identification of the criteria that enable firms to act, creating new products/services that satisfy these requirements. A technological frame is hence defined how "actors categorize a technology relative to other technologies and which performance criteria they use to evaluate the technology" (Kaplan & Tripsas, 2008). In the ferment phase of a new technology, considering the basic uncertainty that deals with any new technological development, several feasible frames are competing, since technologies can be used in different ways, for different purposes and according to different evaluation criteria. This leads to product diversity, when new players come into the market. In these early days, when firms face high uncertainty, previous knowledge background may be a relevant factor influencing the actual designs, since firms may apply old technological frames heritage of the previous routines. The same dynamics apply to the users´ side, since different users, coming from different markets too, will understand technologies differently. Since LED lamps are going to substitute, or at least challenging several lighting technologies, it is expected that different users can have different perceptions about such technology, feeding market differentiations and turbulences.

Technological frames depend on the firms´ capabilities exposed to external stimuli, and this paper considers the strategic management thelocus in which those performance criteria are evaluated. Managers´ behaviors depend on perceived stimuli, built over memory "composed of values, perceptions, beliefs, experiences, programs, alternatives, and other knowledge stored in the psychological bank of the individual" (Tosi, 2008) that are believed to be pertinent and useful in such specific context.  Hence, firms with similar capabilities, in term of cognitive elaboration too, are expected to follow similar patterns, since managers may strategically answer in similar ways.

Such dynamics have been already studied by the social cognition literature (Rao, Greve, Davis, Quarterly, & Sep, 2001), in which managements take decision through a systemic process of analysis, or through a process of social imitation, looking at the performance of other firms and competitors, especially when uncertainty is high and the value of new actions is not known. Under such circumstances, social status and relations as well as credibility may influence the imitating behaviors of the industry. Recalling the fundamental uncertainty of the innovative process (Nightingale, 2004), the cognitive perspective indicates that actors need to make sense of new technologies, predicting the possible uses and performances (Kaplan & Tripsas, 2008). Hence, the predictability is mainly constructed during the process of research and development (Nightingale, 2004), where it could be a mismatch between how a technology is expected to work and how effectively does work in the market context. This explains the role of technological constraints in narrowing the number of possible potential technological frames, reducing variety and uncertainty when clear technological performances are exhibited.

This paper uses the concept of “technological frame” to identify how actors understand a technology (Acha, 2004) (Kaplan & Tripsas, 2008), defining the performance criteria considered relevant for the assessment of the usefulness of a technology.  A technological frame helps actors making predictions about the sense of a technology, defining when a technology works or not respect to a preconceived idea.  Thus, as expected by the social cognition literature, individuals´ technological frames can be influenced by other individual and dominant frames through the process of learning.

A technological frame perspective does not only understand how a technology is used, but how it is developed along different patterns of evolution, looking at the actors’ decisions about investing, developing and commercializing new technologies. Technology itself constrains the potential technological frames, since “incongruity will force actors to shift away from the original technological frame to a new understanding of what the technology is and what performance criteria should be applied” (Kaplan & Tripsas, 2008). Hence the relations between individual technological frame, collective ones and the evolution of a technology are mutually related as showed in Figure 2

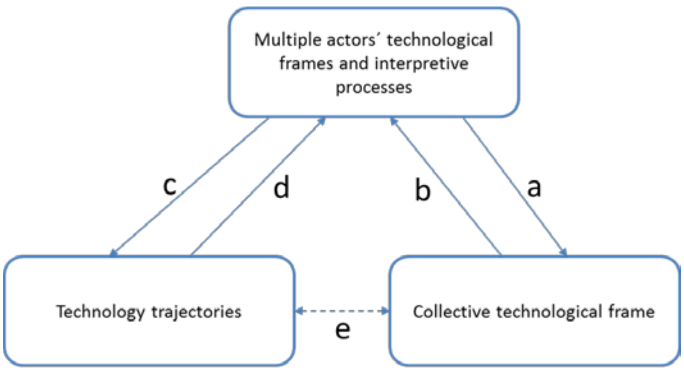


**Figure 1 Relations between technological frames and trajectories** (Kaplan & Tripsas, 2008)**. Letters are explained in the text.**

The relations *a* and *b* define reciprocal influences between the collective frame and the firm one. Firms try influencing the collective domain to shape an environment compatible with its own technological frame (relation *a*), but at the same time the collective domain represents a source of innovation and sense-making (relation *b*). These relations can be more or less conflicting, according to the degree of diversity of each technological frame and how each of them can influence the condition of appropriability of new opportunities. The relation *c* indicates the decision about investing, developing and adopting a new technology coming from the current management technological frame; and *d* the technological constrains that shape the possible technological frames.

### The greening of the market as collective frame

The paper has a specific focus on the greening of the markets as a source of innovation. Lighting accounts for 19% of the worldwide electricity consumption (European Commission, 2011b). For this reason, reducing environmental burden associated to lighting functions became a priority of the modern green policy agenda, in which technological developments has been fostered by appropriate institutional contexts, with the aim of achieving sustainable targets (European Commission, 2011b). in this case, innovation becomes often "eco-", and firms play the role of eco-innovators (M. M. Andersen, 2010).

This societal pressure towards a more efficient lighting use is expected to be found at the collective level, influencing the firm's ones. Thus the institutional context can play a role in leading new technological developments, creating an appropriate set of incentives that can influence the dynamics of the demand and the offer. This is consistent with the evolutionary idea that the institutional settings play a role in influencing diversity, since it may direct efforts of a larger part of population towards eco-efficiency innovations (Safarzyńska et al., 2012). The collective pressure may happen through pressures coming from the policy makers and other actors; hence firms may spot new green opportunities coming from the changing conditions of the market (Arthur D Little, 2005). This increased role for societal actors has been also pointed out as an effect of the different nature of eco-innovation respect to the traditional innovation effects (De Marchi, 2012), due to the double externality problems that happens when firms play the role of eco-innovators but society, at large extent, get parts of the benefits. For this reason, the green agenda is expected to act through the influence of the collective domain on the firm's level (relation b); hence firms involved in greening dynamics may show improved LED lamps performance in terms of energy efficiency, due to the influence of the institutional context over the firms with higher degree of openness towards the collective level.

## The research design

The research design aims at investigating the relations between LED lamps product developments, firm's technological frames and prior knowledge backgrounds, in a context of societal pressures towards the improvements of energy-efficiency performance. This is analyzed through specific research hypotheses, investigated thanks to a combination of several sources as lamps' data, survey, patents' analysis and web sites' textual analysis.

## The research hypotheses

The project seeks to investigate relations between diversity and product development dynamics in the LED lighting market, with a specific focus on the collective dynamics driving efficiency. Diversity is understood as the combination of variety, balance and disparity criteria in the population of LED lighting firms; whereas the innovative dynamics are analyzed through the assessment of the different LED lamp performances, representing the output of each firm's product development effort. Since the main capability considered in the project is the cognitive perspective, diversity refers to what extent firms differ in terms of cognitive perspectives (or technological frames). Precisely, they refer to how firms make sense of LED technology as a lighting opportunity respect to the competing lighting technologies already in the market, indicating which elements or benefits can lead the creation of new business opportunities. Using industry reports, websites and technical publications as sources of information, the following criteria of LED lamps' benefit assessments have been defined:

- LED can provide better **quality of light**, improving human experience and life, increasing sense of safety, security and comfort, and providing new light experience.
- LED can achieve higher **energy efficiency** and long-life performances, being a way to reduce environmental burden associated to lighting services and lamps disposal.
- LED can show improved **design and miniaturization flexibility**, creating new integration opportunities with other materials and technologies in order to produce totally new visual experience. In this sense, the LED technology does not represent just a bulb, but the opportunities that lighting becomes artistic, stylish designed, and functional integrated with other technologies.
- LED can provide higher **economic benefit** for users in terms of reduced life-cycle cost associated to the use of LED technology. This comes from the high efficiency and long-lasting performances, that reduce considerably operating and maintenance costs during the LED life.

These four dimensions represent the elements of technological frames as defined in this paper. The first step of the project seeks to investigate how different combinations appears in the market in terms of variety, balance and disparity. As the diversity of capabilities explain what a firm will do in the market (M. M. Andersen, 2011), it is expected that different cognitive perspectives will result in different product development processes; hence firms carrying different capabilities will develop different LED lamps. Following such line of thought, the first research hypothesis is defined as the following:

a) *Firms with similar technological frames develop LED lamps with similar performance;*

Specifically, the relevant LED lamp features are defined, according to the technical literature, as the following:

- **Light quality**, represented by the color rendering index (CRI) that ranges from 0 to 100. It estimates the capacity of a light to reproduce colors similar to a natural light source. The value of 100 represents the highest fidelity, as performed by the incandescent technology.
- **Light quantity**, represented by the lumens produced.
- **Light color**, represented by the color temperature expressed in Kelvin.
- **Light efficiency/efficacy**, represented by the energy used to produce one lumen. The scale used is the lumens for watt.

As the innovative dynamics are related to the firm's capabilities, it is expected that product development process, even if intrinsically uncertain, follows cumulative patterns, built on the evolution of the firm's capabilities. Literature suggests that variety tends to increase, as firms are more heterogeneous. The LED technology represents an interesting case to test such dynamics, since firms coming from different sectors and backgrounds entered the LED general lighting market from the 90s. This paper uses the following three main knowledge backgrounds to analyze the LED lighting players:

1. **Lighting players** that has added LED technology to the portfolio of lighting solutions;
2. **Semiconductor players** that come leveraged semi-conductor capabilities to enter a new lighting market;
3. **Energy players** that has added LED technology to the portfolio of energy saving solutions;
4. **Others** that do not fit in the previous groups.

As it is likely to expect that firms coming from different sectors differ in terms of capabilities, the investigation seeks to understand whether there are relations between the firm's prior knowledge background and the industry affiliation. Hence the following hypothesis is defined:

b) *Firms sharing similar knowledge background develop similar technological frames*;

So far the hypotheses claim that different technological frames result in different LED lamp features, and that different prior industry affiliations result in different technological frames. A third hypothesis tests direct relations between the industry affiliation and the LED lamps features, skipping the technological frame dimension. This helps checking for the relevance of the technological frame perspective in explaining product diversity. Hence the following hypothesis is added:

c) *The variety of LED lamp features is wider among firms with different prior industry affiliations than the ones with similar ones;*

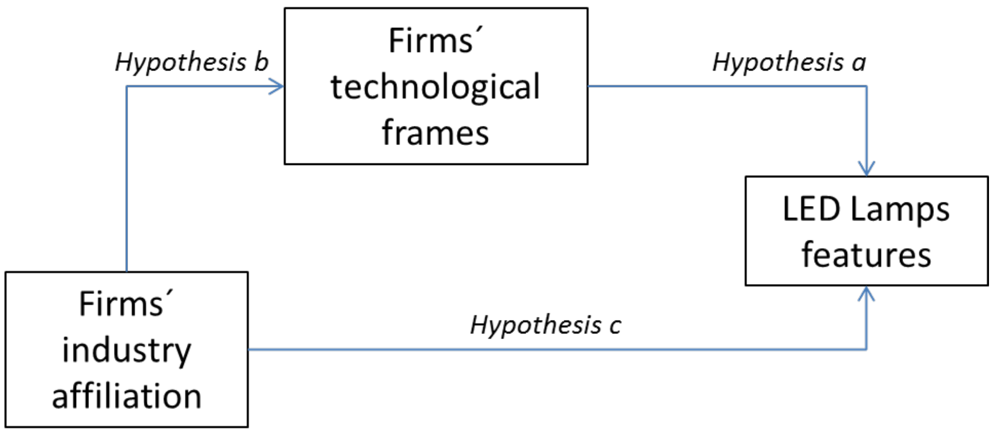


Figure 2 The design of the hypotheses

A further investigation reflects the increasing interest towards the greening of the LED market, as the increasing effort towards energy-efficiency improvements. As already discussed, there is a growing societal interest towards environmental-friendly productions, and this has been mainly translated as an increasing effort towards efficiency.  Thus the double externality perspective seems to indicate that environmental-oriented innovation can be fostered only through active policy makers and other societal actors. Along this line, the paper seeks to investigate which drivers and sources of knowledge/innovation can increase the role of efficiency efforts in firms' cognitive models. For this reason, the paper tests the following hypothesis:

d) *Firms indicating consumers and/or public authorities as the most relevant sources of innovation do develop LED lamps with an higher efficiency respect to the ones of the other competitors*

## The collective domain

The collective domain includes all the external dynamics that can influence the sense-making process of the firm (Kaplan & Tripsas, 2008). In this research design, the collective dimension is represented by the following two elements:

- The diversity of the population of firms, as a proxy of the homogeneity in the LED lighting sector. High value of diversity is expected to indicate a lack of dominant technological frame, hence it is expected that this has low influence of each firm's technological frame.
- The cognitive models of industry associations, users and consumers groups, NGOs and policy makers

Such collective dimension is weighted by the level of interactions that each firm indicates with the collective level. Specifically, two dimensions are included: the importance of external sources in influencing each firm's product development process, and the level of interaction and influence exercised by each firm towards the collective level. These two dimensions define a matrix of possibilities used to classify the relations between a firm and its collective dimension

| Firm's attitude towards the collective dimension | | Importance of external sources on the product development process | |
|---|---|---|---|
| | | High | Low |
| Influence on external sources | High | Open player | Leading player |
| | Low | Passive player | Independent player |

Table 1 The potential combinations considered in the survey (own elaboration)

Using the Community Innovation Statistics (CIS) as source, the collective dimension involves market (suppliers, clients, competitors), institutional (Universities, public authorities) and other (professional conferences, meetings, journals etc) actors.

## Sources of data collection

The following sources have been used to analyze the research hypotheses:

| Dimension | Unit of analysis | Unit of data collection | Sources |
|---|---|---|---|
| LED Lamp features | LED lamps | LED Lamps | - Lightingfacts label |
| Technological frame | Firms | Managers, web sites | - Survey among firms<br>- Analysis of web sites? |
| Firm's knowledge background | Firms | Managers and patent database | - Survey among firms<br>- Patent analysis |
| Collective dimension | Firms, industry associations, NGOs | Managers, web sites | - Survey among firms, industry associations and NGOs<br>- Text analysis of web sites? |

Table 2 Kinds of data and their sources.

LED lamps technical data and the list of producers are gathered by the U.S. "lightingfacts" database. Differently from other programs, as the energy star one, this does not aim at highlighting some specific performance, but at providing clear and standardized information for consumers. Hence this database is expected to be less biased than other specific ones, as the energy star, in which only lamps with specific energy efficiency performance can be admitted. To my knowledge, this is the most comprehensive database of LED lamps in the U.S. market, including almost 7.000 LED lamps and 400 manufactures, from 2009 to 2012. The database provides a valuable source of standardized technical information, defined following specific measurement procedures.

The technological frames, prior's industry affiliation and collective domain have been investigate through the use of a survey among the LED lamp producers included in the lighting-facts database. The survey has been performed both through email and by phone, according to the availability of the interviewees. Thus the knowledge background will be triangulated through a patent analysis, in order to check whether there is a match between the survey and the data gathered by the patents. Last, a qualitative text-analysis of web sites will be used as experimental methodology, with the aim of unveiling the most used keywords. In this case, words and sentences will be connected to the four dimensions of the technological frames, checking for the density of use.

## The pilot test

Before running the survey, a pilot test has been performed, involving few Danish LED lighting firms. The test aimed at check the inter-rater reliability. This is a relevant aspect, since the units of analysis of the survey are the firms, but the units of data collection are the employees. Under this condition, reliability may be compromised by the degree of concordance of interviewees. This can happen since raters can differ in terms of homogeneity of answers, understanding of questions and of the rating scale. In order to test for individual and cultural diversity, the pilot test has been defined according to these dimensions: individual dis-homogeneity and organizational dis-homogeneity, as it may happen that employees of different departments can perceive different technological frames. The pilot test has been designed as following:

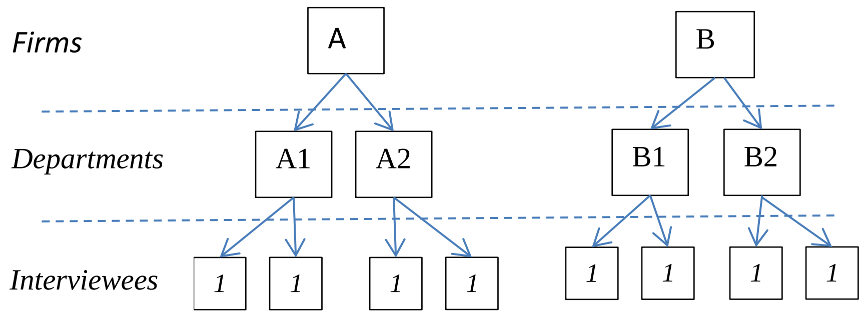


**Table 3 Representation of the pilot test design. Letters and numbers are fictitious**

Inter-rater reliability would be highest in case all the interviewees within the same firm give the same answers. It means that there is a unique firm's technological frame and any of the employees may be interviewed in order to catch it. If differences arise, the department level provides a controlling variable. Whether all the individuals within the same department provides same answers, it means that the technological frame is unique at the level of department, hence comparisons may be done only between the same departments (department 1 and department 2 are represented in the Table 3). In case individual dis-homogeneity, this may hamper the prosecution of the survey, unless reliability can be increased. The minimum requirement to run the test is to have at least two departments within a firm, and two interviewees for each department. Reliability has been calculated merging the four different answering options of a likert scale (strongly disagree, disagree, agree and strongly agree) in two categories: positive (strongly agree and agree) and negative (strongly disagree and disagree), and then confronting them.The ranking used in some answers has been defined through a classic four point likert-scale, with no neutral point. This scale has been used in order to reduce the chance for raters to give neutral, more accepted, answers. Thus this allows the creation of two categories (positive and negative) that can be used to run statistical analysis with few answers.

## The results of the pilot test

In the months of November and December, the pilot test has been performed in order to refine the questions and the answers of the survey and to test inter-rater reliability. 18 raters, representing 13 firms with a Danish/Scandinavian market presence, have been involved, asking them to answer by email or phone the survey. By the 4th of December, 4 pairs of raters have submitted enough coherent information to be compared, with the following inter-rater reliability

| Reliability level | Pair A | Pair B | Pair C | Pair D |
|---|---|---|---|---|
| Indicate market segments you are involved | 75% | 50% | 100% | 75% |
| Indicate non-LED technology you are/were involved | 100% | 50% | 86% | 100% |
| **Indicate firm's knowledge background** | 0% | 0% | 33% | 66% |
| **Please, define your firm** | Agree | Agree | Disagree | Disagree |
| Is your firm a subsidiary | Agree | Agree | Agree | Agree |
| **Drivers of LED growth** | N.D. | N.D. | 80% | 80% |
| **External sources of innovation** | N.D. | N.D. | 50% | 36% |
| LED value chain part you are present | N.D. | N.D. | 66% | 66% |
| Evolution of LED value chain parts | N.D. | N.D. | 0% | 33% |
| Presence in the market | N.D. | N.D. | 66% | 100% |
| Business model used | N.D. | N.D. | 0% | 33% |

Table 4 Inter-rater reliability test (own elaboration). The values are expressed as % or agree/disagree according to the different typologies of answers. The %-value is used for questions in which multiple answers are allowed. The agree/disagree is used for questions in which only one answer is allowed. N.D. represents values that cannot be compared, usually because at least one of the two raters did not answer. In bold the questions used to investigate the dimensions of the research hypothesis

The results indicate high individual in-homogeneity, especially for the question related to the firm's attitudes and perceptions, as the prior knowledge background one. Raters have been expressly asked to indicate whether questions and answers seemed to be incomplete, unclear or misleading. No-one has indicated such issues; hence I have concluded that inter-rater un-reliability does not depend on the quality of the questions used. Similarly, other colleagues did not indicated such problems.

Following the results of the pilot test, several steps have been introduced in order to improve the reliability:

- The firms' units of data collection have been narrowed by every firms' employees to the CEOs or the managers in charge of the marketing/sales department/function. This function has been selected because in many small firms, production function is not properly developed, since many small firms are OEM players, focusing only on market penetration
- Whether possible, a second independent rater, within the same function will be asked to answer the survey
- A methodological triangulation has been introduced in two ways:
    - Using a textual web analysis, in which web sites are analyzed through both through manually, using a third rater, and by software in order to track some dimensions of the survey
    - Using a patent analysis in order to check the prior's knowledge background. It is expected this may work only for medium/big size firms with a developed internal R&D function

## The US residential lighting market

The U.S. lighting market includes almost 8 billions of lamps, that annually consume nearly 700 TWh, about 19% of total U.S. electrical consumption. The residential applications represent almost 71% of installed lamps in 2010 (66% in 2001), 25% of energy consumption (27.1% in 2001)and 8% of total lumens produced (10,1% in 2001). Respect to the 2001 values, the residential sector shows an increase in the number of lamps sector (+26%), compensated by the reduction of daily operating hours (-10%) and the average wattage per lamps (-27%), leading to overall reduction of total electricity use by 16%.

| | Lamps (millions) | | Av. Daily operating hours | | Av. Wattage per lamps | | Annual lumen production (Tlm-hr) | | Total annual electricity use (TWh) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2001 | 2010 | 2001 | 2010 | 2001 | 2010 | 2001 | 2010 | 2001 | 2010 |
| **Residential** | 4,611 | 5,812 | 2,0 | 1.8 | 63 | 46 | 3,912 | 3,320 | 208 | 175 |
| **Commercial** | 1,966 | 2,069 | 9,9 | 11.2 | 56 | 42 | 21,579 | 24,380 | 391 | 349 |
| **Industrial** | 327 | 144[2]. | 13,5 | 13.0 | 65 | 75 | 8,100 | 4,480 | 108 | 58 |
| **Outdoor** | 73 | 178 | 10,5 | 11.7 | 205 | 151 | 4,856 | 8,370 | 58 | 118 |
| **Totale/Average** | 6,977 | 8,203 | 4,8 | 4.7 | 62 | 48 | 38,445 | 40,550 | 765 | 700 |

**Table 5 U.S. lighting market. Genera lighting market information** (Navigant Consulting Inc., 2012b)

The residential market has experienced an increase of the numbers of lamps, but used for a shorter time, with a lower lumen output and lower wattage. The average efficacy can be calculated divided the lighting output (lumens) for the energy input (watt)[3].

[2] The decrease number of industrial lamps is due to different methodological floor space measures, whereas the number of lamps for square meter has effectively declined by 20%.

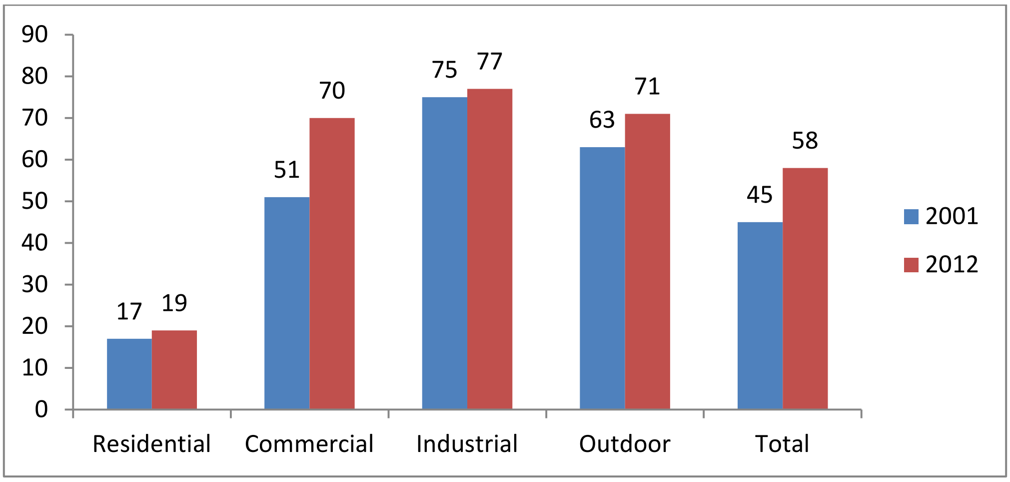


**Figure 3 Average efficiency by sector** (Navigant Consulting Inc., 2012b)

Data shows residential sector is clearly the most inefficient one, due to the reliance on incandescent lamps, with an average of 19 lm/W. Differences in performance mainly depend on the lighting technologies used. The residential sector is widely dominated by the incandescent and halogen one, consuming 85% of residential annual electricity use. The following table provides deeper information about the technologies used in the residential lighting sector, confronting 2001 and 2010.

| Residential segment | % lamps installed | | % wattage installed | | % lumens produced | | % electrical consumption | |
|---|---|---|---|---|---|---|---|---|
| | 2001 | 2010 | 2001 | 2010 | 2001 | 2010 | 2001 | 2010 |
| Incandescent | 84.9% | 62.0% | 89.0% | 78.8% | 66.2% | 49.4% | 87.0% | 77.7% |
| Halogen | 0.7% | 4.4% | 2.0% | 6.4% | 2.7% | 5.1% | 2.0% | 6.9% |
| CFL | 14.3% | 22.8% | 9.0% | 8.4% | 30.4% | 23.5% | 10.0% | 8.6% |
| LFL | | 9.9% | | 5.4% | | 20.2% | | 5.7% |
| HID | 0.1% | 0.0% | 0.0% | 0.1% | 0.0% | 0.0% | 0.3% | 0.0% |
| LED | 0.0% | 0.2% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Other | 0.0% | 0.8% | 0.0% | 0.9% | 0.0% | 0.2% | 0.0% | 0.1% |

**Table 6 U.S. lighting market. Technological data about the residential lighting market** (Navigant Consulting Inc., 2012b).

The residential lighting market shows that incandescent technology is still the dominant one, producing 77.7% of total electricity consumption, but in the last 10 years fluorescent technologies have increased popularity. The LED technology is still in an early stage with few applications mainly focused on decorative lighting and the current competing technology are the incandescent and the fluorescent ones.

The types of fixture used are highly related to the lighting sectors. The following type shows the distribution of the lighting lamps for the residential market.

[3] Data about residential efficacy reported in the table do not match with the ones represented in the figure presented by the U.S. Department of Energy (DOE), since the figure shows an increased efficiency, whereas the table shows a stable efficiency. Further investigations are required.

| Residential market 2010 | Nr. lamps | Average Wattage | Distribution (%) of installed wattage | Annual electricity consumption (TWh) | Annual lighting production (Tlm–hr) |
|---|---|---|---|---|---|
| **Incandescent** | **3.602.809.000** | **56** | **78,8%** | **77.7%** | **49.4%** |
| General Service - A-type | 2.028.184.000 | 64 | 48,8% | 84 | 1.080 |
| General Service - Decorative | 980.054.000 | 44 | 16,0% | 28 | 310 |
| Reflector | 433.929.000 | 69 | 11,2% | 19 | 190 |
| Miscellaneous | 160.642.000 | 45 | 2,7% | 5 | 60 |
| **Halogen** | **256.990.000** | **65** | **6,4%** | **6.9%** | **5.1%** |
| General Service | 26.785.000 | 50 | 0,5% | 1 | 20 |
| Reflector | 168.876.000 | 68 | 4,3% | 8 | 110 |
| Low Voltage Display | 19.348.000 | 44 | 0,3% | 1 | 10 |
| Miscellaneous | 41.981.000 | 82 | 1,3% | 2 | 30 |
| **Compact Fluorescent** | **1.322.525.000** | **16** | **8,4%** | **8.6%** | **23.5%** |
| General Service - Screw | 1.121.452.000 | 17 | 7,0% | 13 | 670 |
| General Service - Pin | 5.386.000 | 22 | 0,0% | 0 | 0 |
| Reflector | 114.754.000 | 17 | 0,7% | 1 | 60 |
| Miscellaneous | 80.933.000 | 18 | 0,5% | 1 | 50 |
| **Linear Fluorescent** | **572.897.000** | **24** | **5,4%** | **5.7%** | **20.2%** |
| T5 | 3.636.000 | 19 | 0,0% | 0 | 0 |
| T8 Less than 4ft | 3.020.000 | 16 | 0,0% | 0 | 0 |
| T8 4ft | 64.022.000 | 26 | 0,6% | 1 | 80 |
| T8 Greater than 4ft | 1.369.000 | 41 | 0,0% | 0 | 0 |
| T12 Less than 4ft | 7.025.000 | 16 | 0,0% | 0 | 0 |
| T12 4ft | 331.790.000 | 27 | 3,3% | 6 | 400 |
| T12 Greater than 4ft | 28.685.000 | 50 | 0,5% | 1 | 70 |
| T8 U-Shaped | 1.155.000 | 27 | 0,0% | 0 | 0 |
| T12 U-Shaped | 316.000 | 27 | 0,0% | 0 | 0 |
| Miscellaneous | 131.879.000 | 16 | 0,8% | 2 | 100 |
| **High Intensity Discharge** | **1.434.000** | **126** | **0,1%** | **0%** | **0.3%** |
| Mercury Vapor | 206.000 | 193 | 0,0% | 0 | 0 |
| Metal Halide | 45.000 | 79 | 0,0% | 0 | 0 |
| High Pressure Sodium | 1.183.000 | 150 | 0,1% | 0 | 10 |
| Low Pressure Sodium | | | | 0 | 0 |
| **Other** | **55.114.000** | **47** | **1,0%** | **0.6%** | **1.5%** |
| LED | 9.175.000 | 11 | 0,0% | 0 | 0 |
| Miscellaneous | 45.939.000 | 54 | 0,9% | 1 | 50 |
| **TOTAL** | **5.811.769.000** | | **100%** | **175** | **3.320** |

**Table 7 U.S. residential lighiting market. LED lamps inventory** (Navigant Consulting Inc., 2012b)

As the table shows, A-type (E14 and E27) and reflector fixtures (as ER, BR and PAR ones), typical used by incandescent, halogen and compact fluorescent technologies, are mainly used in the residential sector. Data from the other lighting segments shows that T-fixtures and High Intensity

Discharge are the dominant technologies. Since the residential and non-residential segments show different dominant lighting technologies, with different performance criteria and achievements, the LED technology competes with very different technological domains, hence the quality and the features highlighted by the LED technology are expected to be different. For this reason, the current investigation focuses only on the residential segment, in which the main competitors are the incandescent and fluorescent technologies.

## The LED expected penetration and savings for the U.S. market

The U.S. DOE estimates that the LED penetration in the market may lead to a reduction of lighting energy consumption of about 46% in 2030, respect to the baseline scenario[4]. Over the period 2010-2030, it means a reduction of 1,800 million metric tons of carbon, and savings for $250 billion at today energy price. The most relevant reduction is expected to be achieved in the residential segment (66.9% of savings) due to the poor efficacy performance of the dominant incandescent technology. The following table reports the evolutions of the lighting scenario over the next 20 years

| | 2010 | 2015 | 2020 | 2025 | 2030 | Cumulative |
|---|---|---|---|---|---|---|
| **Baseline consumption (TWh)** | **694** | **635** | **631** | **641** | **648** | **13,535** |
| Residential | 173 | 142 | 138 | 146 | 153 | 3,105 |
| Commercial | 346 | 325 | 321 | 320 | 316 | 6,806 |
| Industrial | 58 | 49 | 44 | 41 | 38 | 947 |
| Outdoor stationary | 116 | 119 | 128 | 135 | 141 | 2,676 |
| **LED market share** | **-** | **9,5%** | **35,8%** | **59,0%** | **73,7%** | |
| Residential | - | 8,1% | 37,6% | 60,7% | 72,3% | |
| Commercial | - | 5,0% | 27,8% | 52,5% | 70,4% | |
| Industrial | - | 8,8% | 36,0% | 59.2% | 62.3% | |
| Outdoor stationary | - | 29.0% | 64.2% | 81.6% | 87.2% | |
| **Electricity savings (%)** | **-** | **3.3%** | **19.4%** | **33.9%** | **45.8%** | **19.7%** |
| Residential | - | 5.1% | 37.3% | 56.7% | 66.9% | 32.5% |
| Commercial | - | 1.9% | 11.7% | 22.9% | 35.0% | 13.3% |
| Industrial | - | 0.8% | 7.4% | 18.3% | 29.4% | 9.3% |
| Outdoor stationary | - | 6.2% | 23.7% | 40.2% | 51.7% | 25.2% |

**Table 8 Energy saving scenarios for LED technology in the U.S. market** (Navigant Consulting Inc., 2012a)

This scenario considers the following improvements in the LED performance:

| LED product | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| **Led efficiency (lm/W)** | | | | | |
| Lamp | 37 | 113 | 182 | 199 | 203 |
| Luminaire | 70 | 145 | 193 | 202 | 203 |
| **LED lifetime improvement (1,000 hours)** | | | | | |

[4] It is relevant to notice that scenarios do not consider that the light demand in terms of lumens may be impacted by the change towards more efficiency and bright lighting technology; hence all the improvements in efficiency do not lead an increase in lighting consumption.

| | | | | | |
|---|---|---|---|---|---|
| Lamp and luminaire indoor | 25.0 | 44.1 | 48.8 | 49.8 | 50.0 |
| Luminaire outdoor | 50.0 | 68.2 | 73.7 | 74.7 | 75.0 |
| **LED price ($/klm)** | | | | | |
| Lamp | $55.16 | $11.25 | $6.28 | $4.36 | $3.34 |
| Luminaire | $180.88 | $41.81 | $23.69 | $16.55 | $12.73 |

**Table 9 Technological dynamics of LED technology** (Navigant Consulting Inc., 2012a)

The market diffusion is expected to follow the Bass diffusion curve, representing a logistic curve, in which a technology is gradually adopted and the rated of new adopters depend on the installed base, as already tested for other lighting-specific diffusion curve (Navigant Consulting Inc., 2012c).

## The dynamics of the U.S. lightingfacts LED lamps database

The lightingfacts database at the date 12th of November 2012 includes 6,983 LED lamps and 459 firms. The first lamps have been registered the 9th of July 2009, so the database includes 3 years and 4 months. The number of yearly registered lamps has quickly increased over the time, as showed in the following figure

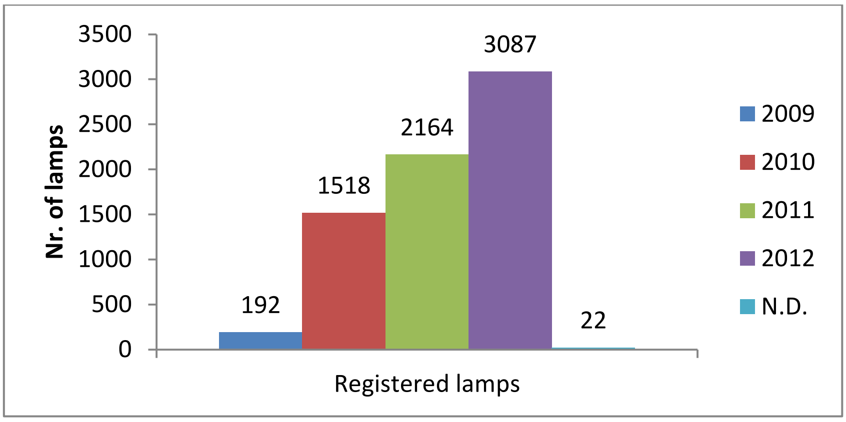


**Figure 4 New yearly registration in the Lightingfacts LED lamps database (own elaboration)**

Lamps are classified according to the type of fixture, as reported in the following table

| Fixture type | N. of lamps | Fixture type | N. of lamps |
|---|---|---|---|
| N.D. | 2 | Refrigerator display case light | 20 |
| Bollard | 18 | Replacement lamp - Decorative | 209 |
| Canopy light | 90 | Replacement Lamp - Directional (MR16) | 483 |
| Cove light | 88 | Replacement Lamp - Directional (Other) | 158 |
| Flood or Spotlight Fixture | 31 | Replacement Lamp - Directional (R20, PAR20) | 207 |
| High-bay and Low-bay fixtures | 131 | Replacement Lamp - Directional (R30, PAR30) | 466 |
| Indoor path/step/rail light | 7 | Replacement Lamp - Directional (R38, PAR38) | 437 |
| Other | 489 | Replacement lamp - Linear T8/T5/T12 | 296 |

| | | | |
|---|---|---|---|
| | | tube | |
| Outdoor area/roadway fixture | 728 | Replacement lamp - Omnidirectional (A Lamp) | 265 |
| Outdoor decorative fixture | 213 | Replacement Lamp – Other | 119 |
| Outdoor path/step/rail light | 118 | Surface-mounted downlight | 88 |
| Outdoor wall pack | 240 | Surface-mounted fixture (other) | 213 |
| Outdoor wall-mounted porch lights | 88 | Surface-mounted or recessed troffers | 313 |
| Parking garage fixture | 186 | Track light | 88 |
| Portable desk lamp | 67 | Under-cabinet or Shelf-mounted light | 294 |
| Recessed downlight | 779 | Wall wash fixture | 52 |
| | | **Total** | **6983** |

Table 10 Lightingfacts database November 2012 (own elaboration). In grey fixtures analyzed in the paper.

The analysis focuses on the replacement lamps, except the decorative and the T-fixture ones, plus the recessed downlight ones, widely used in the U.S. residential market. Table 11 represents the yearly segmented lamp fixtures analyzed in the paper.

| Row Labels | 2009 | 2010 | 2011 | 2012 | Total |
|---|---|---|---|---|---|
| Recessed downlight | 53 | 155 | 278 | 290 | 776 |
| Replacement Lamp - Directional (MR16) | 18 | 136 | 125 | 200 | 479 |
| Replacement Lamp - Directional (Other) | - | 35 | 41 | 82 | 158 |
| Replacement Lamp - Directional (R20, PAR20) | 2 | 46 | 91 | 67 | 206 |
| Replacement Lamp - Directional (R30, PAR30) | 10 | 139 | 172 | 143 | 464 |
| Replacement Lamp - Directional (R38, PAR38) | 3 | 132 | 169 | 133 | 437 |
| Replacement lamp - Omnidirectional (A Lamp) | 2 | 63 | 72 | 128 | 265 |
| **Total** | 88 | 706 | 948 | 1043 | 2785 |

Table 11 Lamps analyzed in the paper. Year 2009 starts from July. Year 2012 includes up to 12th of November

Color accuracy (CRI) increased on average from 81.69 in 2009 to 82.39, with standard deviation reduced in the same period from 5.49 to 3.42. Data segmented by fixtures (see Figure 5) seem to show a process of convergence. Fixtures started with a CRI value above 82 in 2009 (Recessed donwlight, R20-PAR20, R38-PAR38, A-lamp) have decreased the average value around 82 in 2012, instead the other fixtures, starting from a value below 82 in 2009, have increased around such value. Excluding year 2009 due to the low number of lamps registered, all the fixtures show a reduction of standard deviation value, except the recessed downlight, which slightly increases from 3.3 to 3.8. It seems to indicate not only a convergence among the different fixtures, but a convergence within each fixture too.

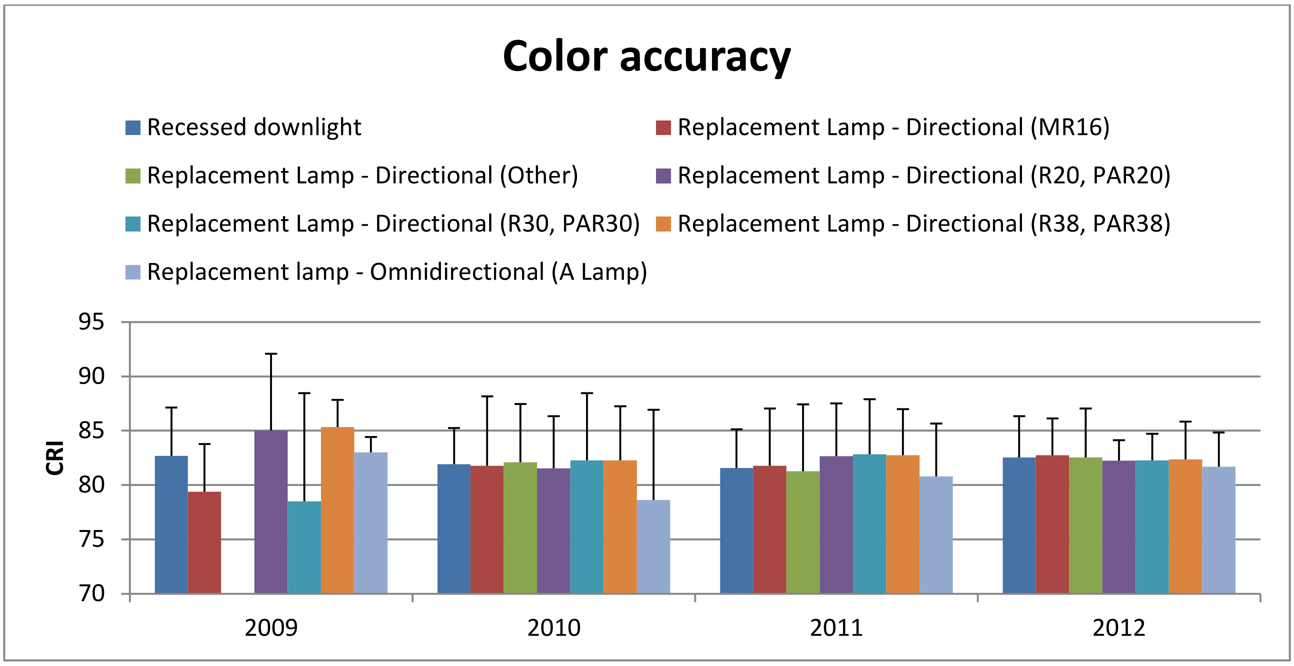


**Figure 5 Color accuracy dynamics in the lightingfacts database. Sample n=2,785 lamps (own elaboration).**

Energy efficiency (lumens for watt) increases from 39 in 2009 to 59.6 in 2012. In the period 2010-2012, all the fixtures have showed an increase between 20% and 35%. Standard deviation increases from 8.73 in 2009, to 9.83 in 2010 and 11.18 in 2012. Fixtures show different standard deviation patterns, with 3 of them showing relevant increase, and the other 4 slightly decrease. Figure 6 indicates such facts.

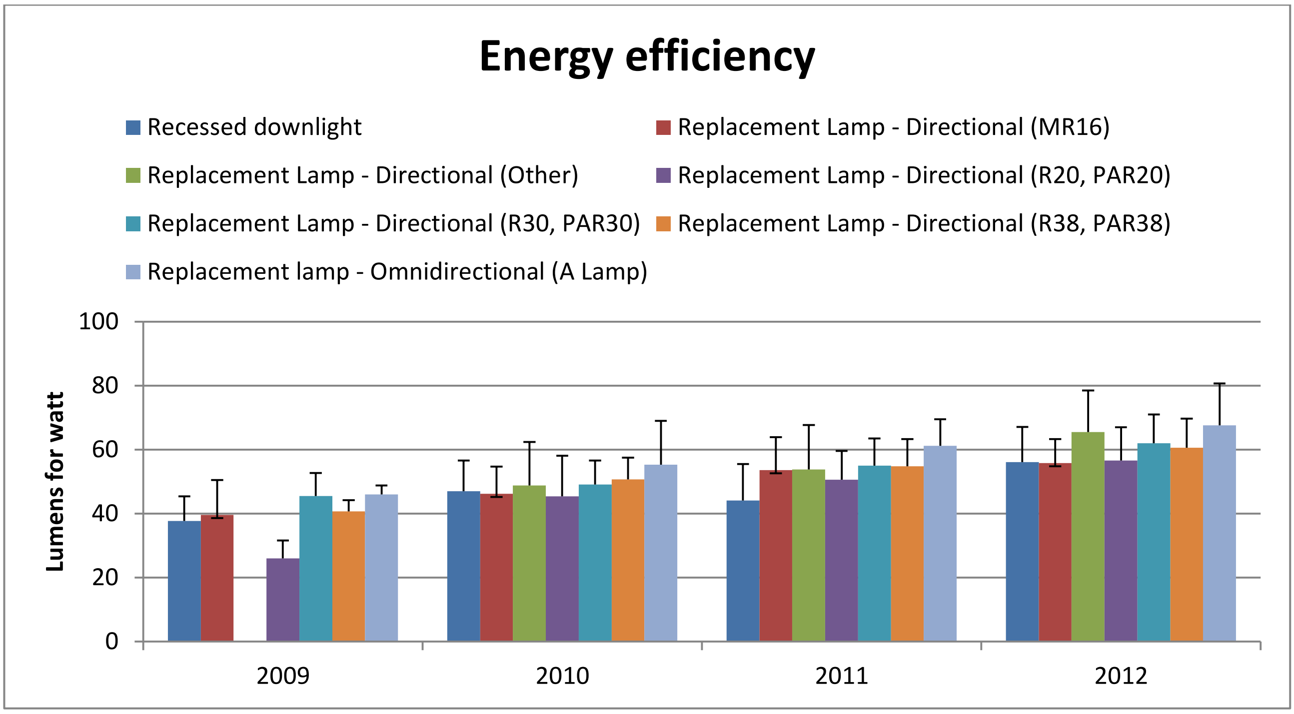


**Figure 6 Energy efficiency dynamics in the lightingfacts database. Sample n=2,785 lamps (own elaboration)**

Increasing of efficiency can lead to different output: an increase of the average quantity of light emitted by a lamp, or a reduction of the average wattage used. Figure 7 shows the dynamics of lighting output in terms of lumens, whereas Figure 8 shows them in term of lighting power (wattage).

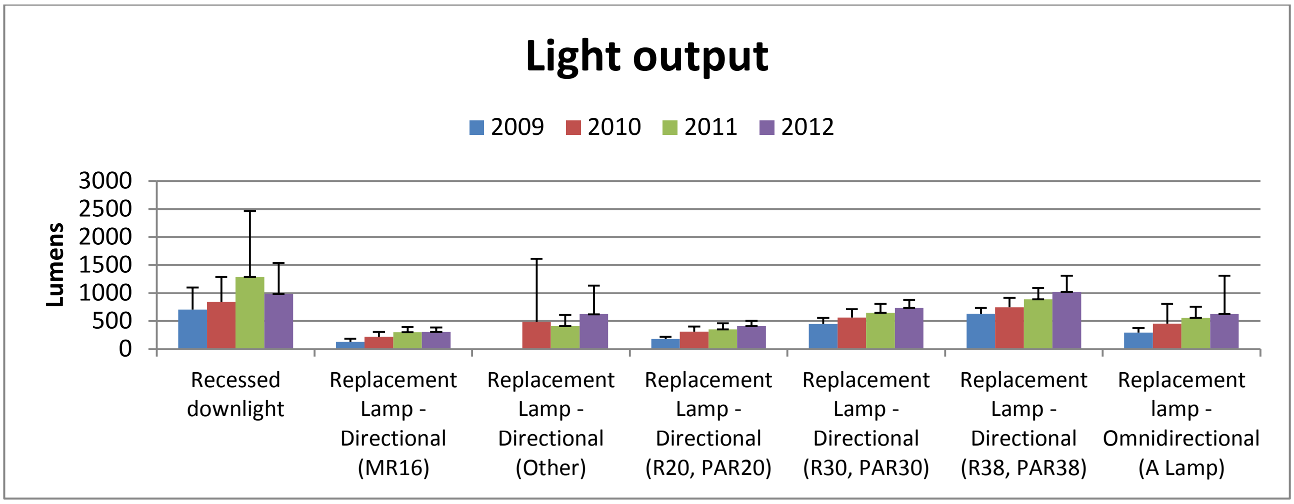


**Figure 7Lighting output dynamics in the lightingfacts database. Sample n=2,785 (own elaboration)**

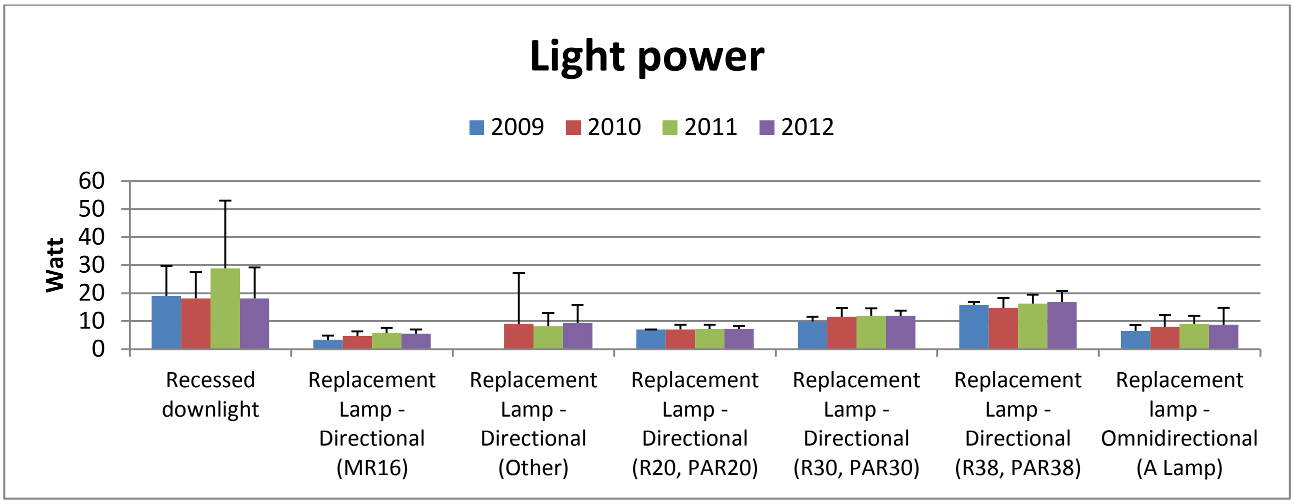


**Figure 8 Lighting power in the lightingfacts database. Sample n=2,785 (own elaboration)**

Lighting output increass of 27% on average in the period 2010-2012, whereas lighting power increases of 5% in the same period. It seems that the +22% average efficiency improvement has been added to the +5% in average energy wattage to allow the +27% of lighting output increase. Considering that the average wattage installed in the A-type U.S. residential market is 64 watt for incandescent bulb and 17 for CFL one, it means that the average lumens installed is around 900-1000 for each lamp. It seems that efficiency is mainly used to catch incandescent bulbs, in terms of lighting quantity as also showed by the recessed downlight fixture, which is the only one to show a decrease in the last year from 1,287 lumens of 2011 to 978 in 2012.

The last dimension is represented by the lighting color, as showed in Figure 9

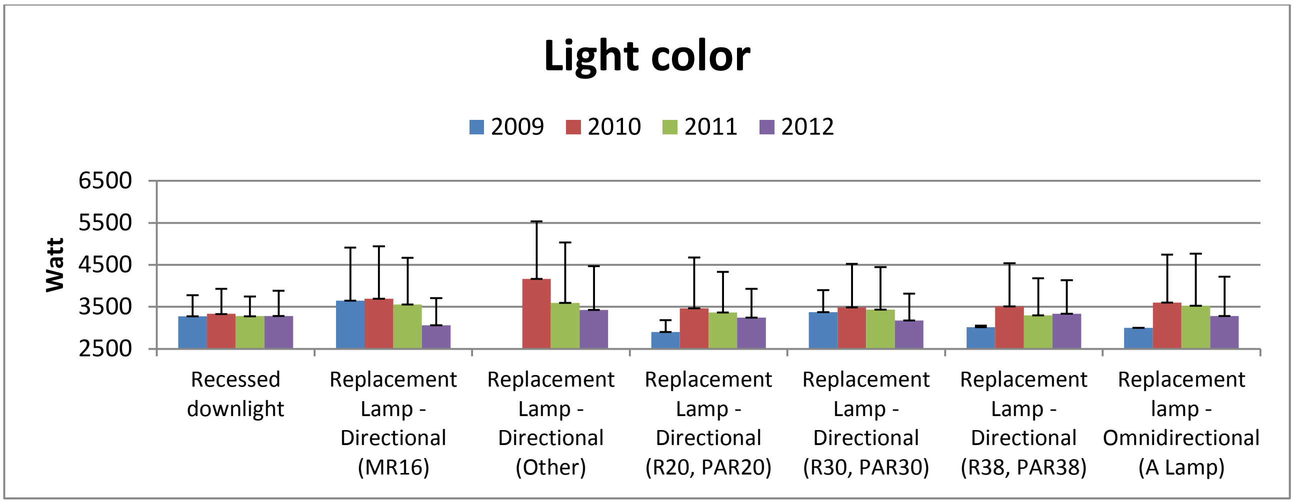


**Figure 9 Lighting color in the lightingfacts database. Sample n=2,785 (own elaboration)**

Data seems to indicate that lighting color converges around 3,300 Kelvin, defined as soft warm, a medium value between 2,800 incandescent bulb, and 3,500 of a warm fluorescent. Also standard deviation shows a reduction from 1,056 in 2010 to 740 in 2012.

## The results of the survey

210 firms representing 2,785 lamps in the lightingfacts database have been included in the LED lighting survey. The sample shows a predominance of small firms, with a mean of 13 lamps, mode of 1 and first quartile of 2, median value of 5, and third quartile of 13. The distribution shows few very small lamps, with one (Philips) having almost 10% of the share, and the first 20 firms representing the half of the lamps sample.

The survey started in the second half of December 2012. At the 17$^{th}$ of December, 40 firms have been contacted, of which 2 have already answered, 4 have accepted to participate and 1 has refused.

## The discussion of the hypotheses

The hypotheses will be discussed as soon as the survey will be closed and answers analyzed.

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