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# Non-disruptive regime changes—The case of competing energy efficient lighting trajectories

Simone Franceschini[a,*], Floortje Alkemade[b,c]

[a] Technical University of Denmark, Department of Management Engineering, Produktionstorvet 426, 2800 Lyngby, Denmark
[b] School of Innovation Sciences, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[c] Innovation Studies, Copernicus Institute of Sustainable Development, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands

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ABSTRACT

Technologies within the same industry are expected to follow similar patterns of innovation, and when the dominant patterns change, this is often expected to have disruptive effects on the industry. However, the three most recent lighting technologies (fluorescent, compact fluorescent, and LED) show different patterns of innovative activities despite similarities in the determinants of innovation; and we observed multiple technological regimes within the lighting industry. Furthermore, we observed changes in these innovative patterns without widespread disruptive effects. While FL and LED quickly improved once they were introduced, CFL struggled for decades. We present an historical case study of the emergence and development of the different regimes and we present possible explanations to be found in market structure and selection criteria. The analysis shows the important role for policymakers in stimulating new technologies in industries with undesirable Mark II pattern through the influence of all the dimensions of the technological regimes.


## 1. Introduction

Policy makers are increasingly interested in new eco-efficient lighting technologies to decrease energy consumption, reduce energy costs, and create new business opportunities (European Commission, 2011). In the previous century, the fluorescent light (FL) and its residential application, the compact fluorescent light (CFL), were considered the most promising future lighting technologies, but today attention is shifting towards light emitting diode (LED) technology (Chappin and Afman, 2013). In order to adequately support the development and diffusion of eco-friendly technologies, insight into their specific innovation trajectories is necessary (Alkemade et al., 2011; Quitzow et al., 2014). This insight is especially needed in the case of alternative lighting technologies because their development seems to deviate from the patterns predicted by theory.

More specifically, the literature describes how technologies within an industry usually develop under the same *technological regime* (Nelson and Winter, 1982), and display similar sectoral patterns of innovative activities (Breschi et al., 2000; Pavitt, 1984; Malerba and Orsenigo, 1993, 1996). These similarities arise because the main determinants of innovation, such as technological opportunities, the appropriation of innovations, the cumulativeness of technological advances, and the properties of the knowledge base, are similar for all firms within an industry (Malerba, 2002). In addition, theory predicts

* Corresponding author. Present address: University of Sassari, DISEA, Piazza Università 21, 07100 Sassari, Italy.
*E-mail addresses:* simonefranceschini@gmail.com (S. Franceschini), F.Alkemade@tue.nl, F.Alkemade@uu.nl (F. Alkemade).

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that changes in these patterns arise mainly as a result of major (technological) discontinuities that disrupt the industry. As we demonstrate in this paper, the three alternative lighting technologies, FL, CFL, and LED, are characterized by different patterns of innovative activities despite similarities in the determinants of innovation; and we observed multiple technological regimes within the lighting industry. Furthermore, we observed changes in these innovative patterns without widespread disruptive effects on the industry.

The three alternative lighting technologies have many common characteristics as they were developed through long-term intensive R&D processes in an oligopolistic context in which General Electric (GE) played a leading role, especially during the R&D phase. The similarities among FL, CFL, and LED suggest that these technologies developed within the same or a similar technological learning regime, and we would therefore expect similar patterns of innovative activity (Malerba and Orsenigo, 1997; Pavitt, 1984). However, once introduced to the market, FL and LED quickly improved through learning and became dominant, while CFL experienced slow progress and struggled for decades. Observing these differences between expected and actual patterns of diffusion, led to our main research question: *How can we explain the observed differences in the innovative patterns of FL, CFL, and LED despite similarities in the main determinants of innovation for these technologies?*

The paper is organized as follows: Section 2 describes the theoretical framework, and Section 3 gives a brief description of the methodology. Section 4 presents the history of the alternative lighting technologies. Section 5 discusses the different technological regimes, and Section 6 provides conclusions.

## 2. Innovation dynamics and profit-driven industry evolution

Profit is the main driver of a firm's innovative efforts (Jacobides and Winter, 2007). Schumpeter pointed out that firms develop both short-term and long-term profit strategies to seize the value of innovation, commonly defined as a new combination of elements with a final value superior to the sum of the value of the individual elements (Schumpeter, 1934). Short-term profit strategies aim to seize current profits in the market through decisions about price and quantity (Jacobides et al., 2006), and thus focus on protecting the firm's current products and market share (Teece, 1986). Long-term profit strategies focus on the generation of novelties in a context of uncertainty (Langlois, 2007) and the creation of new profit flows. This strategy corresponds to the well-known Schumpeterian concept of creative destruction that refers to an innovations' disruptive effect on profit flows (Cantwell, 2000; Lundvall et al., 2002).

In order to develop its portfolio of short- and long-term strategies, a firm considers both the potential value of a future innovation, the actual chance of capturing this value, and the innovation's impact on current profit flows. This relation between short-, and long-term strategies leads to a strategic dilemma for the firm: on the one hand, a consistent flow of short-term profits is necessary to generate resources to sustain long-term strategies, but on the other hand, new innovations may negatively affect short-term profits, causing firms to shy away from developing them. Since firms have heterogeneous capabilities developed through cumulative patterns (Cantwell, 2000; Jacobides et al., 2012; Mowery, 2010), they develop complex, individual, and time-dependent (Jakopin and Klein, 2012) innovation strategies.

Schumpeter captured this complexity of innovation activities in different markets in two stereotypic market models, often labeled as Mark I and Mark II (Breschi et al., 2000). The Mark I model highlights the role of newcomers who develop innovations that disrupt the incumbents' short-term profits (Chandy et al., 2000). As soon as these newcomers stabilize the novelties they have brought to the market, they focus on short-term profits and become the new incumbents, creating space for other future newcomers (Andersen, 2012). Management literature, and previous case studies, have identified the pivotal role of entrepreneurs in this process (Schumpeter, 1934; Venkataraman, 1997; Tilley and Parrish, 2009; Hockerts and Wüstenhagen, 2010; Hekkert et al., 2007; Markard and Truffer, 2008). Incumbents are often regarded as playing a more defensive role in sustainability transitions. Garud (1994) describes how incumbents often reject new technologies "because of the strength and inertia built into their existing technological". The competences of incumbent firms developed within this existing technological paradigm are geared towards the old technology (Penrose, 2016; Christensen, 1997; Anderson and Tushman, 1990). Furthermore the small niche markets that help to shape the new technology are often not financially attractive to large firms (Christensen, 1997). However there also exists empirical evidence of incumbent firms that are able to adequately adapt to radical technological change and competence-destroying innovations (Arend, 1999; Hill and Rothaermel, 2003; Afuah, 2001).

The Mark II model highlights the role of stable oligopolistic incumbents as main innovative players (Mowery, 2010). In this mode incumbents are dominant because they can exploit short-term profits and thus sustain new innovative efforts. Hence, market power is a means and not the reason for incumbents' dominance and in both models the locus of competitiveness is innovative capacity. Recent literature has proposed combining Mark I and Mark II patterns into new market models in which technological evolution is depicted through the interaction of small and big players who mutually benefit from their different capabilities (Andersen, 2011).

The literature about the determinants of innovation and technological regimes has further specified the Schumpeterian innovative patterns (Malerba and Orsenigo, 1997), thereby connecting the Schumpeterian patterns of innovation to the knowledge-base characteristics that occur at the sectorial level. A technological regime is defined as the combination of four determinants: opportunity—how easy it is to innovate—, appropriability—the possibility of extracting profits from innovation—, cumulativeness of knowledge—the extent to which new knowledge builds on earlier knowledge—, and the knowledge base—the nature and means of knowledge—, and their combinations define the different Schumpeterian patterns. The determinants of innovation have been used to explain the different Schumpeterian patterns of innovation (Cohen and

Levinthal, 1990; Malerba and Orsenigo, 1990, 1993, 1997). High opportunity has been associated to market turbulence and instability, because it attracts newcomers, and high appropriability is expected to return stable and concentrated market structures, because successful innovators are able to preserve competitive advantages. High cumulativeness is expected to result in persistency of innovators and, so, in more stable market structure. When the innovative pattern in an industry changes from Mark I to Mark II or vice versa, this is often caused by major technological discontinuities or changes in the technological regime. Such technological discontinuities, or paradigm changes (Dosi, 1982) can have disruptive effect on incumbent firms when the new technologies require new technological competencies (Christensen, 1997). When the technologies are embedded in larger technological systems, as is often the case with infrastructure dependent technologies, the disruptive effects can extend beyond the industry and lead to transformations of socio-technical systems (Perez, 1983; Freeman and Perez, 1988; Kemp, 1994; Kemp and Soete, 1992). In the case of lighting technologies we did however observe changes in innovative patterns with only minor disruptive effects on the industry and its broader socio-technical context.

## 3. Methodology

The unit of analysis is the innovative pattern that characterizes the development of the three alternative lighting technologies. We propose a qualitative historical case study based on a content analysis of the available academic and non-academic documentation produced in the last century. We used a snowball method starting from the works of Bijker (1995), Loebner (1976), and Rogers (1980). Bijker (1995) provided an in-depth study of the birth of the fluorescent light, Loebner provided an overview of the early development of LED, and Roger wrote a report for the US congress in which he depicted the long-term evolution of the US lighting industry and market. Starting from these three core references, we identified further relevant literature, and actors. We collected several types of documentation, such as laws and regulations, companies' internal and external documents, and interviews, as well as studies and reports from both the scientific and the grey literature. We scanned the documentation for information about firms' strategies and about the four dimensions of our analysis: opportunity, appropriability, the character of knowledge base and its degree of cumulativeness. We narrowed the scope of the analysis to the US market for two reasons. First, we found that the US General Electrics (GE) Company played a pivotal role in the development of each of the major lighting technologies addressed in this paper, with the US lighting market as its main market. Second, the US lighting market is well documented in English allowing us to include sources dating back to the beginning of the 20th century, which we could not fully do for the European context where the major lighting players were Phillips (Dutch) and Osram (German).

## 4. The history of competing lighting technologies

This section describes the observed innovative patterns and strategies of innovation of the most important alternative lighting technologies developed in the last century (Edison Tech Center, 2013). The analysis is divided in four periods. The first describes the lighting market at the beginning of the 20th century, when the first fluorescent tube was announced. The second describes the period 1940–1970, when the fluorescent tube diffused and the first visible LED was announced. The third describes the period 1970–1990, when the CFL started entering the residential market, and LED diffused in complementary markets. The last period, starting in the 1990s, describes the birth of the LED lighting market, and the final phasing out of the incandescent bulb.

### *4.1. The quasi-monopolistic lighting sector at the beginning of the 20th century*

The incandescent bulb was the sole electric lamp present in the lighting market at the beginning of the 20th century. At that time the fluorescent technology was not yet a competitor, although the possibility of producing light through fluorescence was already known in the second half of the 19th century and the first prototypes appeared at the beginning of the 20th century, based on the work of Hewitt and Germer (Bright and Maclaurin, 1943).

Similarly for LED, Round at Marconi Labs reported the "*curious phenomenon*" (Schubert, 2003) of cold light emission from a diode while working on a cat's whisker detector for the development of the radio in 1907. In 1920, Losev, a researcher at Russia's Central Radio Laboratory (CRL), reported a detailed description of electroluminescence and potential uses for "*fast telegraphic and telephone communication, transmission of images and other applications*" (Daukantas, 2012 p. 34), but Losev's death during the siege of Stalingrad in 1942 prevented him from further developing his intuition. Fluorescent and diode lights represented a fundamental shift in the scientific history of lighting, because, for the first time in human history, incandescence (lighting by heating) was no longer needed to generate light (Lowry, 1953).

At that time fluorescent technology was already considered a potential lighting technology although not yet stable and mature, while the light emission from diodes was no more than a curious side-effect associated with the radio amplifying properties of semiconductors and it was not further investigated for several decades (Loebner, 1976). As result, incandescent lighting technology was the only reliable and mature electric lighting technology. In fact, in 1937, incandescent lamps had a share of nearly 96 percent of the electric lighting market (Bright and Maclaurin, 1943). The US-based firm, General Electric (GE), directly controlled 59.3 percent of the incandescent light market, and indirectly almost 86.6 percent through its license program (see Table 1).

**Table 1**
Share of US market for incandescent lamps in 1937. Source (Bright and Maclaurin, 1943).

| Firm | Market share (%) | GE license classification[a] |
|---|---|---|
| General Electric Co. (GE) | 59.3 | Licensor |
| Westinghouse Elec. & Manuf. Co. (WE) | 19.0 | A-type |
| Sylvania Elec. Prod. Inc. | 4.4 | B-type |
| Consolidated Elec. Lamp Co. | 2.8 | B-type |
| Ken-Rad Tube and Lamp Co. | 1.1 | B-type |
| Other 20 domestic firms | 8.8 | Unlicensed |
| Importers | 4.6 | Unlicensed |

[a] See on text for license explanations.

The A-type license granted a firm the right to sell any kind of lamp in any quantity, whereas the B-type only granted the sale of large incandescent lamps in limited quantities (Bright and Maclaurin, 1943). Independent firms and importers accounted for less than 14 percent of the market. In addition, GE strengthened its position by: (i) establishing mutual agreements with major foreign lamp producers who agreed to sell lamps exclusively in their own countries; (ii) maintaining its unique position as the only firm to produce all necessary parts in-house, causing other firms to depend on GE or other external suppliers; (iii) joining with Westinghouse (WE) to promote a lighting fixture association of hundreds of firms to control incandescent bulbs fixtures; and (iv) creating partnerships with energy utilities to develop electric turbines and generators. In this period, the US lighting market was a clear example of a Mark II quasi-monopoly market with GE playing a leading role.

### *4.2. 1940–Development of the fluorescent light market and of the visible LED*

GE was interested in the work of Hewitt and Germer on the fluorescent light and decided to acquire the first patents and to hire Germer to further develop it (Peter et al., 2013). Their strategy was to reach a stable, reliable development stage before commercializing the innovation (Bright and Maclaurin, 1943). Despite this attempt to keep the development a secret, the first fluorescent lamp was exhibited at 1938 New York World's Fair, after engineers and other specialized actors, which knew high-efficient fluorescent prototypes were in development, insisted that they would be demonstrated (Bright and Maclaurin, 1943). The interest in the new technology was the result of three main drawbacks of the successful diffusion of the incandescent bulb (Inman, 1939): (i) an increase in the cost of electricity; (ii) problems with electrical wiring overload; and (iii) an increase in indoor temperature because of heat dissipation from incandescent bulbs. These problems were especially critical for non-residential users which had an intensive use of electric light and mostly during daylight hours, when the electric grid was working at full capacity and indoor temperature was already higher. The first fluorescent lamps met stakeholders' expectations about energy efficiency as they already achieved an efficacy of 30 lumens/watts, compared to 14 lumens/watts of the incandescent bulb, and an average expected life of 2500 h, compared to 1000 for the incandescent bulb.

Following its success at the fair, GE and WE separately announced the market introduction of the new fluorescent light in 1938, and the first 200,000 lamps sold quickly, even though the price of a lamp was about 6x-15x higher than the price of an incandescent lamp of the same wattage. But GE and its partners considered the new fluorescent lamp a risk (Bright and Maclaurin, 1943; Rogers, 1980) and kept their focus on incandescent technology while continuing to develop the fluorescent light.[1,2] GE worried that an infant technology would hamper its image of affordability and would open space for competitors. Energy utilities were concerned that more energy efficient lighting solutions would harm their profits[3] (Bijker, 1995 p. 227), and lighting-fixture manufactures worried about the technical changes required by shifting from a bulb to a tube shape.

In 1940, Sylvania, a US lighting manufacturer that started its business in 1901, decided not to acquire a GE B-type license for the FL, but rather to develop its own version (Bijker, 1995 p. 233). This strategy was possible because many GE core patents expired and GE's licensing system was ruled a violation of anti-trust laws (Rogers, 1980). As a result, GE ended its agreement with WE, and many patents were licensed to competitors free of charge. GE's share in both the fluorescent and incandescent markets fell, and other players began to develop their own lamps and parts (Rogers, 1980). As a result, compared to a 1937 market share of 4.4 percent for the incandescent bulb, Sylvania quickly obtained 20 percent of the new fluorescent market, becoming GE's first relevant competitor. In reaction, GE and WE increased their efforts in the new fluorescent market (Bright and Maclaurin, 1943).

The market quickly grew from 200,000 fluorescent lamps sold in 1938–79.1 million in 1947 (Bright, 1949 p. 410), especially in the office and retail markets. During the 1950s, fluorescent lighting technology improved considerably: Manufacturing costs decreased and efficiency increased. In 1951, fluorescent lamps produced more lighting, expressed in lumens per hour, than incandescent lights (Smithsonian Institution, 2014a). However, the popularity of the fluorescent tube did not

[1] "*The fluorescent Mazda lamp should not be presented as a light source which will reduce lighting costs.*" GE statement of policy, 1939 (Bright, 1949 p. 404).
[2] "*We will oppose the use of fluorescent lamps to reduce wattages.*" WE internal policy (Bright, 1949 p. 404).
[3] "*I am very, very much disturbed over the utility reactions which I am sure we are going to have as soon as we announce the longer, larger and higher wattage fluorescent lamps.*" Internal memorandum of the GE lamp department to the GE lamp department executives (Bright, 1949 p. 402).

reduce overall energy consumption (Fouquet and Pearson, 2006) because in order to appease utility companies, fluorescents were not promoted as replacement of less energy efficient incandescent bulbs, but as the opportunity to expand existing lighting applications.

In that period, diode research continued outside the lighting market. Bell Labs was working on more energy efficient telephone switches, replacing vacuum tubes with semiconductors. In collaboration with Signal Corps Laboratories (SCL), a part of the US Army, the two organizations better explained the relationship between amplifying and lighting properties in the 1950s. At that time the industry's priority was to develop electroluminescent, solid-state devices to substitute the energy-hungry cathode ray tube in televisions (Dempewolff, 1962). Even unsuccessful R&D efforts focused on non-LED materials contributed to a deeper understanding of electroluminescence, knowledge that was later essential to develop LEDs.[4] Following these failures, only a few large firms had enough resources to continue LED research. Among them was GE, whose rectifier department announced a major breakthrough in 1962 with the invention of both the first infrared and the first visible red LEDs. GE commercialized the first visible red LED in the same year. As Holonyak, the inventor of the first visible red, explained, it was the GE rectifier department and not the lighting department that developed and announced this major breakthrough, because LED was considered a technology for the electronics market. Only after its invention, did the GE lighting department become interested in LED technology.[5]

By 1962, important actors from the electronics industry entered the new technology and were exploring technological options closest to their existing knowledge bases, indicating the cumulativeness of the knowledge base; Hewlett-Packard (HP) developed an extensive research program to investigate 17 different semiconductor materials, and then focused on Gallium arsenide phosphide (GaAsP) (Loebner, 1976). In 1962, HP started a cooperation with Monsanto, the leading supplier of GaAsP, to develop an LED alphanumeric display (Ashrafi, 2005; Borden and Pighini, 1969). The collaboration did not last long, as both firms were concerned about becoming too dependent on one another. Monsanto produced the first commercial numeric display based on LED, the MAN-1A, and HP closely followed. Numeric displays were the first early market, and soon IBM introduced LED-based displays in CPU working activity indicators. Other markets followed, such as wristwatches, calculators, phones, optocouplers, and optical mice (Haitz and Tsao, 2011). The birth of the new LED display led to the development of new competences, and spurred new alliances (e.g., Busicom and Intel), spin-offs (e.g., Litronix from Monsanto), and the entry of newcomers from other markets (e.g. HP, Hughes Aircraft, National Semiconductor, Fairchild, and Texas Instrument).

### *4.3. 1970–Increased focus on environmental performance, the CFL and the first LEDs*

As result of the increasing performance of fluorescent technology, incandescent lamps disappeared from the non-residential lighting market. Starting with 42 million units in 1945 (5.3 percent of the sold incandescent lamps), the sale of fluorescent lamps rose to 284 million in 1974 (18.5 percent) (Rogers, 1980). However, in the same period, the sale of incandescent lamps rose from 794 million in 1945–1,532 million in 1974, mainly because of the growth of the residential market, the largest in terms of installed number of bulbs, that was still dominated by the incandescent technology. In fact, only a few residential consumers were interested in bulky, flickering and expensive CFLs that did not fit with the majority of existing fixtures.

GE announced the first spiral-shaped compact fluorescent light (CFL) in 1976, but decided to shelve the invention because of its high production costs[6] (Kanellos, 2007), while working on its further development. The secrecy of the project is confirmed by the 1980 U.S. national lighting report, in which the CFL is not mentioned in the list of lighting inventions up until 1978 (Rogers, 1980). Developments however continued: Philips introduced the SL lamp, the first non-spiral CFL lamp, in 1980 (Kanellos, 2007) at a price of 16 times that of a standard 100-watt bulb. The SL lamp had an efficiency of 50 lm/watt, a rated lifetime of 5000 h. Later GE overcame a technological hurdle to produce a dimmable fluorescent lamp in 1988. Since the 1980s, production costs further decreased (Ellis et al., 2007; Iwafune, 2000; McDonald and Schrattenholzer, 2001), resulting in a CFL price close to the price of the traditional incandescent bulb.

Meanwhile, LED researchers sought to develop the other primary colors, blue and yellow, in order to produce the full light spectrum (Borden and Pighini, 1969). In 1970, Craford, Holonyak's first graduate student, announced the invention of the first yellow LED along with an improved red LED at Monsanto Labs, and Bell Labs announced the first green LED (Rostky, 2001). Creating a blue LED was most challenging, because blue lies in the opposite light spectrum of red. RCA seemed to be closest to developing blue LEDs when it announced a bright violet LED in 1972, but the company collapsed in the following years. The production of a new flat TV that could be hung on a wall like a painting had driven RCA's efforts. Again, as with earlier

[4] "*Schon, a most prominelnt ZnS luminescence theorist, established two fundamental criteria which no contemporary LED designer can ignore . . .*"(Loebner, 1976 p. 685), and later, "*We expected that the results [of LED and non-LED research]. . . would aid each other and increase fundamental understanding of electroluminescence in both materials*" (Loebner, 1976 p. 686).

[5] As Holonyak stated, "*. . . and even though I'm getting some support from . . . the Rectifier Department, it's taking me in the direction of something that will be a light emitter, which won't be as useful to him [the rectifier department] as it will be to the Lamps Department. That Lamps Department is now working out arrangements with other people to get back in this, because the LED has become really a lamp, and is beginning to do major things. And the Lamp Department at GE can no longer ignore that*" (Ashrafi, 2005).

[6] Ed Hammer, leading GE scientist working on fluorescent solutions, remembered, "*I was told it could be a little better than an incandescent bulb, but that was about it. . and the new lamp would have required 25 million of investment to be produced*" (Kanellos, 2007).

attempts in the 1950s, replacing the cathode tube was the main reason for developing electroluminescence applications. In the 1970s, Monsanto, a pioneer in LED technology, quit the growing business and sold its activities to General Instruments (Monsanto, 2012). LED technology diffused in several lighting markets in which the full RGB spectrum was not needed, such as disco-lighting systems (the first "Saturn I–IV LED lighting systems"), exit signs, automobile central brake lamps (Daukantas, 2012; Moore, 1999), and traffic lights.

In this period, the 1970s, energy efficiency became increasingly important on the US political agenda. In 1965, the first major power blackout occurred in the northeast of the United States. Although the main cause was a human error, the event stressed the capacity problems of the power grid and of energy efficiency as a potential strategy to address these problems. Two other major events that increased influence the involvement of policy in the energy agenda were the 1969 Santa Barbara oil spil and Rachel Carson's best-selling book Silent Spring, culminating in the 1970 National Environmental Policy Act (NEPA). Although NEPA did not specifically address the lighting, it indicated the need to connect the policy-making process to environmental issues. In addition to environmental concerns, the oil and energy crises in the 1970s increased concerns about energy security. This resulted in several energy policies and acts aimed to increase efficiency and conservation, such as the 1973 Project Independence, the 1975 Energy Policy and Conservation Act, the 1977 National Energy Programme,and the 1980 Energy Security Act. U.S. President Carter created the Federal Energy Administration (FEA) in 1974, which successfully merged with the newly created US Department of Energy (DOE) in 1977, and declared a national energy supply shortage in 1979, Both institutions had the specific aim to address the 1970s energy crisis and the 1973 oil crisis. As recognized by the same USDOE (2006), the commitment to increase the efficiency of the energy sector spurred industry efforts to create residential fluorescent solutions. The energy efficiency agenda also mobilized other relevant stakeholders that represented important political lobbies to promote new policies for energy efficiency, among which the foundation of the Alliance to Save Energy (ASE) in 1978 and of the American Council for an Energy Efficient Economy (ACEEE) in 1980.

### *4.4. 1990–the maturity of the CFL and the birth of the white LED*

In the 1990s policy activities that promoted energy efficiency intensified, and the lighting sector was one of the targets of policy intervention. The 1992 Energy policy act mentioned the need of developing energy efficient light. In the same year, US EPA introduced ENERGY STAR as a voluntary labeling program to promote energy-efficient products. In 1993, US the Government approved the Climate Change Action Plan which led to the 1993 Green Light Programme, which encouraged the use of energy efficient lighting. In 1997, the US EPA expanded the ENERGY STAR® labeling program to residential light fixtures, and, in 1999 to a specific labeling program for screw-based CFLs (Calwell et al., 2002). In that period, the Pacific Northwest National Laboratories (PPNL), a branch of the U.S. Department of Energy, introduced a project to promote the most promising CFLs, which helped many small overseas companies to advertise high-quality CFLs in the U.S. market. In addition, the contextual EU anti-dumping tariffs of up to 75 percent imposed on Asian CFL manufacturers (Calwell et al., 2002) encouraged many of those firms to shift their focus towards the U.S. market and increased competition.

The policy intervention did not stop with the new millennium as demonstrated by the 2000 Energy Policy and Conservation act, and the 2001 National Energy Policy. In 2006, 32 ENERGY STAR CFL programs were in place, totaling $50 million. In 2009, these programs had increased to 109, totaling $252 million. In addition, lighting actors showed a relevant lobbying activity. In 2007, Philips launched the "Lighting Efficiency Coalition" in collaboration with very influential other energy and environmental stakeholders like the Alliance to Save Energy, the American Council for an Energy Efficient Economy, Californians Against Waste, the Natural Resources Defense Council, and the Earth Day Network. The coalition had to purpose to propose legislative measures to incorporate high-efficiency lighting technologies in homes and offices. Simultaneously, the National Electrical Manufacturing Association (NEMA) supported the ban proposal for non-efficient energy lamps.[7]

Among the different US states, California was a front-runner in the CFL market. Following the serious reduction of the state's energy reserves and the subsequent 173 days of energy emergency in 2001, California launched several initiatives to boost the CFL residential market. The multi-year California Residential Lighting and Appliance Program began in 1999 and aimed to reduce the price of CFLs and create a competitive market. An example of the program's activities was a training program in new CFL solutions for 180 retail store employees. The Californian government also directly distributed 1.9 million CFL lamps to end users, advertised the CFL's benefits in the media, and increased electricity tariffs to stimulate market formation for the more energy-efficient lighting technology (USDOE, 2006). As result of the combination of state and federal measures, state programs distributed more than 10 million CFLs only in 2001 alone (XENERGY Inc, 2002). In the period 2006–2008, Californian authorities launched the Upstream Lighting Program (ULP) to reduce energy demand and 92 percent of the program's overall savings were achieved through CFLs (Kema Inc., 2010). In addition, to prevent the use of incandescent lamps under the new building code,high efficiency lights were not allowed to have medium sized screw-base sockets, and the sale of incandescent lamps with GU-24 bases was banned (California, 2008).

As result of these energy efficient efforts, new CFL lamps the CFL appeared in the US market. For example Litetronics commercialized the first spiral-shaped CFL in 1995 (Litetronics, 2010; Smithsonian Institution, 2014b). In California alone,

[7] "*The entire discussion of phase out of least efficient general service light bulbs' has been at the industry's initiative. This is not a case of manufacturers dragging their heels, but of leading the way. New standards-setting legislation is needed in order to further educate consumers on the benefits of energy-efficient products*." Kyle Pitsor, NEMA Vice-President, US Senate Hearing 110–195 on 12th of September 2007.

CFL market share quickly rose from 1 percent in the final quarter of 2000, to 8 percent at the beginning of 2001 (Calwell et al., 2002; Iwafune, 2000), and to 20% in 2009 (Swope, 2010). Only one decade afterwards, almost 100 ENERGY STAR manufacturing partners were active on the overall U.S. market, producing 1600 unique CFL lamps. Including repackaging initiatives, the market included 234 brands and over 4,500CFL products (D and R International, 2010).

The fast growth of the CFL market also resulted from the increasing compatibility and interoperability, with existent lighting fixtures due to standardization, even though at the beginning of the 1990s, CFL lamps were still incompatible with about 60% of residential lighting fixtures (USDOE, 2006). Interestingly, this lack of standardization was partially used by policy-makers to promote lighting standards that were incompatible with the Edison traditional socket, as in the California Title 24 case. Standardization with traditional lighting fixtures also occurred through the miniaturization of old CFLs. Most manufactures moved from a single U-shape tube design, to double or triple U-shaped tubes (Iwafune, 2000). Standardization of the description of light quality was also needed as consumers could not easily understand and evaluate the lighting properties of CFL lamps. While for the incandescent light, wattage was the only relevant measures, the CFL required consumers to understand other concepts such as lumens, color rendering index (CRI) and the correlated color temperature (CCT). This resulted in consumers' dissatisfaction and the need to develop lighting labels that could help users to compare the fluorescent lamps with incandescent lamps.

At the same time, LED research led to important breakthroughs. In 1989, US-based Cree company announced the first blue LED, and in 1993 Japanese Nichia announced the first high-bright blue, the result of a research project at Nagoya University that had started in 1981 (Daukantas, 2012). Enable by the invention of the high-bright LED, Nichia announced the first white LED in 1996, illustrating the important role the relevant role of new Japanese players. The scaling up of LED production in the 1980s and 1990s enabled a new, more advanced manufacturing process called Metal Organic Chemical Vapour Deposition (MOCVD). Although this process, which had been known since the 1960s (Grodzinski et al., 1995; Samsung, 2004), was very expensive and sensitive to environmental conditions, it was the only option for mass production of very pure LED components, an essential condition to develop high-bright LEDs (Daukantas, 2012; Shimizu and Kudo, 2011). In the 1990s, the MOCVD technique enabled the production of 25 lumens/watts for red and yellow LEDs, and six lumens/watts for blue and green LEDs, where other processes could achieve only about one lumen/watt (Grodzinski et al., 1995).

The availability of all primary colors opened op many new potential applications for LEDs. HP and Philips initiated a collaboration to investigate potential applications for the white LED in 1994, and created a joint venture two years later. At that time, LED technology was expected to achieve an efficiency of 50 lumens/watts by 2010 and consequently was not considered a solution for the general lighting market because fluorescent technology was more efficient (Haitz and Tsao, 2011), although LED were considered to have potential applications in specific lighting markets.

This perspective drastically changed in 1999 when HP and Sandia National Laboratories presented revolutionary predictions indicating that LED could achieve up to 200 lumens/watts and manufacturing costs could be dramatically reduced (Haitz and Tsao, 2011). These new predictions, known as "Haitz's law," suddenly changed the lighting industry and LED became a general lighting technology. As a result, new players entered the market. In a joint venture with HP (through Agilent), Philips created Lumileds in 1999 to develop and commercialize high-powered, high-efficiency LEDs for a wide range of uses. In 2007, Philips acquired 100 percent of Lumileds. Similarly, OSRAM took over the semiconductors division from Siemens in 1999, creating OSRAM Opto Semiconductors through a partnership. In 2001, OSRAM took full control of the company to offer a full range of general lighting LED solutions. Both firms entered the LED general lighting market by internalizing specific semiconductor capabilities.

The new expectations about LED lighting technology shifted the attention of policy makers towards specific projects that aimed at developing this technology. Private and public R&D investments nearly doubled compared with forecasted investments in pre-1990s industry reports (Haitz and Tsao, 2011). Haitz and Tsao noted that the U.S. government decided to fund both LED and the very novel organic LED (OLED) technologies, and as a result could not sustain the $500 million in R&D funds required to achieve a white LED with an efficacy of 150/200 lumens within 10 years (Haitz and Tsao, 2011). Asian firms filled the technological gaps in LED, and many, including Nichia, Samsung, LG Innotek, Seoul Semiconductor, Sharp, and Toyoda Gosei, obtained relevant positions in today's market. The value of the LED market is expected to stabilize because the price reduction in LED components will compensate for the increase in quantity sold (Peters and Wright, 2012). Therefore, given the high level of competition, some actors think that the LED market is no longer profitable. Among others, Philips and Siemens have decided to quit the LED components business. Of the different market segments, backlight and mobile applications are expected to quickly decrease, and general lighting applications to quickly increase.

## 5. Characterizing the different technological regimes

The history of lighting technologies illustrates how technologies that develop within the same industry can follow different innovative patterns (*technological regimes*), and that a change of regime can occur without disruptive effects on the industry. In this section we further elaborate on the different regimes that we observed, thereby explicitly identifying four determinants (opportunity, appropriability, knowledge base, cumulativeness of knowledge) for each of the alternative lighting technologies as well as the different combinations of technological developments, firms' strategies, market structures, and institutional context.

### 5.1. The first regime—up to the 1930s

This period is characterized by low opportunity for energy efficient lighting, very high appropriability, and a relatively simple industry knowledge base. The demand for other more advanced lighting technologies was very low, resulting in low market opportunity for more efficient lighting technologies. The lighting market showed a very high level of appropriability, as illustrated by the dominant position held by GE throughout the whole value chain. At the same time, the relatively straightforward knowledge base of incandescent technology enabled low production cost. Consequently, GE's dominance was built on the construction of oligopolistic market barriers. Such barriers allowed GE to control the market, reduce production cost and to sell incandescent lamps in a quasi-monopolistic context. This first regime showed a typical Mark II structure which resulted in a substantial profit –flow[8] that enabled GE to develop the fluorescent tube in a protected technological niche. The lack of market pressure towards more efficient lighting technologies allowed GE to slow down the diffusion of fluorescent lamp in favor of further testing and development.

In this period, LED technology was still at an infant stage, and its potential lighting application was not yet discovered. In the early years of the 20th century, energy efficiency became a key driver for the non-residential lighting market, whereas in the residential lighting market, other selective forces, such as light quality and design, and the availability of fixtures, were more important. In this context, fluorescent tube technology had great value in the non-residential market because of its higher energy efficiency compared to incandescent bulbs.

### 5.2. The second regime—1940s—1960s

Three major discontinuous elements characterize this period. First, the diffusion of the incandescent light overloaded the existent electric infrastructure and created major issues in relation with indoor comfort. As a result the non-residential sector, which was using the majority of electric lamps, started asking for more energy efficient lighting technologies, creating a new demand for the fluorescent tube.

Second, antitrust policies and expiring patents weakened GE' oligopolistic barriers, lowering appropriability, and new firms entered the lighting market. New companies, like Sylvania, launched own R&D programs, focusing on the development of fluorescent tubes. Consequently, the fluorescent tube went through a steady process of incremental innovation, which lowered production costs and increased efficiency. Within one decade, the incandescent lamp was replaced by the fluorescent tube in the non-residential lighting market, while it kept a dominant position in the residential one.

Third, the shifting attention from incandescence to fluorescence increased the complexity of the knowledge base of the lighting market. The principle of incandescence was widely known and processing methods were quite cheap. Therefore, knowledge about incandescence technology was not a barrier for newcomers. In contrast, fluorescent and LED technologies were novel and had a complex knowledge base that was built through a highly cumulative process. In fact, both technologies are based on novel physical principles (fluorescence and luminescence); therefore, development of these technologies required a new set of capabilities in both research and development and new productive processes.

The combination of these three factors created more opportunity for innovation and competition for the energy efficient light, creating favorable conditions for the development of fluorescent tubes in the non-residential lighting market. Meanwhile, the complexity and cumulativeness of the knowledge base favored established lighting firms. The result was a fierce competition between GE, the leader of the market, and Sylvania, the follower.

At this point LED was still not ready to enter the lighting market, but it developed in the new electronics market, where energy efficiency was a relevant driver of technological development. Only with the development of the first visible red LED, this technology started attracting the attention of the lighting market, but only for very specific niches.

### 5.3. The third regime—from the 1970s up to the 1990s

The third period showed two major discontinuities. First, we observed the rise of an energy and environmental political agenda which promoted energy efficiency in all sectors of the economy. As a result, energy efficiency became a more important driver for development in the residential market. At the time, this market was the biggest segment in terms of installed number of lamps, and it was still dominated by the incandescent bulb.

Second, fluorescent light became available for the residential market when GE and other lighting companies announced the CFL. At that time, the fluorescent light was considered the future of light, and the CFL attracted the attention of all the major lighting companies. Shrinking the fluorescent tubes, increasing the reliability of the fluorescent light, improving interoperability with existent fixtures, promoting consumers' awareness, and lowering the production cost were the main issues faced by the CFL in its attempt to conquer the residential market. These issues became the focus lighting R&D programs.

The combination of these two discontinuities made the residential light market a new arena of competition for the lighting players and fuelled technological learning of fluorescent technology and its adaptation to the specific needs of the

[8] In 1935–1936, GE's profit from incandescent lamps represented 64–88 percent of costs, 39–47 percent of net sales, and 20–30 percent of invested capital. "In fact, the lamp's department of General Electric contributed from one-third to two-thirds of total profit while adding only about one-sixth of total sales." (Roger, 1980 p. 19)

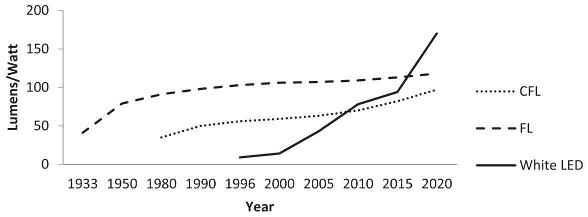


**Fig. 1.** Energy efficiency of the most popular indoor lighting technologies: historical values and predictions. Sources: Craford (2014), Narukawa et al. (2010), Navigant Consulting Inc (2012a,b, 2009) and USDOE, (n.d.).

residential market. Meanwhile LED continued its development and diffusion in the electronics market. Since the 1970s, LED started appearing in specific niches of the non-general lighting markets, where the lack of white LEDs was not an issue.

### *5.4. The fourth regime—since the late 1990s*

This period is characterized by three major discontinuities. First, environmental issues got a central position on the US political agenda, and many policies targeted the diffusion of energy efficient solutions in the lighting market. Second, US policy makers focused on removing oligopolistic barriers through specific policies which encouraged newcomers to enter the market, thereby lowering appropriability conditions for the incumbents. Third, the discovery of the white LED and of Haitz's showed the potential of LED technology and changed the perspective of the lighting industry which shifted focus from the fluorescent light to the LED.

The combinations of these factors increased the market value of energy efficient lights in the overall lighting markets, and reduced appropriability conditions. This combination spurred incremental innovation in fluorescent technology for both residential and non-residential applications. The main drivers of this incremental innovation were lower production costs and improved light quality. As result, fluorescent technology today surpasses incandescent in the residential market because of its greater efficiency paired with acceptable quality.

Meanwhile, Haitz's law deeply changed the future scenario for the lighting market, as LED became the expected new dominant technology. Therefore, firms developed two alternative strategies: (i) to substitute incandescent bulbs with CFL bulbs on the short-term, protecting their existing CFL profit flows, and (ii) to substitute CFL bulbs with LED bulbs on the long-term. Because the knowledge bases for these technologies are highly cumulative, and CFL knowledge is specialized, some firms with specific semiconductor knowledge focused immediately on the second strategy, trying to shorten the development time of LED as much as possible. However, other firms with a lighting background, such as Philips and Osram, focused on exploiting both strategies, although to develop LED technology they had to acquire semiconductor capabilities through an intense process of fusion and acquisitions in the market. In fact, in only two decades, LED outperformed fluorescent tube in terms of light output, production costs and efficiency, and became comparable to the incandescent bulb in terms of light quality and reliability. Today all competitors on the lighting market have LED in their portfolio of technologies.

### *5.5. The long-term evolution of the lighting technological regimes*

We observed three specific long-term patterns of development of the determinants of technological regimes in the lighting market. First, opportunities associated with the development of more efficient lighting technologies steadily increased over the time. At first, efficiency was not a main driver of market selection. Then, in the 1940s, energy efficiency became first relevant for the non-residential lighting market, and since the 1960s, energy efficiency became important in the residential lighting market as well. Finally, in the 1990s, energy efficiency became a relevant criterion of technological selection for the entire lighting market. The increasing opportunities have spurred the development and diffusion of new lighting technologies. Fig. 1 shows the evolution of efficiency over time for these three technologies.

Second, the lighting knowledge base has become more complex. The beginning of the electric lamp industry was based on the technologically relatively simple incandescent lamp. After that, the focus on fluorescence and luminescence created a need to develop more complex and advanced knowledge through R&D programs. Policy makers responded by supporting and establishing R&D projects and funds in order to speed the technological evolution of the recent lighting technologies. Consequently, the development of the LED lamp was the result of very intense research projects which involved several industry and academic research groups.

Third, the US lighting market became more competitive. Starting from a quasi-monopoly, dominated by GE, the lighting market today is an arena of local and global players. Two factors explain this transformation. First, US policy makers have enforced several pro-competitive policies which have weakened GE's monopoly. Second, LED technology has changed the knowledge base of the lighting industry, and it has reduced the importance of the highly cumulative CFL knowledge base. As result, newcomers from the semiconductor and electronics industries could enter the lighting market.

The change in the determinants of the lighting market resulted in a gradual transformation of the lighting market structure from a Mark II model to a Mark I. This transformation is the consequence of several forces which influenced the lighting market

**Table 2**
LEDs and markets.

| Decade | LED primary colors | Main markets and applications |
|---|---|---|
| 1960s | Red | None |
| 1970s | Red, Green | Alphanumeric red display |
| 1980s | Red, Green | Brake lamps, disco-lighting systems |
| 1990s | Red, Green, Blue | Traffic lights, automotive industry, exit signs, specialized non-white lighting |
| 2000s | White | Backlighting illumination, specialized white lighting |
| 2010s | White | Backlighting illumination, general lighting |

in different directions. Increasing opportunity and lower appropriability were essential components of the transformation towards a Mark I structure. Instead, the evolution of the knowledge components had opposite influences. On the one hand, the increasing complexity of the knowledge increased the cumulativeness and the stability of the innovative process. On the other hand, LED technology changed the nature of the knowledge base, and created a new knowledge base which helped newcomers to entry the market.

The different Schumpeterian market structures help to explain the different patterns of development and diffusions of the fluorescent lamp (both tubes and CFL) and the LED. Fluorescent technology development was influenced by strong oligopolistic barriers in both residential and non-residential segments. The diffusion of the tubes in the 1940s was possible due to the combination of a strong demand for high efficiency solutions in the non-residential market, and the disruption of the dominant position of GE. Instead, due to the lack of demand for energy efficient light in the residential market, the oligopolistic barriers slowed the pace of diffusion of the CFL for some decades.

The market entry of LED followed a different pattern than CFL, because the technology has the characteristics of a general purpose technology (Shimizu and Kudo, 2011) and could diffuse in complementary markets (see Table 2), which enabled technological learning and allowed it to circumvent the oligopolistic barriers present in the lighting industry.

The timing for LED was thereby favorable as well; its potential as a general lighting technology was not widely acknowledged until the late 1990s, when it became a potential competitor for the general lighting market. In that decade, the position of the dominant incandescent technology was already weakening under the pressure of increasing demand for more efficient lights, pro-competition policies, and the diffusion of fluorescent lighting. This situation created favorable conditions for the development and diffusion of the new LED light and it was able to quickly improve through technological learning.

Policy dimension influenced the transition of the different regimes in three ways. First, the policy makers promoted energy efficiency creating more market value for energy efficient lighting solutions. Since the beginning, the policy agenda did not target the lighting sector but the overall economy. Since the 1990s, we observed that there were specific policies to promote energy efficiency in the lighting industry. Second, the policy makers steadily promoted pro-competitive policies which lowered the defensive strategies of dominant players. Third, policy makers started to support R&D lighting policies when the knowledge base became more complex, as it happened with CFL and LED.

## 6. Conclusion and implications for policy

In the 20th century, the lighting industry developed three energy-efficient alternatives to the incandescent light bulb, FL, CFL, and LED. Each technology's history of development shows different patterns of innovative activities, despite similarities in the determinants of innovation. While FL and LED quickly improved through learning dominated the market once they were introduced, CFL learning was much slower and it struggled for decades. More specifically, we observed multiple technological regimes within the same industry, and this paper illustrated how the different technological regimes arose in the lighting industry.

The lighting market was characterized by an oligopolistic pattern of innovative activity since the beginning of the 20th century when the incandescent bulb was dominant. Typical of an oligopolistic market, the patterns of diffusions of new technologies heavily relied on firms' strategies and market power. The development of FL and CFL initially took place within this regime, and they were in direct competition with the incandescent bulb. But in the 1950s, the barriers of incandescent technology were weakened by anti-trust rulings, the expiration of relevant patents, and an aggressive market strategy from competitor Sylvania. The increasing importance of energy efficiency played an important role in diffusing FL and CFL technologies. The non-residential lighting market was already demanding new energy-efficiency lights, and FL represented the industry's answer. In the mid-20th century, energy efficiency was not a relevant driver of market selection in the residential market and consequently, the development of residential energy-efficient solutions was not an industry priority. As a result, a weak-learning process characterized CFL technology development for decades. The turning point was in the 1990s, when policy makers seriously promoted energy efficiency in the residential light market as well. In fact, improving energy efficiency was considered a viable solution to reduce both the demand for new power plants and the environmental burden associated with the provision of light. Policy makers perceived the CFL as one of the most effective solutions to quickly control the increase in demand for energy. As result, important incentives helped to diffuse CFL technology, and development accelerated as CFL became attractive for the residential market. Changing attitudes towards energy consumption also emphasized the connection between environmental problems and energy-efficiency dynamics. As illustrated in Section 3, the first fluorescent tubes were not marketed as energy-efficiency solutions that could reduce energy consumption, while the CFL had the explicit purpose of reducing energy consumption for lighting.

LED technology followed yet another pattern: initially developing outside the lighting industry as a general-purpose technology it avoided the oligopolistic barriers the fluorescent technology had faced. Initially, LED was not considered a viable competitor to incandescent technology and was able to circumvent the lighting regime to grow stronger in other niches in industries characterized by Mark I patterns. When LED finally matured in the new millennium as a general-purpose lighting technology, the lighting market had changed considerably. First, policy makers had weakened the oligopolistic barriers, and LED contributed to those changes by allowing semiconductor players to enter the lighting market. Second, energy efficiency had become an important market selection criterion in the residential segment, which made LED a viable substitute. Finally, LED introduced more Mark I elements into the lighting industry but without disrupting the entire industry structure.

Diffusion was rapid for the fluorescent tube because the market was ready to accept a new technology, but slow for CFL because of market disinterest. In addition, we showed that LED technology is an example of a less disruptive combination of market structure, long- and short-term strategies, and related industries that has changed the technological regime in the lighting industry. More specifically, because of the particular circumstances in which other industries (with other innovative patterns) offered a niche environment for LED to develop, LED was eventually able to bypass CFL as a most promising technology, demonstrating a non-disruptive way to go from Mark II to Mark I.

The history of the lighting technological regimes shows the important role for policymakers in stimulating new technologies in industries with undesirable Mark II pattern. Policy makers influenced all the dimensions of the technological regime: opportunity, appropriability and knowledge base. The opportunity dimension was influenced since the 1970s, when policy makers starting promoting efficiency in the lighting sector, efforts that have increased with the new millennium with the push to secure energy supplies and to reduce environmental burdens, thereby creating a demand for energy efficient lighting solutions. The appropriability dimension was influenced by the relevant role that policy makers had in destroying the oligopolistic barriers that slowed the pace of diffusion of fluorescent tubes. In the 1940s, anti-trust decisions allowed other firms to break down GE's monopoly stimulating the diffusion of FL. Similarly, in the 1990s, both the California state and the federal level launched several initiatives to enhance competition in the CFL market. The policy makers also helped, through specific R&D programs and initiatives, to fund several research activities that aimed at developing the complex knowledge dimension of fluorescent and luminescent lights. The combination of these actions promoted a more competitive and innovative lighting industry, which resulted in a quick pace of development of the lighting technologies in the recent decades. More in general, we identified that policy makers have stimulated the evolution of the lighting innovative patterns through changes to the selection environment of the market and through the lowering of entry barriers, as in the case of anti-trust policies, and instruments of demand pull such as market formation for new technologies which brought new competences in the lighting industry, as demonstrated in the California case.

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