



Future indoor light and associated energy consumption based on professionals' visions: A practice- and network-oriented analysis

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ABSTRACT

Through the insight and visions of Danish lighting experts, this manuscript investigates relationships between future lighting technologies and practices and the expected impacts on energy and lighting consumption. The light-emitting diode (LED) will be the dominant technology of the future *smart* light systems. Though, energy efficiency is expected to improve, new market players will appear and new lighting opportunities will be exploited that, in turn, will increase the demand for light. A rebound effect is expected. The overall impact on the future consumption of energy is uncertain, so we conclude that political guidance is needed if society wants to assure the reduction of energy consumption through widespread diffusion of smart LED lights.

1. Introduction

The provision of light is one of the societal needs that is expected to reduce its consumption of energy (IDA, 2011; EPA, 2011; European Commission, 2012; Oosterhuis, 2007), with expected potential of saving up to 70% of the current level (European Commission, 2011). Consequently, many lighting innovations have attracted societal attention due to their promising benefits for energy saving (Bertoldi and Atanasiu, 2010; EPA, 2011; Haitz and Tsao, 2011; Lee, 2000; Mahlia et al., 2005; Menanteau and Lefebvre, 2000; Wall and Crosbie, 2009; Weiss et al., 2008).

However, several scholars highlighted that past increases of efficiency in the provision of lighting did not actually reduce the associated consumption of energy (Franceschini and Pansera, 2015; Nordhaus, 1998). Fouquet and Pearson (2006) identified four distinct revolutions in lighting services, and in each of them efficiency and consumption of light skyrocketed. Tsao and Waide (2010) reviewed three centuries of energy consumption for light and concluded that there is a massive rebound effect associated with an increased efficiency in the provision of lighting. Furthermore, Tsao et al. (2010) indicated that there is not sign of saturation in the future demand for light, warning about immense future rebound effects.

Given the prevailing societal strategy to reduce energy consumption through the diffusion of promising lighting innovations and the contrasting findings of the rebound effect literature on lighting services, it is not trivial to evaluate to which extent such promising lighting

innovations will be able to fulfill their promises without a clear political guidance (Hekkert et al., 2007). For this reason, it is important to accompany analyses of technological transformation and market acceptance of novel energy efficient lighting technologies with analysis of the expected new lighting practices.

The rebound effect literature has tried to couple technological innovations with changes in practices of consumption, especially using long-term historical analyses (Fouquet and Pearson, 2012) or modeling of individual agents' behaviors in response to increase of efficiency (Lay et al., 2013; Min et al., 2014; Saunders, 1992). While these approaches can provide solid knowledge about past and present dynamics, they are less useful in analyzing future developments because they cannot easily account for potential future changes (Bijker and Law, 1994). Therefore, the present study proposes a complementary approach that explicitly accounts for qualitatively changing behaviors in future contexts.

Building on the traditions of foresight and scenario methods (Amer et al., 2013; Bootz, 2010; Kosow and Gafner, 2008; Miles et al., 2008), this study suggests a future-oriented approach for analyzing novel lighting technologies, lighting practices and rebound dynamics. The approach is centered on cognitive mapping technique (Downs and Stea, 1973) that describes elements and relations between elements in practice, and hereby establishes a system and network perspective on use of new light innovations. More specifically, we interviewed professional experts and produced individual cognitive maps representing future visions for indoor non-residential light and lighting in the Danish context.

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We argue that future looking analysis of rebound effects can fruitfully draw on the systemic perspective on innovation and technology development that in recent years have received increased emphasis both within studies of innovation and technological change in general (Geels, 2004a; Hekkert et al., 2007) and within technology foresight and scenario approaches specifically (Andersen and Alkærsg, 2016; Saritas and Nugroho, 2012). At the core of the system oriented literature is the idea that sociotechnical change and innovation are dependent on interactions and co-evolvments of several, heterogeneous elements. One of the rationales for the increased emphasis on the systemic perspectives is to move away from technology deterministic and linear models of technology development and integrate demand aspects and socio-economic elements in the otherwise strongly technology-push and science-push oriented approaches that appeared in many technology foresight activities earlier (Georghiou and Cassingena Harper, 2011; Jørgensen et al., 2009; Smits and Kuhlmann, 2004).

The results of our study confirm that the future lighting scenario is dependent on the changing interconnections between technologies, policies, and practices. For example, the LED technology is not only considered more efficient than other lighting technologies, but also considered superior with respect to many other dimensions (e.g. versatility, customizability) and it is expected to encourage new practices that will increase the demand of light. Increasing efficiency will be accompanied by more attention to quality of light, human health, and effects of light on productivity. These dimensions are expected to increase the demand of light. New players are expected to appear to fully exploit the opportunities of the intelligent future light. The existence of such dynamics indicates the possibility of contradictory and unexpected dynamics for energy saving, with the time dimension as an essential component. In the short term, gains of efficiency will deliver important savings of energy. In the long term, changes in the drivers of market selection and the evaluative criteria of lighting solutions will result in an increase in the light demand. These results suggest that policy makers must carefully judge the systemic impacts of innovative policies in respect to new practices in the society to predict potential unexpected outcomes of policies that are designed to reduce environmental burden through efficiency only.

The paper has two contributions which are relevant for light practitioners, policy makers and scholars and experts of the rebound effect. Firstly, it provides new knowledge about the rebound effect thanks to a systemic approach which explicitly addresses rebound dynamics through the analysis of relationships and networks between elements of lighting innovations and practice. The case is lighting, but the approach can be used in any areas exposed to eco-innovative forces. Secondly, the paper provides new, practice-oriented knowledge to the current literature on light technology which mainly focuses on the technical dimensions of the diffusion of LED (light-emitting diode) technology.

The article is structured as follows: Section two briefly reviews the current rebound effect literature on light and provides a short, contextualizing description of the discourse about light, lighting, and energy in Denmark – the location of our study. Section three describes the methodology. Section four presents the results of the case study, and section five discusses them. Section six sums up the conclusions and highlights the main findings and limitations.

2. Energy efficiency and consumption in the provision of light: The literature background

2.1. The rebound effect literature about light and energy consumption

The work of the British Economist Jevons (1865) about the increasing consumption of coal due to the increase of the efficiency of coal engines is widely recognized as the initial milestone of the rebound effect literature has focused on understanding under which conditions an increase of the efficiency of utilization of any resource may lead to an increase of its consumption. For a general overview of the rebound

effect literature readers are invited to consider, as starting points, the existing seminal works by Sorrell (2009a, 2009b) and van den Bergh (2011). Here we delimit ourselves to the works focusing on the energy rebound effect for lighting. Bright and Maclaurin (1943) reported that the total number of installed light bulbs increased because of the diffusion of the fluorescent light. Similarly, Bright (1949) and Nye (1992) reported that the overall use of light¹ increased when the incandescent light replaced the oil and gas lamps. Such dynamics have been confirmed by long-term historical studies which go beyond a specific technological change in the light bulb. For example, Fouquet and Pearson (2006) studied the evolution of lighting efficiency and consumption in UK over seven centuries and concluded that light consumption increased by 25,000 times in the last two centuries. Similar conclusion were achieved by Herring (2006) which noticed an increase of 400 times in the intensity of public road light per mile of road. Bowers (1998) suggested that throughout history people have used light to lengthen their day and to increase productivity, and found that gains in efficiency led to more usage of light. In addition, Franceschini and Pansera (2015) pointed out that the rebound effect for lighting is the result of the present dominant societal discourse about innovation which encourages new demand for lighting instead of energy conservation.

While the literature is unanimous concerning the importance of the rebound effect in cases of *fuel poverty* (Guertin et al., 2003; Herring and Roy, 2007; Roy, 2000), findings are more controversial about developed countries (as Denmark). On the one hand, Nadel (1993) suggested a smaller direct rebound of 10% or less for lighting, similar to the findings of Greening et al. (2000). Howarth et al. (2000) have investigated the US Green Lights programme and conclude that the rebound effect is not of great empirical relevance because the demand for light is cost-inelastic in the industry and tertiary sectors, a finding confirmed by Schipper (2000). However, on the other hand, Verbeek and Slob (2006) found that the diffusion of energy-saving lights has increased the consumption of energy in Dutch households because ‘most people not only replaced existing bulbs with the new light-saving ones, but also used the new bulbs to illuminate places where there was no light before, such as the garden or the garage’ (p.4). Similarly, Mills and Schleich (2014) reported that luminosity is increased with 48% when German householders switch from the incandescent bulb to the LED light. Therefore, the magnitude of the rebound effect in developed economies is still a controversial issue which deserves more analyses.

In addition to the rebound effect literature that has highlighted the contradictory relationship between light efficiency and energy consumption, we explored the socio-technical, system-oriented literature about sustainable transition in the provision of light to gather knowledge about the ongoing dynamics. Lighting can be framed as a socio-technical function that ‘has the purpose to fulfill the human need of performing visual tasks’ (Franceschini and Pansera, 2015, p. 77). The socio-technical approach encompasses not only the production side, but the diffusion, and the use of any innovation (Geels, 2004b), an essential aspect to understand the qualitative dynamics of the rebound effect. Surprisingly, we found very few works providing a ST-transition analysis of light. Moreover, most of these works focus on developing countries (Bensch et al., 2017; Harish et al., 2013; Lay et al., 2013; Rehman et al., 2010) and their ST-systems cannot easily be compared to the Danish ones. We found only two studies which explicitly analyze the ST-transition associated to new lighting technology in developed contexts. Smink et al. (2015) showed that lighting incumbents implemented institutional strategies to favor fluorescent light against the LED technology, before they passed a tipping point, after which they actively supported the LED technology. Marletto et al. (2016) highlighted the role of changing business models and political discourse

¹ ‘Where once 5 or 10 fc were deemed adequate, from 50 to 75 fc are not now considered excessive’ (Bright, 1949)

through which lighting innovators competed for the market. The authors concluded that the future light system shows quite radical changes for both the dimensions. The light discourse is becoming more complex and new business models are likely to occur shifting from the sale of bulbs to the provision of light systems. The studies point out the importance of the institutional context in which actors act and interact in the lighting area, including an increasing societal pressure towards using more efficient light.

2.2. Energy efficiency and consumption in the provision of light: The Danish context

Denmark has promoted policies for energy efficiency and energy savings since the oil crisis in the 1970s. In some periods the total energy consumption decreased despite economic growth (ENS, 2008) and Denmark is now among the most energy efficient countries in EU and OECD (Eurostat, 2016; IEA, 2017). The goal for the period from 2010 to 2020 is a reduction in total energy consumption on 7% (transport excluded) (KEB, 2012). Lighting constitutes about 5% of the total energy consumption and it constitutes an important share of total electricity consumption for business, industry, and public institutions (Johansson and Rizzo, 2008; Munck and Clausen, 2008, p. 5).

Lighting is an important sub-area for energy savings in governmental action plans for energy savings (TEM, 2005), although it does usually not appear explicitly as an individual policy area (KEB, 2013, 2012; Regeringen, 2001). Denmark was one of the early movers concerning public support programs for compact fluorescent lamps (CFLs) (Martinot and Borg, 1998). Light sources were one of the first focus areas for EUs and Denmark's energy labelling schemes for products. Lighting received 16% of the total funding in the period 2002–2011 (Dansk Energi, 2012) in the public support program for research and development projects about energy saving and efficient energy use.

Use of natural light in building design is culturally embedded and institutionalized in architectural practices and building norms. In current years, there is used more glass in new buildings in Denmark than ever before and there is a tendency to large glass facades, not least in new office buildings (Johnsen, 2002; Johnsen et al., 2011). Since the first national building code (Boligministeriet, 1961), there have been requirement of a certain amount of window surface and natural light in rooms. In recent years, the interplay between natural light and electric lighting has been specified in functional requirements, with natural light as the primary and preferred type of light and electric light as supplementary (EBST, 2008, 2006). While the connection between natural light and energy earlier was a heating matter primarily (loss through windows), the connection to electric light and electricity consumption is now made explicit in the building code. It is required that the light and lighting shall be energy efficient (DECA, 2010), and today windows and natural light are described as a matter of health and well-being.

3. Methodology

3.1. Technology foresight and cognitive mapping

The aim of foresight analysis is not to predict the future, but to make systematic and qualified analysis of likely future developments and interconnections and, through this, enable a present-time assessment of opportunities (Piirainen and Gonzalez, 2015). It is widely acknowledged in the literature that foresight and scenario analyses must be designed according to the specific purpose and the resources available (Popper, 2008; Saritas and Nugroho, 2012). There is considerable variation in how systemic aspects in connection with technological change are addressed. At least four different perspectives exist: 1); a socio-technical systems perspective with focus on socio-technical configurations and co-evolution of technologies, use practices, and institutions (Elzen et al., 2004; McDowall, 2014); 2) an innovation system

perspective with focus on innovation dynamics, actors, and institutions in specific innovation systems (Andersen and Andersen, 2014); 3) a generalized system thinking perspective where the external context in sense of social, technological, economic, environmental, political and value systems is considered (Saritas and Nugroho, 2012); and 4) a broad group of studies that address selected demand perspectives, societal needs, or economic or environmental aspects in addition to the otherwise pronounced technology and science push orientation of traditional technology foresight approaches (Andersen et al., 2007; Georgiou and Cassingena Harper, 2011; Jørgensen, 2004; Rasmussen et al., 2005; Smits and Kuhlmann, 2004).

The methodology of our study is primarily related to the first mentioned system perspective with its attention to connections between heterogeneous (social as well as technical) elements and technology use in practice. Moreover we build on the finding that mapping of network relations, i.e., interdependencies between elements can constitute a central method dimension in foresight and scenarios analyses (Davis and Pyper, 2015; Magruk, 2011; Nugroho and Saritas, 2009). In addition, our methodology can be seen as related to the 'functional' foresight perspective that focuses on functions of technologies in the use context (Aprea et al., 2016, 2014).

The methodology was designed to collect information about future lighting technologies and practices. The technologies and practices were assessed as individual elements and with respect to their mutual connections through interviews with experts in the field. We follow Miles and Huberman (1994) that argue that the richness of the information derived from interviews has the strength to reveal critical interactions of complex social phenomena. Indeed, individuals remain a main source of knowledge (Rosales Carreon, 2012). Major innovations are expected to occur in the coming years, however, the future intricate interactions do not exist in a vacuum, but as knowledge and expectations in the mind of the different actors that interact (Jorna, 2006). With their deep and comprehensive insight in the field, experts constitute a good information source for our study.

We use the cognitive mapping technique (Tolman, 1948) to investigate and systematize the descriptions of expectations by the different experts and to explicate the relations between elements in future lighting practice. Cognitive mapping can be defined as a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in their everyday spatial environment (Downs and Stea, 1973).

The cognitive approach has earlier been applied in connection to innovation and technological foresight (Amer et al., 2016; Biloslavo and Dolinšek, 2010; Boe-Lillegraven and Monterde, 2014; Bootz, 2010; Kaplan and Tripsas, 2008; Swan, 1997). Kaplan and Tripsas (2008) argue that the cognitive dimension is important for understanding the dynamics of technology change and that models of technological progress, e.g., economic, organizational and behavioral models that ignore cognitive factors may result in spurious conclusions. This is not least the case in early phases of technologies' life cycles where uncertainty is considerable and there is not a widely-shared frame of understanding of the new technology, but different frames created by the involved actors' cognitive foundations including assumptions about the future, knowledge about alternatives, and views of consequences of pursuing different alternatives. The technology does not evolve in a frameless context, but co-evolve with the frames through the actors' activities. The specific historical experiences and affiliations of the actors influence their framing and interpretation of the technology. These findings are similar to findings made in the sociology of technology (Bijker, 1995).

3.2. Operational aspects

We made the interviews and constructed cognitive maps (see Appendix 1 for an example) with reference to a specific focus question

relevant in the experts' professional domain: "Imagine that you have to explain your perspective about the use of energy for indoor non-residential lighting in 2030 to a client who knows little about the subject. Which elements would you take into account?"

The year 2030 was fictional and the interviewees were aware of that. Nevertheless, the indication of a year was needed to avoid different subjective interpretations of concepts of mid- and long-term futures.

We decided to narrow down the analysis to indoor non-residential lighting as result of the *ex-ante* analysis. Firstly, the residential and non-residential value chains are highly different, with different players, business models and users' behaviors. Secondly, the lighting markets show very different degree of efficiency in the use of lighting technologies (Navigant Consulting Inc., 2012). Incandescent/halogen technologies are still relevant in the residential market, whereas the fluorescent technology dominates the non-residential market. The different technological regimes make the two segments hard to compare. This was confirmed by all the interviewees, who highlighted that their thoughts should not be applied to the residential market. The focus on a country (Denmark) was chosen because the country level still matters in the usage of lighting due to, e.g., differences in regulatory frameworks (e.g. the building codes) and different climate and cultural conditions.

A total of 17 experts were face-to-face interviewed. They were 7 women and 10 men, between 27 and 62 years old. Interviewees were selected, among professional experts which work in Denmark. Variety in the set of experts involved was an important criterion for selecting of the individual experts. The interviewees had different backgrounds and represented different expertise areas and positions in the light sector, ranging from suppliers of light systems, experts on light in buildings, architects, to experts on energy efficiency and consumption. They came from firms (primarily) and research organizations. They performed different roles in companies and research institutions. Each interview lasted between one and 2 h, and it was audio-recorded for further analysis. Participation was voluntary. The only incentive to encourage participation was the promise to give each of them the personal cognitive map.

We followed the directives proposed by Wolcott (1990) to guarantee the validity of the answers we obtained during the knowledge elicitation process: i) elaborate an interview guide, ii) pre-test the interview guide, iii) avoid the modification of the interview guide structure during the interviews, iv) listen carefully, v) produce annotations that are as precise as possible, vi) write early, vii) employ a unique format to transcript the interview, and viii) corroborate the information with the interviewee. Each interview included four phases.

- First phase. The interview started with a brainstorming session in which the interviewee was asked to write down on sticky notes all the elements he/she would mention to answer to the focus question as stated above. The interviewer did not mention any specific aim (e.g. addressing energy savings) and participants were encouraged to present any important elements, even in form of uncertain elements and wishes. Participants were asked to include only one element for each sticky note. By way of example, they were suggested not to write complex sentences like "Technology A to improve comfort in offices" in a sticky note, but to use different sticky notes for each element (in the example three sticky notes for each element: technology A, comfort, office use).
- Second phase. The interviewees used a blank A2 paper sheet to freely position the sticky notes on, and to draw arrows (representing relations) between them. The direction of the arrow represented the direction of the influence. For example, an arrow going from A to B meant "The development of A will influence the development of B". The interviewees could design as many arrows as wished, without any limitation. In that phase, interviewees were still allowed to add elements not mentioned during the first phase.
- Third phase. The interviewees assessed each element note through

two dimensions: i) the potential for energy savings; ii) the feasibility of development up to 2030. Potential for energy savings was defined as the contribution of such element to energy saving if properly implemented within 2030. For each of the two dimensions, interviewees could use a low/medium/high scale.

- Fourth phase. The interviewer reported the sticky notes on a Cartesian coordinate system in which the two dimensions were represented through the scale (low, medium, high). The interviewer also reported the arrows as designed by the interviewee. The interviewee was asked to give some thoughts and general explanations on the overall map.

All the phases were kept separated. Any materials used during a phase were not showed during the previous phases. The reason for this was to avoid contamination between the aim of the interviewer and the interviewees. Therefore, the overall picture (the cognitive map) was only presented by the interviewer during the fourth phase.

Ex-post evaluation of the interviewees confirmed the validity of the results. After one week, the interviewer sent a two-page report including the individual cognitive map and the main interpretations given by the interviewer. Interviewees were asked to evaluate the degree of agreement using the following 4-point Likert scale: 1. Total disagreement; 2. Disagreement superior than agreement; 3. Agreement superior than disagreement; 4. Total agreement. We asked the interviewees to give frank answers and not to please the interviewer, highlighting the importance of honest evaluation for the scientific analysis. Two interviewees gave "two". The rest gave "three" or "four". Among the two negative respondents, one highlighted that the final map was too complex to be useful; the other said that the map was too obvious to be useful. No one stated that the cognitive map was a misrepresentation of his/her own thoughts.

Once the interviewees validated the interviews, we analyzed the data. First, we defined *ex-ante* a list of 8 categories² based on our understanding of the literature about light and lighting systems. Second, we standardized similar elements to allow comparisons between interviewees. Standardization was performed according to: i) the actual written content of each sticky note and; ii) the interpretation, also using the audio records, given by the interviewee when the content was unclear or overlapping. Each researcher, independently, evaluated the elements and identified categories. We ended up with a common list of 14 categories (see Results), agreed by all researchers, that classified all the elements. The last step was the use of Excel 2010 and Gephi 0.8.2 to analyze elements and their network. We used the audio transcripts to understand whether the relationship between two connected elements was positive (reinforcing) or negative (weakening).

4. Results

4.1. Elements

The interviews produced 17 individual cognitive maps containing 216 elements (i.e. sticky notes) and 381 relations. The 216 elements have been evaluated according to their potential for energy saving and grouped in 14 categories, as reported in Table 1.

Economy represents the most popular category. *Technology* was the only one to be cited by all the interviewers. *Building regulation* has been extracted from the general *policy* category because of the specific importance of building regulation in the interviewees' answers. Note that energy savings does not itself appear as one of the overall categories identified. The rest of this section describes the main elements and relationships between the categories.

Economy. Cost saving and purchase price are the most frequently

² Daylight, Design, Light Management, Market Dynamics, Policy and society, Tech Efficiency, User, Other.

Table 1

List of categories and the reported energy saving potential. For each category, the table indicates a short description of main elements, the number of elements (No.) associated to each category, and the number of interviewees (Int.) who cited at least one element in this category. Bold in the energy saving column represent the median value.

Category	Main elements	No.	Int.	Energy saving potential		
				Low	Med	High
Economy	Price, cost, markets, business models and general market considerations	33	14	12,1%	33,3%	54,6%
Dynamic light	Elements of flexible light system (e.g. controlling sensors, intelligent light, system management, software, light zoning)	28	16	7,1%	39,3%	53,6%
Technology of electric bulbs	Components, technologies, and other elements of new electric bulbs	23	17	0,0%	30,4%	69,6%
Quality & comfort	Considerations about comfort of users and quality of light	22	13	54,5%	36,4%	9,1%
Policy	Policy (excl. Building regulations) and societal issues (e.g. specific motivation, sustainability)	19	12	0,0%	10,5%	89,5%
Light players	Actors and their specific actions (e.g. lobbying, cooperation) in the lighting market	17	9	17,6%	41,2%	41,2%
Customized light	Elements of light customization as a customized product to the users' needs and moods (from the light system for the users)	16	10	37,5%	37,5%	25,0%
Daylight	Components and technologies for harvesting and using daylight	13	10	0,0%	46,1%	53,9%
Integrated light sources	Elements about new innovative light sources (e.g. OLED surfaces emitting light)	10	8	30,0%	60,0%	10,0%
Building regulation	Building regulations policies	10	8	10,0%	20,0%	70,0%
Esthetic/emotion	Elements related to the beauty of light	8	6	62,5%	37,5%	0,0%
Health	Considerations about human health	7	7	71,4%	28,6%	0,0%
Human productivity	Light as element of human productivity	5	5	60,0%	20,0%	20,0%
Individual controlled light	Considerations about the capability of users to regulate and adjust light (from the users to the light system)	5	5	20,0%	20,0%	60,0%

observed elements in this category. The connection between the two elements is expected to occur through the diffusion of new business models, functional-based and with a life-cycle perspective.

Dynamic light. The future of the light is smart, that is, the lighting systems will have the ability to control the light. Various typologies of sensors are mentioned. Moreover, interviews indicate the diffusion of new light management practices, and specific software. The combination of new software, technologies and management practices will change the lighting from being a sum of individual controlled bulbs, to a complex and integrated illuminating system.

Technology of electric bulb. The diffusion of LED is the dominant expectation of all interviewees. Some of them differentiate between LED and OLED (organic LED), whilst others indicate OLED as the evolution of LED. Among the first, there is the idea that OLED is a different technology that will allow the integration of lighting sources in different surfaces and contexts. Therefore, OLED is expected to drastically change the concept of light, even in respect to LED. Future lighting applications will mix OLED, used as general background and 'bulbless' light, and LED, used in more traditional bulbs. Among the second, there is the idea that OLED will replace LED, but this process is slow and goes beyond 2030, because LED is ready, whilst OLED is still in an infant stage.

Quality of light. Quality and comfort are essential elements in the design of future lighting scenarios. Better light experience is mentioned as an important dynamic of future light. Thus, some interviewees mentioned thermal comfort as an element that will be considered more in future lighting systems.

Policy. The sustainability discourse in policy and society is expected to play an important role in the future. Many interviewees mentioned different policy instruments such as (energy) taxes, new light standards, and green public procurement. Some interviewees mentioned the greenwashing political perspective which may lead to ineffective solutions. In addition, light pollution is indicated as a phenomenon which is not addressed by policy makers.

Light players. The lighting value chain is expected to change. Lighting designers will become more important players, because they are core actors for the design and plan future light systems. Lighting designers will cooperate more with architects and lamps manufactures. For some interviewees, lighting designers will emerge as a new fresh set of players, whilst the rest expects big lighting players to acquire such competences and move from selling lamps to selling lighting systems. Electronics players may enter the market, by exploiting the competencies and the opportunities acquired with LED and OLED technologies for displays. An interviewee highlighted that the lighting industry is

increasingly intertwined with the videogame industry. The collaboration will further develop because the videogame industry needs lighting designers to develop realistic light experiences. Thus, videogames provide inspiring settings to show new lighting opportunities which can be replicated in real contexts.

Customized light. Customized light will be an essential dimension of the future light system. People will use lights that are tailored for specific purposes. Customized light will be evident in shopping experiences and working spaces.

Daylight. The interviewees mention windows, blinds, mirrors, and sun tunnels as part of the future light system especially in the construction of new buildings, while daylight use only rarely can be developed significantly through retrofitting.

Integrated light sources. A little less than half of the experts identify elements in this category. The concept of light bulbs may disappear in the future, replaced by illuminated environments in which any kind of surfaces can be a source of light. Displays and screens will be used as sources of light, even if not yet recognized as such. Windows and walls will produce electric light to compensate when the natural light is not sufficient in terms of intensity and color.

Building regulation. The building code is often indicated as a measure that will influence the future light systems. Other indicated measures are the building certifications (e.g. LEED), the Danish DGNB institution, which assesses the overall performance of a building, including the environmental sustainability, and the Danish DS700, the standard for the use of light in building.

Esthetic/emotion. The emotional role of light is pointed out as element of future light system by a minority of the interviewees. **Health.** Future research will better understand how light influences human health, and this information will be part of the future light design. **Human productivity.** In the future, firms will better consider how lighting settings influence productivity. The design of lighting systems may become part of any firms' strategies. **Individual control.** Few elements refer to the direct control of future light practices by the users. Manual switchers are not expected to be part of future light settings.

A number of the categories contain elements that can be expected to involve an expansion of the use of light and light technology and a development in the functional role of the light. These include dynamic light, quality & comfort, customized light, integrated light sources, esthetic/emotion, health, and human productivity.

4.2. Relationship between the elements

Fig. 1 represents the results of the network analysis of the relations

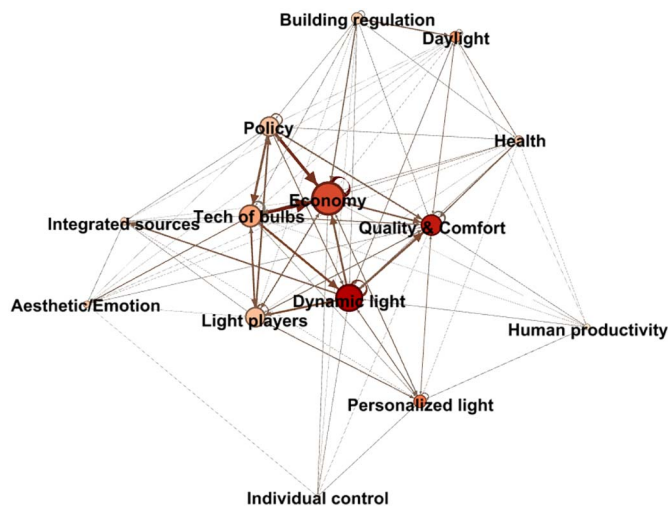


Fig. 1. The network analysis of the future lighting scenario. Nodes represent categories of elements and size of nodes the total weighted degree. Degree indicates how many nodes are connected to a specific node. The weighted degree adjusts the degree value for the number of interviewees which mentioned the node (the maximum weighted degree value is the number of nodes multiplied for the number of interviewees). Color of nodes represents the value of betweenness (darker is higher).

Table 2

Network parameters for the lighting system. Betweenness is a measure of centrality of a node which represents how many times a node is in the shortest pattern between two other nodes.

Label	Normalized betweenness	Degree			Weighted degree		
		In-	Out-	Tot	In	Out	Total
Dynamic light	0.073	13	12	25	53	51	104
Quality & comfort	0.066	13	12	25	50	28	78
Economy	0.055	14	10	24	77	53	130
Personalized light	0.044	10	9	19	25	19	44
Daylight	0.034	10	9	19	20	17	37
Tech of bulbs	0.030	10	12	22	32	52	84
Light players	0.021	8	11	19	30	44	74
Esthetic/emotion	0.018	6	7	13	9	9	18
Policy	0.018	9	11	20	30	43	73
Health	0.017	7	9	16	9	19	28
Building regulation	0.015	9	9	18	16	23	39
Integrated sources	0.015	9	5	14	18	5	23
Human productivity	0.007	4	7	11	6	10	16
Individual control	0.003	5	4	9	5	7	12

between the different categories and Table 2 reports the main network parameters. The analysis confirms an interconnected and systemic character of the future socio-technical lighting systems.

It is worth noticing that the central categories do not necessarily reflect the most popular ones. *Policy* and *technologies* have a relatively high weighted degree, but rank low in terms of centrality (betweenness). *Dynamic light*, *quality & comfort* and *economy* have the highest centrality measure and high weighted degrees.

Economy, *technology of bulbs*, and *dynamic lights* are the categories with the highest outer degree. They are the categories with the most direct influence on other categories. *Economy*, *quality and comfort*, and *dynamic lights* are instead the categories with the highest number of incoming links. They are the categories most directly influenced by other categories.

Table 3 presents relationships between the target and source elements categorized by the potential for energy saving.

There are 120 relationships between elements that both rank high for energy saving potentials. This represents almost one third of the total number of relations. Hence, the lighting network is expected to

Table 3

Weighted degree according to potential for energy saving.

No. of relationships according to potential for energy saving		Target			
		Low	Medium	High	Total
Source	Low	23	26	18	67
	Medium	22	45	39	106
	High	28	60	120	208
	Total	73	131	177	381

contain several relations between different elements which have a high contribution to energy saving. The specific number of connections with self-reinforcing loops is hard to calculate with our methodology because the typology of relationship (reinforcing vs. weakening) is addressed only through a qualitative analysis of the interview.

Several the relations may generate rebound effect. One place to look for this, is the group 'high-low' which includes 28 elements. The technology of bulbs appears as source 12 times, followed by policy (6). Health, esthetic, and quality of light are the most relevant targets. For example, interviewees highlighted that the technology of bulbs (i.e. the LED technology) will increase the attention towards the health dimension and the esthetics, whilst the policy dimension will increase the focus on the development of better quality of light.

The group 'low-high' (18 elements) indicates the elements that are not thought to deliver energy saving but that seem to impact elements with high energy saving. They may represent the positive 'paradox' that is the existence of elements which are not thought to deliver energy saving but they will do it by influencing other elements. Economy (5), health (5), and quality of light (4) are the most important sources of that group. They are expected to impact the development of new LED technology and the building regulation. According to the interviewees, LED technology will be pushed because of its better quality, while the building regulation will be impacted because of health issues related to the use of daylight.

Table 4 reports the relationships between the different elements in terms of most influential and most influenced categories for each category. The most influential categories represent the ones that generate most of the connections which influence the considered category, vice-versa, the most influenced categories represent the ones that are the target of the connections starting from the considered category.

Esthetic/Emotion. The technology of bulb dimension strongly influences the esthetic/emotional category, because LED technology is expected to improve the esthetic value in respect to fluorescent light. At the same time, the esthetic/emotional dimension is expected to push the development of integrated sources of light, and the attention towards quality and comfort.

Building regulation and daylight. Both categories are clearly intertwined: building regulation influences daylight practices, new daylight practices and solutions influence building regulation. In addition, *building regulation* is intertwined with consideration about lighting and heating cost (economy dimension), while daylight is clearly connected to new knowledge about health effects of light, and increasing attention towards quality of light, which will impact the dynamic light concept, because daylight will be integrated in the general lighting management system.

Dynamic of light. The dynamic light shows an impact on the overall quality of light, but it also features relevant internal correlations, because they dynamic system is actual a complex infrastructure composed by several connected technologies and elements dependent on each other. Thus, the technology development of bulb is expected to impact the dynamic light category, because of the already mentioned features of customizability and versatility the LED technology.

Economy. Besides internal correlations, LED technologies is expected to play a great impact on the economy dimension, through the delivery of more efficient solutions. Similarly, the economy dimension is

Table 4

Most influential and influenced categories for each category. Percentages indicate the share of the total inner edges (most influential categories) and outer edges (most influenced categories) that connect a category to the other ones. For example, 44,4% of elements which influence the category “esthetic/emotion” comes from the category “technology of bulbs”; and 22% of elements which starts from ‘esthetic/emotion’ ends in the category “integrated sources”.

Category	Most influential categories		Most influenced categories	
1.Esthetic/emotion	Technology of bulbs (44,4%)	Daylight, health, integrated sources, light players, policy (11,1%)	Integrated sources, quality and comfort (22%)	
2.Building regulation	Daylight (25%)	Economy (18,8%)	Daylight, economy (22%)	
3.Daylight	Building regulation (25%)	Health, quality and comfort (15%)	Building regulation (24%)	Dynamic light, quality and comfort (17,6%)
4.Dynamic light	Dynamic light (20,8%)	Technology of bulbs (17%)	Dynamic light (21,6%)	Quality and comfort (17,6%)
5.Economy	Economy (23,4%)	Technology of bulbs (18,2%)	Economy (34%)	Quality and comfort (13,2%)
6.Health	Building regulation, Technology of bulbs (22,2%)		Quality and comfort (26,3%)	Daylight (15,8%)
7.Human productivity	Personalized light, quality and comfort (33,3%)		Dynamic light, personalized light, quality and comfort (20%)	
8.Individual control	Esthetic/emotion, building regulation, dynamic light, economy, personalized light (20%)		Dynamic light, personalized light, economy (28,6%)	
9.Integrated sources	Dynamic light (33,3%)	Esthetic/emotion, light players, policy, technology of bulbs (11,1%)	Esthetic/emotion, daylight, dynamic light, economy, personalized light (20%)	
10.Light players	Light players, technology of bulbs (23,3%)		Dynamic light (18,2%)	Light players, policy (15,9%)
11.Personalized light	Dynamic light, economy, light players (16%)		Dynamic light, economy, light players, quality and comfort (15,8%)	
12.Policy	Light players (23,3%)	Economy (20%)	Economy (27,3%)	Technology of bulbs (20,5%)
13.Quality & comfort	Dynamic light (18%)	Economy (14%)	Economy (17,9%)	Dynamic light (14,3%)
14.Tech of bulbs	Policy (28,1%)	Economy (18,8%)	Economy (26,9%)	Dynamic light (17,3%)

expected to negatively influence quality and comfort of light, because efficiency and cost saving dynamics may reduce the efforts towards better light quality.

Health. The increasing importance of the consideration about health effect in the use of light is going to influence the light quality and the daylight dimensions. On the other side, LED technology is expected to improve the quality of current light source. Similarly, building regulation is expected to improve the health dimension by forcing the use of better-quality electric light and daylight.

Productivity. Human productivity is intertwined with the quality of light and the personalized light, resulting in the development of dynamic light systems which will customize light quality in respect to the specific human needs, as result, working environment quality is going to increase with a positive impact on human productivity.

Individual control. The individual control dimension relies on many dimensions, because human active interaction is part of a process of personalization of light and of development and use of more flexible and dynamic light systems.

Integrated source. The usage of ‘bulb-less’ light solutions will be a part of the future dynamic light system, increasing the esthetic experience of light. LED is an enabling technology, however cost-related issues will pose some relevant issues in the transition phase.

Light players. New light players which have the competence to develop and design dynamic light systems will appear, and they will have a pivotal role in lobbying the policy level. Change in industry structure is therefore an element that will influence future policies for lighting. The competences of such future players will depend on the strategy of the current light and semiconductor players.

Personalized light. The personalization of lighting solutions is intertwined with dynamic light, economy, and light players. The former will give the infrastructure for personalization of light, and the latter the actors developing it. The analysis shows a strong looping-back system, in which the personalization of light will also call for new light players able to develop dynamic light solutions.

Policy. The policy level is expected to influence the pace of development of LED and, because of the lobbying activity previously mentioned, it is also expected to be influenced by the strategies of new lighting players. Thus, the policy level is expected to be intertwined with the economy dimension, because of the importance of efficiency in current energy policy.

Quality and comfort. This dimension is intertwined with the development of a dynamic light system and more economic dimension. The

connection with dynamic light shows that the concept of quality of light is not simply the development and diffusion of light with better chromatic rendering index, but the capability to develop light systems which adapt to the conditions of the environment, creating the ‘right’ lighting environment. The economy dimension may become a barrier towards the development of high-quality oriented light systems. To overcome such cost issues, it is important that the quality and comfort dimension stresses the positive effects on health and human productivity, previously mentioned.

Technology of bulb. This dimension is clearly pushed by consideration about cost of energy (economy) and environmental aspects (policy) with important repercussions on the development of the dynamic smart light.

As final remark, Table 5 presents the missing opportunities for energy saving, which are the elements identified by interviewees as having high potential for energy saving but low degree of feasibility. These five elements indicate opportunities for energy saving that may not develop because of technical, economic, or societal limitations.

5. Discussion

The discussion focuses on the findings on potential rebound mechanisms for energy consumption. Medium or high potentials of energy savings are identified by a majority in 10 out of the 14 categories. At the same time, however, energy saving is not among the overall categories of elements. In this sense, it is a secondary type of element.

The results show consensus on three trends which together can be said to reflect the base of the current light-oriented policies for energy savings. Firstly, technological development will occur in the shape of LED technology and of lighting control systems (cf. Leslie et al., 2005; Mohamaddoust et al., 2011) and directly contribute to energy savings. The two technologies are intertwined and constitute the base of the

Table 5

Missing opportunities for energy saving according to interviewees.

1. Attention to the quality of light fixtures. Usually good fixtures are more expensive, but they can reduce the consumption of energy
2. Low attention to the used watts. Users pay attention to the installed watts (purchasing behavior) but they tend to ignore the actual used of light (i.e. total consumed wattages) over the time
3. Lack of focus on funding ‘bigger’ research projects which can create critical mass
4. Development of portable light which can minimize the use of general light
5. The underuse of daylight in the existing buildings

diffusion of *smart light* systems and dynamic light. Secondly, energy policy can be expected still to emphasize energy efficiency providing incentives to widespread diffusion of the energy efficient technologies. Thirdly, sustainability will be a central dimension both in policy and public discourses about lighting.

However, besides these elements, the results showed several other important systemic relationships which may generate rebound effects. First and most directly, other considerations about the function and use of light such as comfort, esthetic, customization, health, and productivity will become central in the future and expand the purpose of lighting systems. The attention of developers, customers, and users to energy and cost savings as selection criteria may be reduced relatively in favor of a more complex set of objectives. The functional expansion is spurred not least by a widespread interest in the new technological opportunities.

The functional level is the first of four central levels of rebound mechanisms identified through the analysis. The others are: the technological level, the organizational-structural level, and the normative level.

The technological level has already been mentioned above. In addition to the expanded use potentials connected with the individual technologies, our results point to the importance of the technology-technology relationships as mechanisms contributing to rebound effects. The integration and mutual synergies between technologies expands the potentials for use even further than the individual technologies. For example, *smart* LED light systems are not only very efficient system, but also as superior to current light solutions with respect to many other characteristics (e.g. versatility, dimmability, quality of light). As result, the future smart LED light system might open new unforeseen types of applications which can increase the demand of artificial lighting. For instance, virtualization of windows (i.e. using organic LED films on displays to emulate outdoor view of a window). Instead of 'just' a source of light, the smart LED system represents a complete visual experience.

The third level of rebound mechanisms consists in the structural-organizational transformation of the lighting sector when new types of players appear in the lighting value chain and new cooperation networks and business models are established. Our analysis points to that these structural-organizational changes play an important role for the development of the new market solutions, like future *smart* LED light systems. The dominating part of the current lighting sector has a bounded view that still perceives the LED light as a new bulb, and not a new frontier in the users' interactions with illumination.

Finally, the normative level is the level of public discourses, norms and policies that indicate what light and lighting systems should be and requirements they shall fulfill. To a certain degree the normative level is connected to and reflects the functional level and use of lighting in practice. However, the dynamics can be different and go through other, also more indirect connection chains and forums, e.g. lobbying activities, advocacy coalitions, public debate, and political discussions. Our analysis shows that other policy areas than energy saving policy are involved, including building regulation and policies on working environment, labor market, and health. Among the mechanisms are also an increase in knowledge development on the relationship between light, health, and human productivity.

We stress the rebound effects are systemic and typically occur through several of the levels in the complex socio-technical systems.

As an additional transversal element, the time dimension is essential for understanding the dynamics. In the short-term, efficiency and sustainability focus will drive the diffusion of LED technology with important impacts on energy saving. This is indicated by the high degree of feasibility stated by the interviewees on these dimensions. The LED developments will shrink consumption of energy due to the increased efficiency in the provision of light, enforcing the consensus about the efficacy of the current policies. However, in the long term rebound effects can be expected. It will take time because it requires new

arrangements of practical, technical, as well as organizational competences and goals. Consequently, the actual dynamics leading to energy saving might paradoxically pave the way, in the long-term, for new usage of light.

While our method does not allow for a quantitative account of the size of the rebound effect or a measuring of the influence of the different levels, our analysis clearly shows the rebound effects will appear through several different mechanisms. Whether the effect in total is bigger or smaller than the energy savings created is an open question.

Finally, we mention that though some of the elements (e.g. within policy, building regulation and daylight) to some extent are shaped by the local, Danish context, the small-country character of Denmark is confirmed by the refer to some dynamics which are going to occur *anyway* because of global trends in the lighting domain, especially in connection to the transformation of *light players* and the diffusion of the new *technology of bulbs* (i.e. LED and OLED).

6. Conclusions

The systemic analysis provides a fruitful approach to understanding dynamics of energy consumption for lighting. In fact, the combination of the static and network analyses indicates a complex picture in which many elements interact. We conclude by summarizing the main findings and the contribution to the rebound effect literature.

First, technological development is quickly going to take place. Second, LED is not just a more efficient lighting technology, but it is superior in respect to many parameters (quality, customizability, and miniaturization). Third, policy is identified as having the highest potential for energy saving, and sustainability plays a role in shaping the social commitment towards energy saving. But, and fourth, new practices and issues will arise thanks to the new possibilities given by a smart light system based on LED and these practices are likely to increase the demand of lighting. Fifth, new players, which integrate new and old capabilities, will enter the market to exploit the potentiality of the future smart LED light system. Sixth, the overall impact on energy consumption is likely to drop during the first stage of technology replacement but the long-term trend is unclear because of the new solutions promoted by the future lighting players. Seventh, future lighting policies will face more complex decisions because energy efficiency will not anymore be the main (or only) criterion of policy selection.

In this sense, rebound effects are not a one-dimensional matter of action and reaction, but complex phenomena that involve multiple dimensions and heterogeneous connections. The systemic network perspective provides a fruitful approach to understanding the qualitative changes behind innovations which increase, among others, efficiency of the economic process. In this case, policy makers shall be aware that effective policies are not simply the ones which offset the cost benefits delivered by the increase of efficiency, but also the ones which consider the overall changes in the current practices.

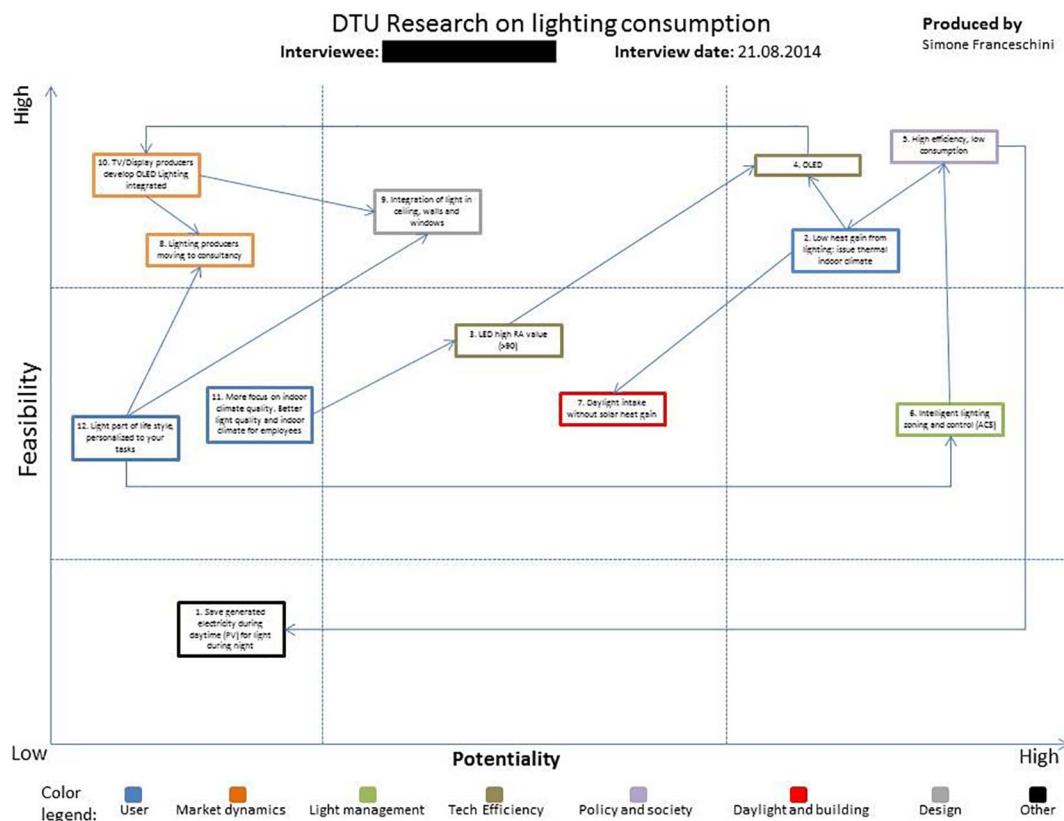
The contribution of this paper is two-fold. First, it provides new knowledge about the dynamics of lighting sector and describes some relevant rebound effect mechanisms which may occur. To our knowledge, this is the first work where such rebound mechanisms are described in detail looking at the systemic interplay of heterogeneous elements including new technologies, use practice, players, business models/solutions, and institutional dimensions. Our study points out the need of the political guidance of lighting innovation if society wants to assure net energy reduction in the provision of light. On the one hand, policies that encourage the development and diffusion of LED technology are effective ways to increase the efficiency of the provision of light. On the other hand, policies which target energy efficiency shall be carefully designed. Future lighting discourse and practices will be more complex, because trade-offs between efficiency, health, use-value, functionality, energy saving, and productivity are likely to be evident as soon as LED will develop, new lighting opportunities will arise, and further knowledge will be developed. In the future, lighting policies

shall choose how to integrate and balance these different aims. Shall environmental sustainability still be in the top of the agenda, even when it contradicts with decisions about health and quality of life? These are complex decisions which go beyond this study and reside in the domain of politics. Unfortunately, the awareness of this complexity is still neglected in traditional analysis about the expected benefits of technological changes in the lighting technologies (European Commission, 2012), creating a risk for the social and environmental sustainability of the future light systems.

Second, the paper shows that a network oriented analysis may provide useful qualitative information about the potential future rebound effects. In the specific case of lighting, we found that the potential rebound effect is a combination of technology (smart LED),

market capabilities (new light players), and new institutional assets (new perspectives about lighting) which might end up with new practices about lighting which will increase energy consumption. However, we stress that such approach can be fruitfully applied to describe other sectors than lighting. By doing so, we stress that a future looking network-oriented approach is a valid complement of traditional long-term historical studies or econometrics model. In our view, our approach becomes essential when radical innovations are expected to occur in fast changing contexts, with the effect of disrupting current socio-technical systems. Under these circumstances, we think that a future looking perspective (as in this work) is better positioned than a past-looking one to capture such radical changes.

Appendix 1. Example of an interviewee's final cognitive map



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