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Explaining the Diffusion of Energy-Efficient Lighting in India: A Technology Innovation Systems Approach

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Abstract: Electricity consumption from lighting accounts for about 15% of total power demand and 5–6% of greenhouse gas emissions in developing countries. It is therefore a promising avenue to achieve considerable energy savings through technological innovation and upgrading. India has been very successful in recent years with a nationwide roll-out of modern light-emitting diode (LED) applications. This study uses the framework of technology innovation systems to identify the actors, institutions, and processes behind the diffusion of this technology. Our findings indicate that national innovation strategies, along with low-carbon technology (LCT) transfer policies, helped to bring down the cost of LED lamps in a rapidly expanding domestic market. Based on the findings, we further explore lessons for broader issues of low-carbon technology transfer and suggest an emerging intermediate step between north–south and south–south technology transfer.

Keywords: low-carbon technology transfer; technology innovation systems (TIS); energy-efficient technologies; LED; sustainable energy; developing countries

1. Introduction

2015 was an historic year for global sustainable development efforts, with the Paris Agreement at COP21, and the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), coming into life. Both agreements place a strong emphasis on clean energy development, in particular in energy-poor developing countries, where the lack of modern energy services affects a wide range of economic and social issues, and is disproportionally impacting women and children [1,2]. With more than 860 million people in the world today without access to electricity and 2.6 billion people that rely on the traditional use of biomass for cooking and heating [3], this is not an easy challenge. Moreover, the problem will be further exacerbated by a growing world population and increasing economic development, and thus energy demand, in many parts of the world. Future solutions must also emphasize the consumption side of energy systems in order not to waste additional energy supply by using outdated energy-intensive technologies. This is also being reflected in a recent assessment by the International Energy Agency that suggests that more than two-thirds of the global economically viable energy efficiency potential will remain unrealized under existing policies [4]. A promising sector for energy savings from technological upgrading is lighting. Globally, electricity from lighting accounts for about 15% of total power consumption and 5% to 6% of worldwide CO_2 emissions [5]. While developed countries like Japan have managed to reduce their lighting footprints with advanced energy-efficient lighting technologies, such as light emitting diodes (LEDs), to as low as 10% of their total electricity consumption [6], a developing country like Nepal is spending as much as 21% of its total electricity supply on lighting services [7]. These examples demonstrate how the global fight against energy poverty could be accelerated if the international community would increase its efforts to assist developing economies in implementing energy efficiency measures. For example, through the transfer of modern energy efficiency knowledge and technologies, which is emphasized in SDG 17 as the need for partnerships in technology transfer for low-carbon technologies (LCT). The Intergovernmental Panel on Climate Change (IPCC) defines LCT transfer as "*a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders such as governments, private sector entities, financial institutions, NGOs and research/education institutions*" [8] (p. 4) clusiont tranablished and problished and prominemtly hime can help with nt mechanism (CDM) cap and trade).

India is a developing country with a population of more than 1.25 billion and it is predicted to overtake China as the world's most populated country by 2030. However, India faces many developmental challenges, especially regarding the supply of modern energy services. About 68% of the country's population still live in rural areas and depend highly on the use of traditional energy sources, such as wood, biomass, and agricultural residue, for their cooking and lighting requirements [9]. At the same time, the country is also one of the fastest growing economies in the world and is facing an ever-increasing energy demand to fuel its rapid industrial and economic development. The Indian government has initiated several policies in recent years to address this energy dilemma. It aims to provide unified access to electricity to 1.25 billion people through highly ambitious targets, such as adding 175 GW of renewable energy capacity by 2022, and an increased focus on energy efficiency. India is attempting to do something which no other nation has ever done before: to build a modernized industrial economy, and at the same time bring light and power to its entire population, without significantly increasing carbon emissions [9].

Among the energy efficiency policies initiated by the government, the "LED Lighting Initiative" was initiated in 2015. Overseen by the Energy Efficiency Services Ltd. (EESL) (New Delhi, India), an organization founded by the Indian Ministry of Power, one of the aims was to distribute 600,000 cost-competitive LED bulbs per day over the span of two years. This was supposed to stimulate domestic consumption and thus help to develop a modern domestic LED manufacturing industry [10]. Another goal was to replace 35 million street lights, nationwide, with LEDs, which would essentially mean a reduction of electricity demand for street lighting from currently 3400 to 1400 MW, thereby saving 9000 million KWh of electricity annually [11]. As of August 2020, more than 366.4 million LED bulbs and 10 million new LED street lights have been distributed under the scheme [12,13]. Furthermore, a huge technological capacity building and localization effort has been taking place in India due to this policy. Today, most major lighting product manufacturers have established a presence in India, and those who have not, are trying to enter the market. The cost of a 9 watt LED bulb distributed under the Indian government's Domestic Efficient Lighting Programme (DELP) (also called *Unnat Jyoti by Affordable LEDs* (UJALA)) is only USD 0.8 (INR 56), the lowest price anywhere in the world [14]. Further, all this happened in a country which, just a few years ago, did not have any domestic LED manufacturing industry to speak of.

Our study uses the technology innovation systems (TIS) framework to identify the actors, institutions, and processes behind the diffusion of LED technology in Indian society. It explores the question of how the country managed to avoid the pitfalls and barriers that usually hinder technology transfer and implementation efforts in developing countries. The article will proceed by introducing the reader to our theoretical and methodological frameworks, before presenting the research findings and a discussion of what lessons the Indian experience can teach us for the broader issues of low-carbon technology transfer in and between societies.

2. Theoretical Framework

Barriers to the diffusion of energy-efficient lighting have been studied at various levels, ranging from general discussions over barriers towards diffusion of compact fluorescent light (CFL) lamps [15] to more detailed research on technological innovation in solid-state lighting at the pilot scale [16]. However, until now, there has been limited research focusing specifically on large-scale diffusion of energy-efficient LED lighting technology in developing countries. This study builds on the growing empirical literature of the technology innovation systems (TISs) approach [17–22], which aims to understand the barriers and enablers to the adaption and diffusion of certain types of environmental friendly technologies, such as renewable energy and energy efficiency technologies. Carlsson and Stankiewicz [23] (p. 94) define TIS as "*a network of agents who interact in a specific economic/ industrial area under certain institutional infrastructure or set of infrastructures and are involved in generation, utilization and diffusion of technology*". It argues that all innovations are a collective activity that take place within the setting of specific innovation systems, which can be subdivided into national/regional, sectoral, and technological innovation systems. Every technological innovation is embedded in its own specific TIS, with associated actors, structures, and processes that influence the outcome of the innovation process. A well-functioning system will be highly supportive of the development of a certain innovation, while unsuccessful innovation processes point to certain barriers within the TIS. Painuly [24] developed a useful set of analytical categories for the identification of barriers to the diffusion of renewable energy technologies, which can also be applied to our case of technological innovations systems of LEDs: (1) market failure/imperfections; (2) market distortions; (3) economic and financial factors; (4) institutional factors; (5) technical factors; and (6) social, cultural, and behavioral factors). A typical TIS analysis starts with the identification of the structural elements that make up the TIS environment, followed by a functional analysis of processes within the TIS to systematically identify factors that drive or hinder the development of a particular technological field.

The structural elements of any TIS environment include actors, networks (interactions), institutions, and infrastructure (technological artefacts) [25,26]. However, structural factors alone cannot explain the success or failure of a technological innovation. It is necessary to also investigate the dynamic interactions among different structural components of TIS to understand the outcome of a specific technology innovation and diffusion process (such as the successful market penetration of LEDs in India). The functions of innovation systems approach has helped researchers overcome this limitation [27]. Using the functions for the analysis of TIS allows not only for a systemic mapping of innovation determinants but also for the identification of the system's strengths (enabling factors) and weaknesses (barriers). Such an analysis in turn allows for the formulation of policy targets and the development of policy instruments to meet those targets [28]. Certain 'event types' linked to one of the functions can influence the trajectory of the innovation process and potentially even derail it. Since the nature of these events differ considerably between technologies, each study needs to identify the relevant key events for its specific research focus to guide the analysis and to allow for an assessment of the performance of the TIS [28,29]. Table 1 showcases the functions and associated event types that we adapted specifically for the LED sector development in our Indian case study.

Table 1. Event types associated with the functions of innovation systems in the Indian LED sector. Source: modified after [21,25,27,28].

System Function	Event Types (Modified for the LED TIS Environment in India)
1. Entrepreneurial activities	Number of experiments, pilot, and demonstration projects by the private sector for LED lighting; new businesses in LED lighting technology; capacity to produce and develop technology domestically
2. Knowledge development	Formulation of energy efficiency and LED lighting standards; studies related to LED technology development, market formation, industry cooperation, and feasibility studies
3. Knowledge exchange	Accessibility of publications and standards related to energy efficiency in lighting; accessibility of reports related to LED technology development, market formation, industry cooperation, and feasibility studies; workshops, conferences or exhibitions related to energy-efficient lighting and more specific to LED lights
4. Policy support	Government bodies relevant to energy efficiency and LED diffusion in the Indian lighting sector; policies, initiatives, and explicit targets to promote energy efficiency in the lighting sector; policies, initiatives, and explicit targets for the development and diffusion of LED lighting technology
5. Resource mobilization	Government financing of demonstration/large-scale deployment projects; financial capacity building; founding of R&D facilities and testing labs; access to (micro) credits for energy-efficient lighting, including LEDs
6. Market formation	Tax exemptions for energy-efficient lighting products, including LED technology; subsidies for energy-efficient lighting; implementation projects in energy-efficient lighting, including LED technology by government or private actors
7. Advocacy support	Lobbying activities for energy-efficient lighting, including LED lighting technology; expressed support for energy-efficient lighting technologies by key opinion leaders in the government and the private sector; increased media interest on energy-efficient lighting technology

Another important factor in the analysis of technological innovation systems in developing country settings is the international dimension, in particular the role of technology transfers between countries. Traditionally thought of as a unidirectional movement of knowledge and products from developed countries (the "north") to developing countries (the "south"), the growing importance and capabilities of industries in emerging economies created another movement between developing countries, the so-called "south–south" technology transfer [30]. The international dimension of innovation through technology transfer has gained significant recognition in recent years and added an additional component of comparability in sustainability transition analyses [17,18,20]. During the literature review in the initial stages of our study, it became apparent that certain key barriers to technology transfer issues, especially intellectual property rights (IPRs) and standardization [31], also played an important role in the domestic innovation and diffusion processes of a cutting-edge technology, such as LEDs, in India. We therefore followed the examples of previous studies, such as Binz et al. [20] or Bento and Fontes [18], and included an additional layer of analysis into our functions, which integrates the spatial dimension of international technology transfer with the local barriers to implementation and adaptation.

3. Methodology

Our qualitative research design followed a multi-step approach, including desk research, the construction of an online questionnaire, and expert interviews with key actors. The first step involved an in-depth literature review of a variety of sources, including research papers, newspaper articles, as well as grey literature, such as working papers or policy briefs from governments and think tanks. This was followed by the development and distribution of an online questionnaire among

36 member companies of the *Electric Lamps and Components Manufacturers* (ELCOMA), which is a non-profit umbrella organization for the lightning industry in India and actively involved in the process of LED lighting diffusion. The questionnaire was meant to complement the initial literature research and to help identify relevant stakeholders and experts about LED lighting technology in India. Although only 6 out of 36 companies responded to the online survey, this preparatory step helped to further sharpen the analytical framework and to identify appropriate partners for the following 17 face-to-face interviews with Indian government representatives, academics, and relevant stakeholders in industry and non-governmental organizations (Table 2). The strength of in-depth qualitative research is simultaneously also its weakness, as common constraints, such as limited resources, only allow the gathering of small interview samples. We tried to address this issue by choosing a heterogenous mix of interviewees, representing different positions across the value chain of LED technology, from development and manufacturing to marketing and sales.

Table 2. List of expert interviews.

Organizations	Investigation
Government: Energy Efficiency Services Limited (EESL), Ministry of New and Renewable Energy (MNRE), South Delhi Municipal Corporation (SDMC); Office of Superintending Engineer, SDMC	Interviews: 4
Manufacturers: LED technology companies operating in India, incl. Toyoda Gosai Co. Ltd.; Orange Tek; Zhong Shan Yi Tai Fu Lighting Ltd.; Rama Industries; Fulham (India) Pvt. Ltd.; Wellmax Lighting; Indo Japan Specialists in Lighting; Kwality Photonics; Precision Components and Engineers; Sieger LED Industries	Interviews: 9
Business Associations: Electric Lamp and Component Manufacturers Association of India (ELCOMA); LED Products Manufacturer's Association (LEDMA)	Interviews: 2
Not-for-profit organization: The Energy and Resources Institute (TERI), GIZ India	Interviews: 2

The semi-structured interviews were the key part of the study and included general questions about the Indian LED sector, as well as questions specifically tailored to the role of the interview partner in the process of domestic LED technology development. A semi-structured interview format has the advantage that it allows the inclusion of topics brought up spontaneously by the interviewees themselves and that it gives the researcher the opportunity to conduct the interview in a more flexible way. For instance, during the interview with international business actors, it became apparent that some of them did not have very detailed knowledge about the government policy for large-scale diffusion of LED lights in India. In these cases, the questions asked during the interview were transformed into hypothetical settings. The questionnaire was guided by the seven TIS functions and corresponding event types that were adapted to our specific case study of LED lighting technology in India (Table 1). It also addressed barriers and challenges that different actors were facing and what influence government policies had on improving the effectiveness of the system as a whole. The interviews lasted between one and two hours and were conducted by the lead author in September and December 2016. The conversations were recorded and later transcribed. The interviews were conducted in line with the stipulations of the United Nations University's ethical research guidelines. All interview partners were informed about the aims of the research project and provided verbal informal consent to participate. Since not all interviewees were comfortable to be named in the final article, only the name of the organization and their position are mentioned in the text.

4. Results

In 2006, the LED technology sector in India was still rather underdeveloped. There was just one local LED packaging company and no multinational company was thinking about entering the market [32]. In 2016, the Indian LED sector had already evolved into a market worth more than US$ 1 billion annually, shared by 27 large and medium, and more than 600 small-size manufacturers, while all major international chip producers had established branch offices in India [33]. According to a senior-level representative at ELCOMA, the major challenges to LED development in the early days of the Indian LED sector were the lack of localized standards, high technology costs, intellectual property rights (IPRs), and the negligible market size (Interview, ELCOMA management, 16 September 2016). However, only a few years later, India had managed to successfully establish a domestic LED technology industry. The following subsections will examine the key actors and processes behind this development by disaggregating it through the lens of TIS functions (Table 1).

4.1. Entrepreneurial Activities

This function describes activities by existing or emerging industrial actors to create and market technological innovations [28]. A major obstacle to the entrance into the Indian LED market was initially the lack of industrial standards. This was eventually resolved in 2012, when the IEA en.lighten initiative successfully facilitated the adoption of international LED standards localized for Indian usage through a collaboration of the Bureau of Indian Standards (BIS), the Bureau of Energy Efficiency (BEE), ELCOMA, and the International Electro-Technical Commission (IEC) [34]. In total, 12 international LED lighting standards were adopted in India, out of which 8 were modified to local conditions [35]. The establishment of local standards enabled the Indian LED manufacturing industry to evolve from merely importing final LED products to the creation of a considerable domestic industrial capacity in the latter stages of the value chain. For this reason, the LED lighting products imported to India saw a growth of 59% and 69% during 2014 and 2015 (worth USD 131 million and 222 million, respectively). The supplier nations included China with a share of 85%, followed by 5.4% from South Korea and 2.4% from Thailand [36]. During our interaction with LED companies in India, each one of them said that they imported LED chips from overseas due to the high investment cost of setting up LED chip manufacturing facilities and India's lack of R&D in this sector. One of our interviewees from the manufacturing sector said: *"Why should I invest in making my own LED chips when I can import them at cheaper cost"* (Interview, Rama Industries, senior level executive, 20 September 2016). Another Indian-based LED luminaire company expressed the common sentiment this way: *"Setting up a LED chip manufacturing facility in India is difficult, because it needs huge investments and we are at least eight years late in R&D. Given the technology and IPR cost we cannot compete with the rest of the world, especially with China and Taiwan"* (Interview, Sieger LED Industries, senior level technician, 14 September 2016). Indian manufacturers are thus heavily dependent on imports for LED chips, which represent around 15% to 20% of the total lamp cost. However, at the same time, they have been quite successful in finding opportunities in niche markets, such as LED luminaire design, retrofitting, or customization, for instance, the Indian-made LED driver circuit, which is currently one of the cheapest in the world (Interview, ELCOMA management, 16 September 2016). Although the Indian LED sector initially lacked domestic research and development capacity and faced restricted access to technology due to intellectual property rights (IPRs) [31], this did not stop the industry from growing at a tremendous pace. LED sales in India jumped from less than 5 million per year in 2014 to more than 520 million in 2018 [37].

4.2. Knowledge Development

This function describes all activities aimed at generating and applying knowledge in a certain field of technology development [28]. One of the most noteworthy efforts taken by the government towards local knowledge development in energy-efficient products in India was the launch of the Energy Standards and Labeling Scheme (S&L) by the Bureau of Energy Efficiency (BEE). The BEE was created in 2002 as part of the Ministry of Power under the provision of the Energy Conservation Act 2001. The agency was tasked with developing policies and programs to increase the energy conservation and energy efficiency provisions in India. The S&L scheme set minimum energy performance standards for electronic appliances and enabled consumers to make informed choices about these appliances. The S&L scheme was designed by the BEE in 2006 and has been regularly updated ever since, with the latest revision released in 2016. The "BEE STAR" labeling system under the S&L programme is similar to the international "ENERGY STAR". Another important step was the publishing of a feasibility report on Economic case to stimulate LED lighting in India by the government in 2010. The report discussed issues pertaining to the economics of manufacturing for LED technology in India and concluded with important recommendations at the local policy level [38]. Arguably, the most important step regarding *knowledge development* was the introduction of local LED standards in 2012. During our discussion with one of the senior-level participants in the former LED standardization committee, he emphasized that there was a need for even further localization of standards (Interview, ELCOMA management, 16 September 2016). To exemplify his argument, he pointed out that internationally accepted standard LED models have holes for the purpose of heat dissipation, which need to be closed in designs for the Indian market to prevent damage from high humidity and dust.

4.3. Knowledge Exchange

This function includes the exchange of information about certain technologies between key actors within the TIS [28]. In India, knowledge exchange about energy efficiency and LED technology at the national level is primarily the responsibility of three entities: The private sector association Electric Lamps and Components Manufacturers (ELCOMA), as well as the government entities Bureau of Energy Efficiency (BEE) and Energy Efficiency Services Ltd. (EESL). ELCOMA decided in 2009 to place a special emphasis on the development of the LED lighting sector in India. The first step was the creation of a new LED chapter to collect information about all LED technology-related activities in the country. The LED chapter was very successful in bringing together all the LED manufacturers and to establish a platform for peer learning in which various domestic barriers for the development of LED technology could be discussed. In addition to serving as a new umbrella body for the domestic LED industry, ELCOMA has been actively involved in the knowledge exchange about LED technology through many workshops and a dedicated white paper series on barriers to LED technology. The Bureau of Energy Efficiency (BEE) is another important actor in the field of knowledge exchange. It was the only government institution responsible for knowledge development and implementation of policies concerning LED technology. It focused in particular on educational activities, such as the organization of regular stakeholder workshops or the production of newspaper articles and TV commercials. However, based on the Energy Conservation Act of 2001, the Indian Ministry of Power established the Energy Efficiency Services Ltd. (EESL) in 2009 to take over the implementation functions of the BEE [39]. The EESL was set up as an energy service company that also served as a consultancy organization for CDM, as well as a resource and learning center for the capacity building of state designated agencies, financial institutions, and utilities in India [7]). Learning the lessons from its predecessors, EESL developed a new and rather innovative strategy for knowledge exchange by combining conventional techniques like workshops and awareness campaigns with a more targeted approach of utilizing public facilities, such as post-offices, banks, and community-level health centers, as product distribution centers. Ordinary citizens, who would visit these facilities on a routine basis, could be reached far more effectively with specialized advertisements and had the opportunity to inquire about additional information directly with the staff of the facility.

4.4. Policy Support

Policy support plays an important role for the development of a TIS, especially considering that policy decisions are always subject to efficient use of scarce resources [28]. The first step towards building an enabling policy environment for energy efficiency activities in India was the Energy Conservation Act of 2001, which was vital for the subsequent establishment of the BEE in 2002 and EESL in 2009. In 2008, the Indian government formulated its National Action Plan on Climate Change (NAPCC) with one of the mission statements focusing on the "enhancement of energy efficiency in demand side energy management" [40]. Additionally, in 2008, the BEE started a nationwide initiative called Bachat Lamp Yojana (BLY) (Hindi for "*save per bulb scheme*") that aimed to enhance energy-efficient CFL penetration in Indian households, at a cost comparative to an incandescent lamp (INR 15/USD 0.23). BLY was so far the biggest policy initiative towards energy-efficient household lighting in India. The program replaced over 29 million incandescent bulbs with CFL lamps in India [38]. The carbon credits saved under the BLY scheme were traded under the Clean Development Mechanism (CDM) of the Kyoto protocol [41]. The Indian government also undertook several fiscal measures, such as a tax rebate policy for LED products in its 2011–2012 fiscal budget. Initially, it reduced the excise duty on LED lamps and LED chips from 10% to 5%. Even though it was increased again to 6% later in the following financial year, the tax rebate to this day remains one of the most lucrative rebates provided for LED technology development by international comparison. The special additional duty was also fully exempted on LED chips used in the manufacturing process of LED lamps in 2012-13. In addition, several state governments took the initiative to reduce their own value added tax (VAT) on LED lamps, for instance, the Delhi government, which reduced VAT on LEDs from 12.5% to 5% in the 2013-14 budget [7]. In 2015, the Ministry of Power simultaneously launched two new initiatives called Unnat Jyoti by Affordable LEDs for All (UJALA) (Hindi for "Domestic Efficient Lighting Programme"), an energy efficiency program for household lighting, and Street Lighting National Program (SNLP), with EESL as the program implementation body. Both initiatives proved to be very successful, with more than 366.4 million domestic LEDs and 10 million LED street lights diffused in the Indian market as of August 2020 [12,13]. Looking at policy support for LED technology by the national and state governments in India from a historical perspective, it becomes evident that the events in 2015 are a result of 15 years of policy work, with the basis laid by the Energy Conservation Act back in 2001. Initially, the national government only half-heartedly supported an already existing bottom-up movement and successfully utilized international instruments like the CDM, before making lighting efficiency a top political priority.

4.5. Resource Mobilization

The gathering and mobilization of human, financial, and material resources is central to the evolution and maturing of any TIS [23,27]. The Delhi government took the lead in 2006 by introducing a "*Buy one get one free CFL scheme*", with the purpose of enhancing energy efficiency among households [7]. While the Indian market price for CFL lamps in 2008 was INR 80–100 (USD 1.22–1.53) per lamp, it was reduced to only INR 15 (USD 0.23), under the subsidized BLY scheme. The government initially aimed to replicate the BLY model for LED lamps in India, but with the crash in carbon markets and dim prospects for the CDM mechanism, the model now faced severe limitations [7]. Commenting on BLY in an interview, a representative from EESL said "*BLY had its days, but for large-scale diffusion of LED lights we needed a better model*" (interview, EESL management, 18 September 2016). As a result, the government launched the UJALA and SNLP schemes in 2015, by far the biggest resource mobilization attempts for energy-efficient lighting in India. In contrast to its predecessor, the BLY scheme, UJALA and SNLP both worked with a "demand aggregation-price crash model", which basically meant reducing cost by stimulating economies of scale. In 2015, EESL invited open bidding from manufacturers for large-scale procurement of LED lamps, and paid all upfront costs. EESL further approached state governments and electricity production and distribution utilities, to sign agreements for creating a value chain for: (1) the public distribution of these LED lamps under the UJALA scheme, and (2) the replacement of existing street lights with LED bulbs under the SNLP scheme. The result of this demand aggregation was a drastic decrease in LED retail prices, which dropped as low as USD 0.8 (INR 56) (Figure 1).

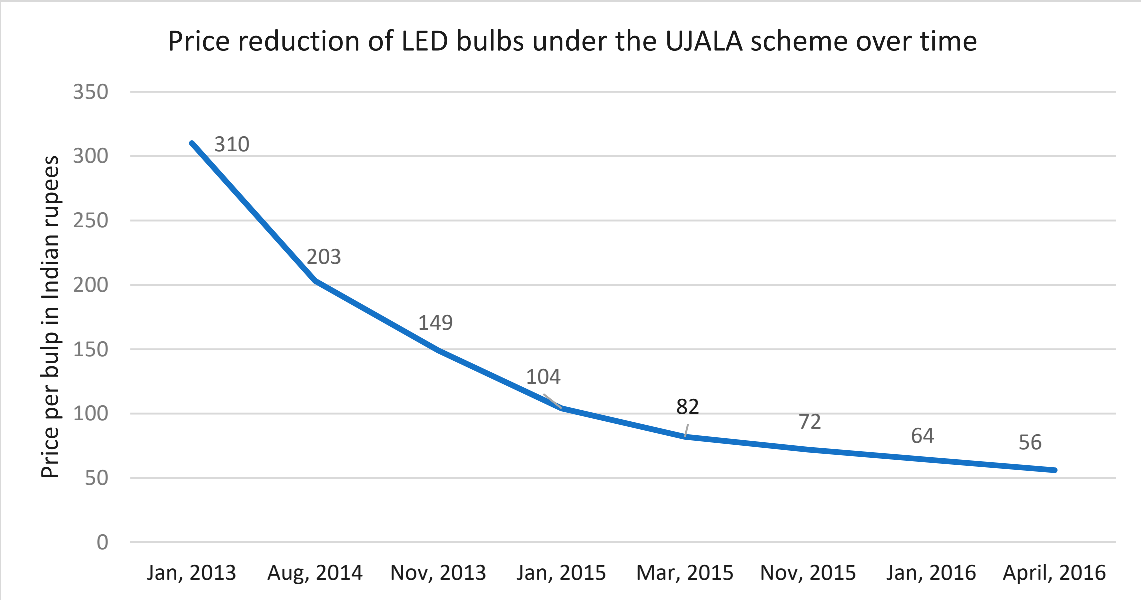

Figure 1. Price drop for LED lamp in India under the UJALA scheme. Graph based on data in [42].

The UJALA scheme provided two different payment options. In a first option, consumers could simply choose to pay the whole cost upfront at once [14]. The second option was a "pay as you wish /on-bill financing" scheme, for which EESL cooperated with the distribution companies to overcome the first-time investment barrier. Consumers were given the choice to pay USD 0.15 (INR 10) upfront per bulb, while the remaining sum was recovered through the monthly electricity bill, charging USD 0.15 (INR 10) per month. The scheme gave each consumer an opportunity to purchase up to eight LED bulbs on one electricity bill. Here, a noteworthy point is that these LED bulbs were not subsidized under the UJALA scheme. Explaining about the cost breakup, our representative from EESL mentioned: "*If per bulb selling cost is USD 1.55 (INR 100), USD 0.35 (INR 23) would be our managing cost, and further working with supply chain, marketing, and distribution cost, we finally are left with around USD 0.11 (INR 7) as our profit margin per bulb*" (interview, EESL management, 18 September 2016). The working model of the SNLP is slightly different from UJALA. EESL approaches the municipalities and does the upfront investment for replacing the street lights with LED lights, the municipalities in-turn save on their electricity bills and use these savings to repay EESL over a payback period of seven years. Beyond this, in 2012, there were three CDM projects implemented in India related to LED lighting [43,44]. While LED technology is constantly improving and getting ever more popular, the true game changer in India in successfully diffusing LEDs in society has been the innovative business model developed by EESL, rather than the technology alone.

4.6. Market Formation

Market formation is a crucial function of any TIS. It aims to shield emerging technologies from the dominance of incumbent technologies and to stimulate demand for the new product [28,29]. In our case study, we found that the BLY scheme in 2008 along with the three CDM projects in 2012 helped with building consciousness among people for energy-efficient lighting. However, the comparatively smaller scale of these events limited their impact for market formation. We already discussed the important role entrepreneurs played in the development of LED technology TIS in India. The tax rebate policy for LED products also played an important role because it incentivized domestic Indian manufacturers to enter the market. As a result, we saw the manufacturing sector developing niche markets for themselves in later stages of the value chain, which included LED luminaire design, retrofitting, and customization. In addition, the demand aggregation by EESL in 2015 greatly supported the market formation of the Indian LED industry. An interview partner representing one of the premier

LED manufacturing companies in India mentioned that the Indian market before 2015 was too small and fragmented to support large-scale manufacturing (interview, Kwality Photonics management, 28 September 2016). The establishment of EESL as a large-scale buyer and distributor had quickly expanded the market, thus enabling an economy of scale in India. Another important role that the government scheme played was the creation of a parallel market for differentiated LED products. Under the UJALA scheme, a person can only buy 9-watt LED bulbs; for LED lamps other than 9 watts, the consumer must buy it from the open market, outside the UJALA scheme. Since consumers who had used the UJALA scheme were now aware about the benefits of LED lighting, they were more likely to use other LED lighting products as well. This had the effect of opening a wider market for other LED-based products that fall outside the government's LED distribution scheme, thus helping with the market creation of LED technology in general. The new market opportunities did not go unnoticed in the private sector, at home and abroad. In an interaction with a senior-level representative from a UK-based lighting products firm, he said "*The Indian market in LED luminaries is growing fast. We are here to enter the market*" (interview, Orange Tek management, 21 September 2016). A representative from Japan explained that the "*huge market size and growth opportunities*" (interview, Toyoda Gosai management, 27 September 2016) led his company to scale up their business activities in India.

4.7. Advocacy Support

This function describes the social acceptance of technology and its corresponding compliance with relevant institutions [29]. The BLY scheme in 2008 was instrumental to counter initial social resistance to change by improving public perception about energy-efficient lighting (interview, EESL management, 18 September 2016). The involvement of ELCOMA starting in 2009 was an important step for engaging LED manufacturers from the private sector. As discussed above, ELCOMA as a lobbying group has played a major role in building advocacy support of LED technology development in India, both at the national and international level. The involvement of EESL in energy-efficient lighting in 2015 was arguably the most important and defining event in garnering political support towards LED technology development in India. However, our representative from EESL told us that the initiatives still had to face many challenges (interview, EESL management, 18 September 2016). While it was relatively easy for the domestic lighting scheme to convince people to buy LED lamps by emphasizing their personal economic benefits in terms of cheaper price and saving on their electricity bills, it proved to be much more difficult to persuade organizations and local governments to install street lights under the SNLP initiative. Local governments in developing countries are more susceptible to corruption and often mistrust higher government levels due to a perceived tendency of top-down policy making by national elites and special interest groups. One such challenge we witnessed in our case study was the conflict of interests at the organization level (interview, SDMC management, 25 September 2016). Indian municipalities receive an annual allowance for the maintenance of street lighting, but the shift to LED-based street lights would have cut down the allowance and led to fears of budgetary deficits, even though the long-term electricity savings would have easily compensated for the short-term losses. Local municipalities tried different strategies to overcome the barrier of conflicting organizational interests. One example was the South Delhi municipal corporation (SDMC), which had already outsourced their maintenance service to a local electricity utility, thereby creating an organizational buffer. The SDMC example also demonstrates the substantial long-term cost reduction made possible by the shift in lighting technology. Before the installation of LED street lights, the municipal corporation used to pay around USD 1.5 (96 INR) per street light to the distribution company for line maintenance, which was reduced to a mere USD 0.45 (23 INR) per street light afterwards. In combination with the savings on the monthly electricity bill, SDMC was able to save approximately USD 250,000 per year (160,000,000 INR) (interview, SDMC management, 25 September 2016).

5. Discussion

Our findings show that the key to the rapid expansion of the Indian LED market was the development of innovative strategies that helped with creating an enabling environment, which either directly addressed or helped to circumvent the major barriers. Although not all barriers that can have a negative effect on low-carbon technology transfer, such as intellectual property rights, restricted access to technology, or the lack of a domestic R&D environment, were addressed in the Indian case, the large-scale diffusion of LED technology has been very successful for the following three main reasons:

Firstly, *technological localization* through standard setting, knowledge exchange, and the creation of niche markets played the most decisive role for the knowledge development in the Indian LED sector. The key event was the retrofitting of international LED standards for localized Indian usage under the auspices of the IEA, which created a regulatory basis that helped to stimulate large-scale private sector investment in the market. Even though India still relies on the import of raw materials for LED production, many new businesses and jobs, as well as local industrial capacity, were created in niche markets in later stages of the LED value chain, such as packaging or the retrofitting of LED lights. Furthermore, with its out-of-the-box approach, Energy Efficiency Services Limited (EESL) developed innovative strategies for knowledge exchange and the raising of public awareness in a developing country in which people have comparatively lower access to traditional print media or internet. The technological localization through local entrepreneurs is also interesting from another perspective. The rapid development of the Indian LED sector, despite the initial lack of domestic research and development capacity and intellectual property right issues [31], is at odds with the literature on low carbon technology transfer, which consistently cites IPR as a prime barrier for development and diffusion of low-carbon technologies in developing countries [32,45–48]. However, when asked during our interviews how the capacity to build subsidiary elements for LED lamps (driver circuits and luminaire frames) had been developed, most local manufacturers claimed it to be indigenous capacity building without any foreign help or assistance. One explanation is that an enabling TIS environment can lead to high rate of technology diffusion even with some key barriers like IPRs remaining unaddressed in a focal country. Another explanation is offered by studies such as Rai and Funkhouser [49], who argue that one of the most important dynamic drivers of international low-carbon technology transfer is in fact reverse-engineering, especially in the context of technology localization. This example shows that the role of reverse-engineering of clean energy technologies as a driver of low-carbon technology transfer is not yet properly understood and invites further study.

A second important factor in the Indian success story was the creation of innovative economic and fiscal support policies. Many of the financial barriers to the alleviation of energy poverty through rural electrification identified by Sovacool [2] also hampered previous attempts to diffuse energy efficiency solutions in India, such as lower income levels of the target group, their low ability to pay, low levels of consumption, geographic dispersion, and the high costs of initial connection and maintenance. The Indian government played a decisive role by creating policy instruments like tax rebates and subsidization schemes that helped to increase demand, which in turn stimulated the initially fragile domestic industrial base. However, rather than technology progress and fiscal support policies, the true game changer in India has been the innovative business model developed by EESL, which had reduced the price of LED lamps for individual customers by providing upfront procurement on an enormous scale and by developing an innovative end-user payment model. The stepping-in of EESL as a large-scale buyer had quickly expanded the market and made domestic large-scale manufacturing economically sustainable in India. The Indian example also shows that this does not necessarily imply the development of domestic capacity in all stages of the manufacturing process, especially for high-end technological solutions, such as modern LED lamps. Instead, it is crucial to stimulate job creation and new business opportunities in niche markets across the value chain of low-carbon technologies.

A third important factor was the establishment of institutional support mechanisms, such as the EESL, as an autonomous implementation agency with clear responsibilities. Previous studies have shown that the best support policies in developing states can fail without independent and accountable institutions to back them up [50]. In political systems with high corruption levels and political frictions between competing levels of government, it is imperative to build different buffers into the design of the implementation agencies and support policies. Even though India encountered many challenges in this regard, EESL and several municipal governments proved to be quite effective in finding innovative ways to bridge or circumvent political conflicts that would otherwise hamper the program implementation. However, the success of the EESL rested on a much longer historical learning process. It can be argued that without the Energy Conservation Act of 2001, neither the EESL, nor the UJALA and SNLP initiatives would have come into existence.

The Role of Low-Carbon Technology Transfer

Low-carbon technology transfer is widely considered a vital component in international development strategies to combat energy poverty and to provide access to climate-friendly technologies to developing countries [46,49,51–54]. It has the potential to bridge some of the gaps between the developed and the developing world and to pave the way to a future in which the costs and benefits of modern energy services are more evenly distributed in and between countries. Our findings not only demonstrated that it is indeed possible to utilize LCT transfer between countries to help address the challenges of energy poverty, but it also shows that it is even possible in a country like India, with a huge and diverse population, various developmental challenges, and domestic political frictions. Furthermore, although it took India 15 years from the Energy Conservation Act in 2001 to the creation of the EESL, which eventually spurred the widespread diffusion and localization of LED lighting, we argue that is possible to shorten this transition time in other developing countries by learning some of the lessons from the Indian example. Perhaps the most influential factor in India was the development of domestic regulatory and institutional mechanisms for supporting the localization of energy efficiency technology. The international community can help to facilitate this process, as seen in the localization of LED standards in India, but each country needs to find its own local strategies adapted to its own unique conditions.

To our knowledge, India is to date still the only country that has developed localized LED standards. However, the Indian success story had implications beyond its borders, since the resulting interest in parts of the developing world has already strengthened the role of Indian knowledge institutes as international knowledge brokers on energy efficiency strategies in developing states. This development is also actively facilitated by the Indian government, which is well aware of the success of its lighting efficiency policies and is actively trying to propagate its domestic experiences and best-practice examples as part of its south–south capacity building strategy with other developing states. The representative of EESL mentioned that his organization had been approached by many countries to share their experiences about the large-scale diffusion of LED lighting. Commenting on the scope of technology and knowledge transfer, the EESL representative explained: "*If we compare with advanced countries like USA, Germany, Japan, clearly this model may not be much beneficial, but for developing countries with similar economies, similar practices and life style, the model can be easily replicated and re-engineered. For instance, we are currently helping Indonesia in developing their LED standards. I am personally coordinating assignments in Myanmar, Indonesia, Thailand, Cambodia and Vietnam, where we have been given the mandate to showcase our best practices and facilitate similar programs in their countries*." (interview, EESL management, 18 September 2016).

In this way, the Indian case also challenges conventional models of international low-carbon technology transfer, which usually only consider the transfer of technology from developed to developing countries (north–south transfer) [55], or the growing cooperation between developing countries, recently accelerated by an increasingly assertive China (south–south transfer) [30,56,57]. In our case study, we found that there is something in between the north–south (N–S) and south–south (S–S) transfer, which is currently missing in the literature. While the developed world ("north") helped India ("south") with improving its domestic LED sector capacity by providing assistance with localizing international LED standards and through investments of foreign companies in the Indian market, this capacity was further transferred to other developing countries ("south"), making the flow of knowledge and technology in essence a north–south–south connection (N–S–S). The novelty of the N–S–S transfer is the adaptation of technological knowledge to local conditions by one developing country, and the provision of this modified knowledge and reengineered technology to countries in similar socio-economic circumstances. This creates higher chances of acceptance in recipient countries than the traditional north–south route, thereby potentially opening a new avenue for quicker clean energy technology transfer processes. We believe the north–south–south perspective might be helpful for the further exploration of the dynamics of technology transfer processes across a wide range of environmentally friendly technologies.

6. Conclusions

Developing countries face many challenges in innovation and deployment of modern energy technologies. This article therefore set out to explore the reasons behind India's largely successful nationwide rollout of modern LED lighting in the span of only a few years. We learned that the story of India's lighting modernization began already more than two decades ago with the first energy efficiency policies. It took India 15 years to reach from the Energy Conservation Act 2001 to the beginning of the wide diffusion and localization of LED lighting in 2015. Although the first attempts to enhance lighting efficiency in India were met with only limited success due to a range of factors, such as a lack of financial resources and domestic know-how, policy makers and industrial players learned at each step from previous failures. The result was the eventual development of innovative strategies that helped the rapid expansion of the Indian LED market. This happened through the creation of an enabling environment in which the major barriers, such as the initial lack of a domestic industrial capacity or a lack of public awareness, were either directly addressed or circumvented.

The main factors for success were the adaptation of the technology to the local needs and capabilities of a developing country, the creation of tax rebates and subsidization schemes tailored specifically to the diffusion of particular technologies, in combination with an autonomous implementation body that had a strong mandate and clear responsibilities. Another important finding was that India greatly benefitted in its early LED development from the support of international actors, for instance, through the help of international organizations in local standard settings or through international businesses that invested in the Indian LED market. Since India demonstrated that it is possible to create a cutting-edge energy technology industry in a relatively short amount of time even in a developing country setting, many other countries seem to be keen to learn from its experiences. The Indian government and industry are equally interested in exporting their newly acquired know-how, thereby creating a new link in the discussion on international technology transfer that sees a technological innovation being imported into a developing country, adapted to local circumstances, and, in turn, further exported as a modified version to other developing countries with similar needs. We believe that this emerging north–south–south cooperation pathway certainly invites future studies to investigate if the Indian mechanism for shortening the transition time could be replicated in other technological innovation sectors and localities.

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