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Original article

Agent-based modeling of the adoption of high-efficiency lighting in the residential sector

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ABSTRACT

Due to the wide use of incandescent lighting, residential sector has much lower energy efficiency comparing to commercial sector. However, adoption of compact fluorescent (CFL) and light-emitting diode (LED) technology in residential sector has been slow because of several obstacles such as high price tag, poor public information, and additional cost to achieve favorable lighting features. A deep understanding on consumer's behavior is needed to support policy development in order to speed up the penetration of CFL and LED in the residential sector. Agent-based modeling (ABM) has been used to capture the dynamics of complex socio-technical systems, and represent a suitable tool. Previous work on ABM of consumer adoption of CFL and LED rely heavily on multi-criteria decision making of the agents. Since light bulbs are not a significant purchase for most households, it is highly possible that customers will not go through complex decision making mechanics. This research establishes an ABM of residential lighting purchase and usage within a hypothetical community and tries to illustrate possible adoption paths under different scenarios. Agents are divided into three groups with different simple decision heuristics when making purchase. Energy consumption and greenhouse gas (GHG) emission from each scenario are calculated and compared. Results of the simulation show that incandescent lamps will eventually fade out of the market even with no policy implemented. After 25 years, annual energy consumption can be reduced by roughly 30% compared to Year 2010. Under best case where incandescent bulbs are banned, the energy consumption reduction can be up to 70%. Among scenarios, incandescent ban and energy saving campaign yield best energy consumption and GHG emission reduction results. LED technology advancement can improve market penetration of LED lighting but has little effect on incandescent fade out. It is also shown that lighting technology retrofitting can achieve higher reduction on electricity consumption and GHG emission than electricity grid improvement.

Introduction

Residential and commercial lighting is an important contributor to total electricity consumption in U.S. According to U.S. Energy Information Administration [1], in 2014 about 412 billion kWh of electricity was consumed by residential and commercial sector in U.S., which is roughly 11% of total U.S. electricity consumption. Between them, residential lighting consumed 150 billion kWh, which is about half the amount of commercial sector consumption. However, a report published by U.S. Department of Energy characterizing the lighting market of 2010 pointed out that residential sector had similar lamp density and average lamp wattage comparing to commercial sector, whereas only 1/6 of average operating hours [2]. The main reason for the low energy efficiency in residential sector is the wide usage of incandescent lighting, including traditional incandescent lamps and halogen lamps.

Due to their low efficiency, incandescent lamps consume more electricity and generate more greenhouse gas (GHG) emission to deliver the same luminance comparing to other lighting technologies. Two types of lighting, compact fluorescent lamp (CFL) and light-emitting diode (LED) lamp are considered as "greener" alternatives to incandescent lighting due to their high energy efficiency. An estimates suggests that if incandescent lamps are banned globally by year 2016, up to 0.2 Gt CO_2e of greenhouse gas emission can be reduced by 2020 [3], which is equivalent to the total carbon footprint of 10,000 cars with each one driving 100,000 km. To offer a comprehensive understanding on the environmental performance of the lighting technologies, several life-cycle assessments that compare incandescent lamp with CFL and LED to evaluate retrofitting benefits had been carried out recently [4–7]. U.S.

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Department of energy conducted a detailed LCA study [4], including a summary to previous studies and a new LCA result to compare incandescent, CFL and LED lighting. Shahzada et al. [5] estimated that to produce 20 million lumen-hours of light, CFL lighting will have 50% reduction on Sustainable Process Index (SPI) footprint and carbon footprint comparing to incandescent lighting, whereas LED lighting will have 75% reduction on these two impact categories. In another study, Bergesen et al. [6] suggests that CFL lighting will have 60% reduction in 13 of 14 impact categories considered including GHG emission comparing to incandescent lighting, while LED lighting will have 80% reduction. Franz et al. [7] compared environmental impact of incandescent lighting with several different assumptions of LED lighting and the worst case results in roughly 70% reduction of GHG emission. Despite these environmental advantages, the adoption of CFL and LED in residential section is much slower than commercial sector. A market report from National Electrical Manufacturers Association shows that during the first quarter of 2015, incandescent lighting, including halogen lamps, still accounts for 53.7% of the total consumer lamps market, whereas CFL lighting claims 40% of the market share and LED lighting has only 6.3% [8]. For commercial buildings, CFL lighting already owned over 90% of market share.

This situation did not remain unnoticed. According to NEEA, over half of stores in northwest region of U.S. had promotional material on lighting replacements since 2013, and various promotions including advertisement flyers, brochures, demonstrations, and websites were conducted [9]. Efforts have been made to develop residential sector energy consumption model to provide insights on the problem. Richardson et al. [10] presented a time-series based bottom-up model to estimate residential lighting energy demand. In their research, an active time series of occupancy was used to calculate the number and time of lighting equipment utilized, with consideration of outdoor irradiance level. The result was compared to historical data and proved to be with high accuracy. Johnson et al. [11] used a Markov chain based approach to model residential energy consumption. The research established a statistical model to represent the activities of different types of occupants during a day and estimated energy consumption accordingly. Meanwhile, predictions of future residential market penetration and energy consumption level are made by several reports and researches. NEEA report [9] presented a residential lighting market share penetration based on expert opinion, predicting that CFL and LED lighting in total will have 49% of market share in year 2016, and 69% of market share in year 2018. DOE report [12] presented a top-down model to predict market penetration and energy consumption. In the model, consumers are cost conscious and the market penetration is calculated by logit regression models based on historical and predicted costs with consideration of technology diffusion curve. The result showed that energy consumption can be reduced by 37% at year 2020 and 67% at year 2030. However, it should be noted that consumers may consider factors other than cost when making decisions. To address the issue, two groups of researchers tried to characterize future residential lighting market with corresponding energy and environmental consequences with agent-based modeling (ABM) approach with consideration of different decision making criteria [13,14]. Residential lighting market consists of multiple parallel households exposed to market information and regulations, which are likely to have different criteria to make decision and change their decisions over time. Therefore, a self-evolving and bottom-up model is desired if one wants to study the long term evolution of the market. ABM adopts a bottom-up computational approach with "agents" imitating actors in real world events. Agents make interactions with each other and the "environment", which is the representation of corresponding conditions, restrictions, and situations in the real world [15]. These features make ABM a suitable tool to simulate residential lighting market for its bottom-up nature and the ability to evolve through agent-to-agent and agent-to-environment interactions.

Among the two ABM studies on residential lighting, Chappin et al. [13] established a network-based agent based model to illustrate energy consumption and GHG emission reduction of residential lighting. In their model, agents made decisions by multi-criteria decision making process with different weights distribution. Agents will also adjust their weight by recent experience and social network information exchange. Detailed lighting products differences were considered with difference in technology, light color, slot type, etc. Several scenarios were explored to show the effect of possible policies. Their result indicated that incandescent lamps will still be the dominant technology after 40 years without policy support, and incandescent ban will be the most effective policy to reduce energy consumption and GSG emission. Hicks et al. [14] present a grid-based agent based model to illustrate possible rebound effects due to energy saving from adopting new technologies. In their model, agents first made random decisions based on a utility function coming from multi-criteria decision results. A survey was carried out to support the multi-criteria decision weighting data. Agents exchanged their opinion with their grid neighbors. Different rates of rebound effect and two possible scenarios were considered. Their result indicated that households will swiftly switch to new technologies, but with high rates of rebound effect, energy consumption may not be reduced.

It should be noted that both of the ABM studies on residential lighting (i.e., Chappin et al. [13]; Hicks et al. [14]) rely heavily on multi-criteria decision making from the agents. Early in 1979, Olshavsky et al. pointed out that such decision making process may not be realistic when facing a purchase that is not important [16]. Later, Hoyer made an experiment to show that most customers make very quick in-store choices by simple heuristics on a single criterion when purchasing common product like detergents [17]. Since lighting bulbs are not a significant purchase for most households, it is highly possible that customers will not go through complex decision making mechanics. Meanwhile, Chappin et al. did not consider use phase cost as a decision-making criterion. However, CFL and LED equipment is actually cheaper considering use phase cost and most CFL and LED lighting products will state this on their package. Also, since the research is conducted in Netherland, several parameters including number of lamps per household, average hours per lamp were different from U.S. situation. In model created by Hicks et al., although the agents make stochastic decisions, their utility function are pre-determined and cannot illustrate possible opinion changes of the public. To address these issues, this research aims to establish an ABM of residential lighting purchase and usage within a community and try to illustrate possible adoption paths under different scenarios. Agents, divided into groups, are applied with simple decision heuristics. The model provides market penetration and total energy consumption estimation of three types of lighting bulbs used in residential sector (i.e., incandescent lamp, CFL, and LED) over time.

Investigative method

This research models residential lighting purchase choice within a hypothetical urban residential community with 500 households using network based ABM approach. To calculate electricity consumption and lifespan of lighting equipment while keeping reasonable simulation speed, the time step of the model is one day. The simulation starts at year 2010 and ends after 25 years (Year 2035, 9125 days), which allows model validation using historical data while capture the market penetration process of CFL and LED. The model is implemented under Repast Simphony 2.3.1 [18].