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Analysis of the energy efficiency potential of household lighting in Switzerland using a stock model

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ABSTRACT

Lighting, a main focus of Swiss energy efficiency policy, is a substantial consumer of energy in the residential sector in Switzerland, requiring 4.1 PJ electricity in 2015 or 6.4% of the sector's total electricity demand. Currently, incandescent bulbs (sales were prohibited in 2014) and halogen bulbs (to be banned in 2018) jointly represent nearly 60% of the installed lighting capacity in Swiss households. In the past few years, the price of light emitting diodes (LEDs) dropped dramatically, offering largely unexploited opportunities for energy efficiency improvement. To assess the energy efficiency potential in household lighting, a dynamic model is developed that accounts for the change of the lighting stock per technology over time.

The first part of the present study describes the stock model which allows to estimate the current and future number of light bulbs in use in households per technology and subsequently the total energy consumption for lighting on the basis of today's stock in households, survival rates based on a Weibull distribution and future sales. In the second part, energy efficiency cost curves are developed to assess the cost-effectiveness of energy saving measures taking into account the cost aspect based on the stock model.

This approach allows modeling the potential energy savings that Switzerland could realize by rapid transition to energy efficient lighting as well as the associated costs. We find that lighting energy consumption in the household can be decreased cost-effectively from 5.4 PJ today to 2 PJ (-62%) by 2035 thanks to replacing incumbent bulbs with highly energy efficient LED technology. In addition, the majority of energy efficiency measures related to the household lighting are highly cost effective with a payback time of less than two years.

1. Introduction

Next to the expansion of renewable energy supply, the implementation of energy efficiency (EE) measures is considered as key strategy for reducing non-renewable energy consumption and CO2 emissions globally [1]. Worldwide, approximately 15% of all electricity demand is related to lighting, making it the third largest electricity consumer among the main energy services after motor-driven systems (in industry sector) and household appliances [1]. It is expected that replacing all inefficient lighting globally would save more than $140 billion and allow decreasing electricity use for this energy service by 80%, thereby reducing worldwide greenhouse gas by approximately 5% and CO2 emissions by 580 million tons per year [2].

The total energy consumption for lighting for EU-27 countries in 2004 was estimated at 95 TWh per annum of which 44 TWh could have been saved by replacing all incumbent bulbs with CFLs [3]. Switzerland is a special case in Europe (next to Germany) by having taken the decision after the Fukushima accident to phase out nuclear energy, which is currently generating 40% of the country's electricity. In order to prepare Switzerland for such fundamental changes and retain its secure and cost-efficient supply of energy while reducing its environmental impacts, the "Energy Strategy 2050" [4] was developed by the federal government. Within this strategy, the first scenario ("Business As Usual" (BAU)) is a continuation of the existing energy policy, whereas the "First Package of Measures" (FPM) aims at increasing energy efficiency and promoting the development of renewable energies. Finally, "New Energy Policy" (NEP) is the most ambitious scenario. The largest electricity savings can be achieved in the residential sector [5], which is reflecting the fact that the residential sector is a substantial consumer of electricity in Switzerland (64.4 PJ per year or 31.6% of the total Swiss electricity use) [6]. Electricity use for residential lighting

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was reported to amount to 4.1 PJ in 2015 [6], representing 6.4% of the total residential sector's electricity consumption.

The lighting industry is undergoing significant technological change: Based on the so-called Haitz's Law, every decade the cost per lumen (unit of useful light emitted) decreases by a factor of 10, and the amount of light generated per LED increases by a factor of 20 [7]. The decreasing costs and increasing performance together with EE programs promoting the use of LED bulbs as well as the ban of incandescent bulbs and possibly also the foreseeable prohibition of halogen bulbs have resulted in a market transition towards LEDs. Attributes like energy efficiency, environmental friendliness, and durability call for the replacement of incumbent bulbs by LEDs. While these are promising developments, the anticipated effect of energy conservation is furthermore delayed due to the gradual use of bulbs which have been stockpiled in the supply chain and in private households. Besides a 'rebound' effect caused by increased lamp luminosity and operation time has been observed (estimated at 23% and 47%) [8,9]. The size of the rebound effect related to lighting services is larger than the rebound effect for total electricity efficiency improvement in the residential sector, which has been estimated between 6.5-21.2% for Europe[1] [10].

These developments (i.e. the combination of technological progress with rebound effects, stockpiling, and floor space expansion) lead to the question how large the EE potential for lighting in the residential sector actually is. In order to answer this question, there is a need for a dynamic model, with stock models typically being the method of choice. In the past, stock models have been applied to gain an understanding of the overall number and age structure of installed household appliances, to estimate the future quantities of obsolete appliances (for waste management purposes) [13] and to study the diffusion of novel appliances for smart grid applications [14]. Stock models are also applied for assessing the impact of EE strategies [15,16] for evaluating recycling policy performance [17] and for projecting future energy consumption [18] and related carbon emissions [19]. However, none of these models included lighting, which may be explained by the limited EE improvement of lighting until the emergence of LED bulbs.

While a stock model is a powerful tool it does not address the cost dimension. The latter is typically studied in the form of country-specific EE cost curves which show the cost of energy conservation (or of CO2 emission reduction) as a function of the absolute energy savings in the country studied [20]. EE cost curves give an integrated perspective on potentials and opportunities and they can serve as a helpful tool to prioritize energy conservation measures [21]. While such curves are rather common to determine the cost-effectiveness of measures in industry (e.g. for iron and steel [22,23], cement [24] and motor-driven systems [25]) they are very scarce for household appliances and in particular for lighting [26]. For Switzerland, a CO2 abatement cost curve was developed covering all sectors [27] and more detailed analyses for EE and CO2 emission reduction in selected industry sectors are being prepared (e.g., [24] Zuberi et al., forthcoming), while there are no comparable studies for household appliances including lighting.

Taking into account the above-mentioned facts, there is an urgent need for analyses of EE potentials for lighting in Switzerland, thereby making use of a dynamic model that accounts for the changes in the stock of installed bulbs for the years to come and considering also the cost aspects. We examine three sets of questions related to household lighting in Switzerland for a 20-year timeframe:

- How will the stock of light bulbs in use evolve considering legislation and the advances in lighting technology in the years to come? And what will be its effect on the energy consumption?
- Which EE measures are most cost-effective and how much energy can be saved applying them? Which measures are not cost-effective?
- How sensitive are the energy saving potentials and the corresponding specific cost to key parameters like discount rate, investment cost, and energy prices?

The remainder of the paper is organized as follows: in the first part of Section 2, the methodology underlying the stock model of household lighting is explained. We then describe the method of determining the costs and benefits of energy efficient lighting by performing a techno-economic analysis. Section 3 presents the input data used and scenarios assumed in this study. Section 4 describes the results including the evolution of future energy consumption of household lighting and the change of the lighting technologies in the stock over time. This section also combines the cost-effectiveness analysis to the probabilistic stock model, which is followed by a sensitivity analysis (Section 5) and conclusions (Section 6).

2. Methodology

2.1. Stock model

This section explains the methodology of modeling stock, survival, and sales of a household appliance type. Stock models, sometimes also referred to as vintage models [28], are based on the principle of mass conservation and can be used to quantify the flow of materials and goods in a system defined by spatial and temporal boundaries. Material flow analysis and substance flow analysis (MFA/SFA) have been the basis of many models serving as a valuable tool for projecting future flows of materials, substances or products ([29,30]), or emissions in the related industrial processes ([31,32]) as well as waste streams ([33–36]).

Different approaches depending on the availability of input data are possible. In the case of sufficient statistical data, the stock is modeled using historical appliance sales data and survival rates over a timespan of at least twice of the appliance's average lifetime. If no historical sales data can be retrieved from statistics, but ownership levels and the number of households are known, the future stock can be modeled based on current stock and future sale projection.

Following the MFA methodology stock models can be described with (see Fig. 1):

$$S(t) = F_{in}(t) - F_{out}(t) + S_0 \tag{1}$$

The inflow covers the replacement (R) of broken lamps and first purchases (FP) related to additional floor space.

$$F_{in}(t) = F_{in,R}(t) + F_{in,FP}(t) \tag{2}$$

The inflow as a result of replacement of broken lamps and increased lighting intensity (here number of lamps) is equal to the sum of all the vintages that are discarded in the given year taking into account the new market shares $c_i(t)$ and $Inc(t)$, i.e. the increase in number of lamps per m2 (both parameters are dimensionless):

$$F_{in,R}(t) = Inc(t).F_{out}(t).\sum_{i=1}^{n} c_i(t) \tag{3}$$

The first purchases made by households are calculated with Eq. (4). The inflow related to first purchases is the number of bulbs

[1] The respective values are typically higher in other regions: up to 72% for China's residential sector [11] and 0–50% for the US [12].