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The life cycle rebound effect of air-conditioner consumption in China

Jingru Liu [a,*], Xin Sun [b], Bin Lu [a], Yunkun Zhang [c], Rui Sun [d]

[a] Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing 100085, China
[b] China Automotive Technology & Research Center, 68 East Xianfeng Road, Dongli District, Tianjin 300300, China
[c] University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK
[d] Jilinhuancheng Rural Commercial Bank, 1888 Tianjin Road, Changyi District, Jilin, Jilin 132001, China

HIGHLIGHTS

- Develop a life cycle rebound effect model.
- Assess the life cycle rebound effect of Chinese room air conditioners.
- Conduct a questionnaire to assess the consumption behavior of Chinese room air conditioners.
- Rebound effect should be considered by energy policy makers.

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ABSTRACT

Governments worldwide are attempting to reduce energy consumption and environmental pollution by confronting environmental problems and adopting more energy-efficient products. However, because of the rebound effect, energy-saving targets cannot always be fully achieved, and sometimes greater energy consumption is generated. Research on the rebound effect from the perspective of industrial ecology considers not only direct energy consumption but also its life cycle negative impacts on the environment with China's rapid economic development and simultaneously improving quality of life, the ownership of room air conditioners (RACs) has increased more than three hundred times, and air conditioners' energy consumption has increased one thousand times over the last twenty years. The Air Conditioner Energy Efficiency Standard is one of the most important measures in China for reducing the amount of energy consumed by RACs. This paper introduces a life cycle based method to estimate the rebound effect of Chinese RACs consumption. This model provides a product's life-cycle view to assess the rebound effect, considering the contribution of both producer and consumer. Based on the established life cycle rebound effect model, we compared urban household RAC consumption behaviour before and after the launch of the Air Conditioner Energy Efficiency Standard. A rebound effect in RAC consumption was found that there was a longer daily usage period in the household as air conditioner efficiency levels improved. The life cycle rebound effect of household air-conditioner consumption was calculated to be 67%. The main conclusion obtained from this study is that policies and regulations should consider the rebound effect when encouraging households to alter their energy consumption patterns.

1. Introduction

As the second leading energy sector in China by consumption, household energy usage has become the focus of substantial attention, and major efforts have been undertaken to generate improvements in household energy efficiency. The main reasons for households' environmental impact involve energy consumption and greenhouse gas emission related to household heating and cooling [1].

The ownership of room air conditioners (RACs) in China increased from 0.34 units per hundred urban households in 1990 to 112.07 units in 2011, which was a higher growth rate than that of other household appliances, with an increase of more than 300 times in just twenty years. According to a report from the Ministry of Construction of China, summer-cooling energy consumption in China increased from 0.40 billion kW h in 1996 to 520.00 billion kW h in 2011 [2]. Electricity consumption by RACs is

* Corresponding author at: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing 100085, China.
E-mail address: liujingru@rcees.ac.cn (J. Liu).

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estimated to account for 30% of the peak summer load in some large and medium-sized cities [3].

To reduce the amount of energy consumed by RACs, China implemented the Air Conditioner Energy Efficiency Standard in 2008, which aimed at phasing out energy-inefficient RACs by incentivizing consumers to purchase highly energy-efficient RACs. However, advances in technology and improvements in energy efficiency – in addition to other relevant developments – also influence household consumption behaviour and paradoxically lead to increased energy consumption and greenhouse gas emissions [4,5], which is a phenomenon known as the rebound effect.

2. Literature review

The notion of the rebound effect was first developed by Daniel Khazzoom in an estimation of energy savings based on mandated efficiency standards for household appliances in the USA [6] and has since been the focus of many studies [7–10]. Four types of rebound effects are identified in both the microeconomic and macroeconomic perspectives in the literature [9,11]: direct rebound effects, indirect rebound effects, economy-wide effects and transformational effects. Direct effects occur when improved energy efficiency decreases the effective price of an energy service and therefore leads to an increase in consumption of that service. This increase will offset the reduction of energy consumption caused by the advanced efficiency. Indirect rebound effects occur when a reduction in the effective cost of an energy service leads to an increase in energy demand for the production of other goods and services. Percentages are typically used to describe the rebound effect, and a backfire effect results when the rebound effect exceeds 100%.

There are varieties of researches regarding to the direct rebound effect of household energy consumption in developed countries. The researches mainly focus on the household terminal energy use in the areas of space heating and cooling, transportation, hot water and lighting. Economic model and social investigation are adopted as the common methods. In the known cases, the sample size varies from dozens to ten thousands. The evidence shows that the direct rebound effect may be less than 30% in industrialized countries [12–14] and more than 30% in non-industrialized countries [15–18].

Household space heating and cooling are the most thoroughly studied area of direct rebound effects. Table 1 summarizes the main features and results in this research area.

In 2001, the concept of the rebound effect was introduced to industrial ecology [5].From the industrial ecology perspective, the rebound effect refers to a behavioural or other systemic response to a measure taken to reduce the life cycle environmental effects – other than energy use – that offsets the benefit of the measure [28]. The research scope of the rebound effect of household consumption has been extended from energy consumption behaviour to energy consumption embodied in household products and services and related environmental impacts. The life cycle assessment method has been used in the area of sustainable consumption to identify which lifestyles are more sustainable and evaluate the effectiveness of sustainable consumption measures, including the role of the rebound effect in the environmental impact of household energy consumption [29,30].

The rebound effect relevant to household RACs has drawn increasing concern over recent years. Studies have shown that the current measures and technologies promoting energy efficiency in China appear to be unable to control the increase in household energy consumption as the result of China's current rapid pace of economic development and the demand for a more comfortable lifestyle [31,32]. Some studies have demonstrated that the direct rebound effect of household energy consumption in China might be at least 30%, and the indirect rebound effect is generally estimated to be much higher than the direct effect [33].

This paper first presents the definition of the life cycle environmental rebound effects of RACs and then describes a methodology to estimate the effects by comparing the carbon footprint of RACs before and after implementation of the Air Conditioner Energy Efficiency Standard in China. The RCEES Life Cycle Inventory was used to estimate the carbon footprint of RACs produced in 2008 and 2012 [34], and a questionnaire survey was conducted to analyse the changes in consumption behaviour given higher energy efficiency and lower energy costs.

3. Methods and data

3.1. The life cycle rebound effect model for household room air conditioners

The life cycle rebound effect of household RACs describes changes in the life cycle environmental performance of RACs as the result of the introduction of new energy-saving technologies and new energy efficiency standards. In this paper, the product's carbon footprint is chosen as the indicator of the life cycle environ-

Table 1
The main features and results of studies on the direct rebound effects of space heating and cooling.

Author/year	Country	Rebound effect	Method	Sample size (year)
Household space heating				
Dubin et al. [19]	USA	19–48%	Discrete–continuous	252
Klein [20,21]	USA	40%	Simultaneous equations model	2157 (1973, 1981, Cross-section)
Schwartz and Taylor [22]	USA	Long 1.4–3.4%	Questionnaire survey	1188 (1984–1985)
Cuijpers [23]	Belgium	31%	Questionnaire survey	2075 (1987–1988)
Haas and Biermayr [13]	Austria	20–30%	Time series analysis	500 (1970–1995)
Nesbakken [24]	Norway	15–55% (average 21%)	Discrete- continuous	1990
Guertin et al. [25]	Canada	Long 29–47%	Model for analysis of energy demand	10,982 (1999, Cross-section)
Gram-Hanssen et al. [26]	Denmark	20%	Questionnaire survey	665 (2010)
Household space cooling				
Hausman [27]	USA	Short 4%, Long 26.5%	Individual behavioural model, price elasticity and discrete choice models	46 (1978, Cross-section)
Dubin et al. [19]	USA	1–26%	Discrete- continuous, engineering thermal load model	214–396 (1981, Cross-section)
Guertin et al. [25]	Canada	Long 34–38%	Model of residential energy demand	10,982 (1999, Cross-section)
Jin [17]	Korea	57–70%	Nonlinear correlation direct estimation	Two household (2002, Cross-section)