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# Fuzzy model of residential energy decision-making considering behavioral economic concepts

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## HIGHLIGHTS

- Fuzzy logic is used to predict cooling energy use considering behavioral economic principles.
- The model accounts for both the efficiency and curtailment dimensions of household consumption.
- The model produces plausible behaviors and the results match historical values reasonably well.

## ARTICLE INFO

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Fuzzy logic
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## ABSTRACT

To gain a fundamental understanding of the factors driving consumer energy behavior and for more effective policy-making, the development of energy consumption models taking into account key behavioral economic concepts is essential. In this direction, this paper presents a fuzzy logic decision-making model incorporating the concepts of bounded rationality, time discounting of gains, and pro-environmental behavior. The fuzzy model is used to characterize and predict consumer energy efficiency and curtailment behaviors in the context of residential cooling energy consumption. The model is developed from the perspective of the human decision-maker and the rules based on human reasoning and intuition. It takes into consideration monetary, personal comfort and environmental responsibility variables to yield predictions of one's air-conditioning purchase and usage decisions. The results from running the model multiple times to simulate a real large urban population are found to match historical cooling energy use data reasonably well. This allows modelers some degree of confidence in the model. Moreover, perturbing key input variables produces plausible behaviors, thus providing additional validation to the model. This work demonstrates the feasibility of fuzzy logic as a powerful method for combining quantitative economic and physical factors with qualitative behavioral concepts in a single mathematical framework for better prediction of human energy behavior, and greater fundamental understanding of the "why" behind energy use that conventional building energy simulation models do not address.

## 1. Introduction

The residential sector accounts for significant amounts of energy consumption and greenhouse gas (GHG) emissions. Residential buildings account for 16–50% of total energy use at the national level and 31% globally [1,2]. Therefore, energy efficiency policies targeting the residential sector are crucial for reducing overall energy demand and GHG generation. Oftentimes, however, there are significant differences between the realized and targeted levels of efficiency [3]. In other words, "energy efficiency gaps" or "energy efficiency paradoxes" [4–6] are widespread in markets. This is likely because policy-makers typically neglect the behavioral aspect of energy use despite the large body of evidence proving the significance of "non-economically rational" human behavior in residential energy decision-making.

Conventionally, energy policies are formulated largely based on traditional, neoclassical economic principles, which view human decision-making as independent from non-monetary values and goals [7], and assume agents make decisions under complete economic rationality, i.e., that they are perfectly capable of making utility maximizing choices. It is starting to be recognized though, by behavioral economists [8] who strive to integrate psychological insights into economic analysis, that human decisions are also driven by personal values, judgment and feelings, and that human rationality is bounded. Nevertheless, the application of behavioral economics to the formulation of energy policies is still very limited.

Hence, this paper aims to advance the integration of behavioral

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economic concepts to residential energy behavior modeling for the purpose of policy-making. Specifically, fuzzy logic [9] is employed to construct an integrated energy behavior model to characterize and predict consumer energy efficiency and curtailment behaviors [10]. The former is about consumers' decisions to invest in energy-efficient appliances, while the latter concerns their day-to-day use of the appliances. Though the two behaviors are motivated by different psychological drivers [11,12], they are best studied simultaneously [12] for a holistic view of the problem. However, efficiency behavior is underrepresented in past studies [13]. This is despite policies targeting it (as compared to policies targeting curtailment behavior) being generally more acceptable to the public [14–16] and having greater energy saving potential [13,17]. Thus, this paper seeks to combine the two behaviors in a single fuzzy framework.

This paper also seeks to incorporate pro-environmental behavioral constructs and their effects on consumer energy behavior to the fuzzy model. At present, while the existence of these altruistic constructs is well accepted in behavioral economics, it is still unclear their exact relationship with energy efficiency and curtailment behaviors [18–22]. In this paper, through experimentation with different configurations of the fuzzy model developed, it is gained new insights into the matter.

Fuzzy logic, an artificial intelligence method, uses linguistic variables and heuristic associations to approximate, in numerical terms, human reasoning and intuition. It is thereby suitable for combining quantitative economic and physical factors with qualitative behavioral concepts. However, only a few fuzzy logic-based simulations of residential energy management have thus far been conducted [23–28]. These studies focused mostly on just energy usage relating to users' curtailment behavior with little or no regards for their efficiency behavior. Further, some of the past studies included only the effects of monetary terms [26]. Others included also non-monetary manifestations [23–25,27,28] but without proper consideration of the underlying behavioral drivers. Thus, the fuzzy model developed in this present paper can be seen as a major improvement over existing related fuzzy models given its incorporation of major behavioral economic principles, and integration of consumer energy efficiency and curtailment behaviors to yield a more holistic take on modeling residential energy decision-making.

To the best of knowledge, this present work is the first to use fuzzy logic to model residential energy consumption from the perspective of behavioral economics. As such, it contributes to the literature in its innovative use of fuzzy logic: (i) to integrate key behavioral concepts (bounded rationality, time discounting and pro-environmental behavior) with economic, demographic and climate variables in the context of residential energy management; (ii) to capture both the efficiency and curtailment behaviors of residential consumers by modeling energy decisions not only at the stage of usage, but also at the prior stage of appliance purchase; and (iii) to simulate the long-term energy consumption of a large urban population. As emphasized by Stern [29], the integrating of variables and concepts of different natures by this study is essential for a comprehensive fundamental understanding of the factors driving domestic energy use. The fuzzy model developed is used to predict the average monthly and annual cooling energy consumptions in Hong Kong, and is validated by comparing the results against historical data. Further validation of the model is realized by conducting sensitivity analyses of key model inputs. From the results, new insights are obtained especially in regards to pro-environmental behavior whose exact influence on residential energy behavior is still uncertain. It is hoped the results will contribute to the development of more effective energy policies.

## 2. Background

### 2.1. Modeling residential energy decision-making

Energy behavior is a multidisciplinary subject that has been studied by investigators from a wide range of disciplines, from social sciences to engineering. Thus, studies on the topic can vary significantly in their objectives and methods. In a comprehensive review on residential energy behavior modeling studies, Lopes et al. [30] grouped the studies into three main categories: (i) quantitative studies which relied mostly on engineering and statistical methods to predict energy use; (ii) qualitative studies which focused on socio-psychological frameworks and theories to explain energy consumption; (iii) and finally, hybrid studies combining elements from the 1st and 2nd categories. This present study can be placed under the 3rd category.

#### 2.1.1. Quantitative studies

Studies in this category rely primarily on technical models to quantify energy consumption. The models can be classified as either "top-down" or "bottom-up" [2,31–35]. Top-down models typically focus on energy supply and demand at the macro level to capture long-term trends, and are usually such that the residential sector is just one among many sub-systems. Top-down models can be further divided into technological and econometric models; the former are mostly about the effects of housing stock characteristics, appliance ownership and trends in technology, while the latter mostly about the effects of pricing (e.g. time-of-use rates and dynamic pricing [34]), income and other economic variables [2,31]. In contrast, bottom-up models aim to predict energy consumption at the regional and national levels by extrapolating from estimated data for selected individuals, households and/or buildings. Bottom-up models can be further characterized as statistical or engineering. The former employs statistical techniques (e.g. regression, conditional demand analysis, neural networks) [35–38] to identify representative patterns, while the latter utilizes detailed simulation models based on building characteristics and climate variables to make predictions [39,40]. In addition, there also exist hybrid models that rely on a combination of both statistical and engineering methods [41]. For more on top-down and bottom-up models and their differences, refer to Swan and Ugursal [2], Kavgic et al. [31], Grandjean et al. [33], Suganthi and Samuel [32], and Fumo and Biswas [35].

Quantitative studies are important as they provide reliable ways of quantifying consumption, and are essential for assessing energy policies, e.g. technology adoption and energy efficiency policies. However, they do not adequately consider human behavioral factors and their effects. This is especially true in the case of top-down models that pay scant attention to individual end-users, and where any reference to human behavior is typically through the traditional economic notions of complete rationality and utility maximization. As for bottom-up models, thus far, their use to represent human behavior is still limited and mostly confined to the contexts of pre-determined occupancy schedules and equipment use patterns [30]. (While there are exceptions outside these contexts [42–44], they are few.) This is despite their greater focus on the decisions of individual agents and greater acknowledgment of the role of behavioral factors (as compared to top-down models).

#### 2.1.2. Qualitative studies and behavioral economic concepts

Studies in this category are essentially behavioral studies concerned with the role of behavioral factors in human energy decision-making. See Wilson and Dowlatabadi [18], Faiers et al. [45] and Frederiks et al. [46] for comprehensive reviews of the subject. The reviews demonstrate the complexity of the problem given the large number of cognitive biases and behavioral anomalies at play. Behavioral economic theories are of central importance to studies of this category as they are essential for explaining decision-making inconsistencies due to the bounded rationality of humans, their time discounting of gains and prosocial behavioral influences [47].

Bounded rationality refers to the deviation of individuals from complete economic rationality due to constraints in knowledge, cognition and time [48]. According to Nobre [49], it leads to decision-making based on imperfect information and heuristics that prevents