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A stochastic optimization approach to reduce greenhouse gas emissions from buildings and transportation

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A B S T R A C T

The magnitude of building- and transportation-related GHG (greenhouse gas) emissions makes the adoption of all-EVs (electric vehicles) powered with renewable power as one of the most effective strategies to reduce emission of GHGs. This paper formulates the problem of GHG mitigation strategy under uncertain conditions and optimizes the strategies in which EVs are powered by solar energy. Under a pre-specified budget, the objective is to determine the type of EV and power generation capacity of the solar system in such a way as to maximize GHG emissions reductions. The model supports the three primary solar systems: off-grid, grid-tied, and hybrid. First, a stochastic optimization model using probability distributions of stochastic variables and EV and solar system specifications is developed. The model is then validated by comparing the estimated values of the optimal strategies and actual values. It is found that the mitigation strategies in which EVs are powered by a hybrid solar system lead to the best cost-expected reduction of CO_2 emissions ratio. The results show an accuracy of about 4% for mitigation strategies in which EVs are powered by a grid-tied or hybrid solar system and 11% when applied to estimate the CO_2 emissions reductions of an off-grid system.

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1. Introduction

To help break down the complex subject matter of climate change, many researchers examined the links between human activities and climate change [2,31,38]. The examination of the literature facilitates an understanding of how GHGs (greenhouse gases) emissions contribute to global warming and what are natural and human sources of GHG emissions. This, in turn, translates to the development and implementation of GHG mitigation strategies. The burning of fossil fuels to generate electricity or drive cars has undoubtedly released carbon dioxide (CO_2) and other heat-trapping GHG emissions into the atmosphere and thus increased the concentration of atmospheric CO_2 emissions [24]. The main human activities that emit CO_2 emissions are (1) the combustion of fossil fuels to generate electricity, accounting for about 37% of total U.S. CO_2 emissions and 31% of total U.S. GHG emissions in 2013; (2) the combustion of fossil fuels such as gasoline and diesel to transport people and goods, accounting for about 31% of total U.S. CO_2 emissions and 26% of total U.S. GHG emissions in 2013; and (3) industrial processes such as the production and consumption of minerals and chemicals, accounting for about 15% of total U.S. CO_2 emissions and 12% of total U.S. GHG emissions in 2013 [6].

To make informed decisions, policy makers need to be familiar with a wide variety of carbon reducing technologies, GHG emission mitigation inventories and potential costs and benefits of specific GHG mitigation strategies. When looking at the GHGs that are associated with electricity generation and transportation, the adoption of hybrid and all-EVs (electric vehicles) instead of conventional gasoline powered vehicles with renewable source of power presents the most effective GHG emissions mitigation strategy [8]. This strategy not only saves considerable amounts of transportation-related CO_2 emissions [10], but also reduces the demand for electricity in buildings, which is mainly supplied by coal-fired generation. Because many factors that affect the success or scale of GHG emissions reductions are uncertain and complex, mitigation strategies are having difficulty delivering the desired outcome sought by policy makers. Thus, urban community

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planners and policy makers are confounded with huge amounts of unknown parameters, in which they wish to find the best solution from all feasible solutions (e.g. the largest GHG emissions reduction that a mitigation strategy can achieve) in the presence of uncertainty. Vehicle's specification (e.g. battery capacity, weight, and optimal energy use), road type and driving behavior (e.g. average speed), and environmental conditions (e.g. temperature and sunlight) are among the many factors affecting either energy consumption or generation and characterized by a significant degree of uncertainty.

To handle uncertainty, this paper presents a stochastic optimization approach to modeling GHG emissions from human activities in buildings and transportation. The problem of optimal GHG emissions mitigation strategy under uncertainty is formulated as a static stochastic optimization with observable state. Since solar energy is the only source of renewable energy that can be applied at a small scale (e.g. directly to the roof decking or solar window), this paper focuses only on the mitigation strategies in which EVs are powered by solar energy. Although mitigation actions through large-scale changes in energy system (e.g. new renewable energy power plant) will undoubtedly result in the largest GHG emissions reductions, they require major changes in the generation part of the energy sector and definitely need more investment. For instance, the establishment of national wide agriculture projects can produce considerable reductions in GHG emissions, around 34 tons equivalent CO_2 per year per hectare [20]. Also, it is possible to reduce 90% of the total GHG emissions from the energy sector by deploying renewable and alternative energy solutions [16].

On the other hand, small-scale GHG emissions mitigation actions (e.g. EVs powered by solar energy) can be accomplished by local communities and characterized by a short decision making cycle, need much less investment, and also eliminate electricity losses in transmission and distribution systems. These all make small-scale GHG emissions mitigation strategies more practical and feasible. What makes this study different from previous energy management or GHG emissions mitigation research is its focus on small-scale GHG emissions mitigation strategies and its validation process. As described later in this paper, a small-scale strategy in which EVs are powered by electricity generated by solar panels achieves the best cost-expected reduction of CO_2 emissions ratio, around $2500 per 1 ton CO_2 emission reduction per year. If we could fit about 20 building plots in a hectare, we can expect to reduce around 60 tons equivalent CO_2 per year per hectare in GHG emissions using an EV + solar energy strategy. When compared with the construction cost estimates of $6 billion to $9 billion for each 1100 MW new nuclear power plant [32], such small-scale strategies can potentially reduce emission of GHGs more than twice the reductions in GHG emissions by a nuclear power plant under a pre-specified budget constraint.

Another principal problem with prior energy management or GHG emissions mitigation research is that optimization models have not been validated with real data. In contrast, the proposed optimization approach is validated by comparing the estimated values of the optimal decision and actual values as realizations of the uncertain elements become known. The present model builds on and extends previous studies conducted by the authors. The research team developed an integrated Building Information Modeling-Geographic Information System (BIM-GIS) model that combines energy use in buildings and transportation infrastructures with occupant and travel behavior [13]. In another study conducted by research team, the effectiveness and possible CO_2 emissions reductions of GHG emissions mitigation strategies were evaluated based on the current trend of energy use in building and transportation sectors [14]. None of these studies have estimated or forecasted the future trend of energy use and CO_2 emissions and both focused on the current trend of energy use in building and transportation. After this introduction, the literature is reviewed and different types of optimization models for energy planning and GHG emissions mitigation are described. This is followed by a description of the research problem and research methodology. The next sections present the data collection and analysis results. The last section provides insight into the validation of the proposed stochastic model.

2. Research objective

The objective of this paper is to develop a stochastic mathematical model for energy consumption and mitigation strategy analysis that maximizes GHG emissions reductions based on the current demand trend and market prices. In this model, we consider EV and solar system costs, as well as the human activities (e.g. time spent in the building, time spent driving, and distance traveled) and environmental impacts (e.g. temperature, humidity, and sunlight) under uncertain conditions.

3. Literature review

A number of researchers have proposed and applied optimization models for energy planning and GHG emissions mitigation assessment. Deterministic models have a long history of being applied to energy planning and energy policy analysis and has steadily grown to a popular approach in the early 1990's [12,15,22]. These models have the advantage of simplicity and clarity; however, they cannot reflect uncertainties existing in GHG emissions mitigation strategies and energy activities. In forecasting future energy activities and assessing GHG emissions mitigation strategies, each component or aspect of the problem could be deterministic, probabilistic, or fuzzy. Thus, development of inexact optimization methods grew and matured essentially over the last decade. Depending on the source of uncertainty, optimization modeling for energy management and GHG emissions mitigation targets can be grouped into the three broad categories of stochastic, interval, and fuzzy approaches.

Stochastic optimization models are more suitable when decision parameters (e.g. temperature and solar radiation) are unknown but can be expressed as chances or probabilities. The solution procedures for modeling optimization problems under uncertainty, or stochastic programming, can be formulated and implemented at various levels such as static problems (when decisions do not affect the probability distributions of the random data), two-stage problems (when we can observe an uncertain outcome after our first decision, and then make another decision), multi-stage or sequential decisions problems (when we can make decisions at multiple-stages based on past observations), stochastic dynamic problems (when the probability distributions for each succeeding stage are influenced or determined by decisions made earlier), and optimization search (when a complete search is impractical, so a solution is guessed and then randomly search pathways are selected to find optimal results) [17,34]. Examples of stochastic optimization models for energy planning and GHG emissions mitigation assessment include [7,25,29].

A critical step in achieving stochastic model credibility is the process of validation, where the outcomes of the model are to be evaluated using the estimation or prediction error once the values of the random variables become known. Although numerous studies e.g. Refs. [3,11,18,19] have focused on the use of stochastic approaches to energy optimization, very few have actually been validated across a range of real metrics. They have been evaluated using simulation or hypothetical scenarios, but these evaluation studies do not necessarily address model validity. There are two