Transdisciplinary Approach to Reduce Electricity Consumption Using System Dynamics

Seyed Hamed Moosavirad[1*], Amirreza Torabi[1], Mitra Mirhosseini[2]
[1]Department of Industrial Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[2]Energy and Environment Research Center, Shahid Bahonar University of Kerman, Kerman, Iran
*Correspondence: s.h.moosavirad@uk.ac.ir

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Abstract: *The electricity sector holds a paramount position in Iran's energy landscape and plays a pivotal role in economic decision-making. The transdisciplinary approach to reducing electricity consumption involves an integrated method that goes beyond traditional disciplinary boundaries. Consequently, to regulate electricity usage through macro and national strategies, it is imperative to contemplate soft and qualitative methodologies employed in the analysis of socio-economic systems, particularly through the lens of system dynamics. This study aims to scrutinize the influence of diverse socio-cultural policies on diminishing electricity consumption utilizing system dynamics as a transdisciplinary approach. Findings from research conducted in Kerman, a province in Iran, underscore that if the current scenario persists, electricity consumption will persistently escalate over the next decade. However, the results indicate that the implementation of pertinent educational and promotional policies can mitigate the growth rate of electricity consumption.*

Keywords: System dynamics, transdisciplinary, electricity consumption, socio-cultural policies

1 Introduction

Electricity, a vital energy source globally, has experienced substantial growth alongside technological and industrial advancements. In Iran, household electricity consumption accounted for 25% and 50% of the total energy demand in 2010 and 2019, respectively (Rahmani et al., 2020). Recent data from the energy balance sheet estimates household electricity consumption in Iran at 2960 kilowatt hours per subscriber. The high per capita electricity consumption in Iran, attributed to the drought crisis and escalating oil and natural gas prices, has led to increased electricity costs. Furthermore, meeting the electricity needs of households, industries, and agriculture poses a significant challenge for electricity distribution companies.

The transdisciplinary approach expands the scientific perspective by integrating disciplinary, interdisciplinary, and multi-disciplinary knowledge and models to broaden the natural science worldview (Mokiy & Lukyanova, 2022). Therefore, the transdisciplinary approach to reducing electricity consumption involves an integrated method that goes beyond traditional disciplinary boundaries. It combines insights, tools, and knowledge from various disciplines, such as engineering, psychology, economics, and sociology, to address the complex challenges related to electricity consumption (Spreng, 2014). This approach seeks to engage stakeholders from different sectors, including policymakers, businesses, and communities, to collaboratively develop and implement strategies for reducing electricity usage (Spreng, 2014). By leveraging diverse expertise and perspectives, the transdisciplinary approach aims to create holistic and sustainable solutions (Costa, 2022). It often involves conducting comprehensive research, engaging in participatory processes, and implementing innovative interventions that consider technological, behavioral, and systemic factors influencing electricity consumption. The approach emphasizes the need for inclusive dialogue, co-creation of knowledge, and the integration of social, economic, and environmental considerations to achieve meaningful and lasting reductions in electricity usage. Balancing electricity demand and supply involves reducing demand and ensuring adequate supply, with social and cultural factors playing a crucial role in reducing electricity consumption. However, analyzing social and cultural policies is complex due to intricate causal relationships among them. System dynamics as a potential instrument for transdisciplinary research approach can deal with these complexities (Forrester, 1993; Gallati & Wiesmann, 2011). In a transdisciplinary approach, system dynamics serves as a valuable method for comprehending complexities within systems, fostering learning, pinpointing reasons for policy resistance, and ultimately enhancing the development of more impactful policies (Brenner, 2013; Gallati & Wiesmann, 2011).

Controlling electricity consumption intensity across various economic sectors is a key energy policy. Evaluating and quantifying electricity consumption and waste is a primary strategy for controlling electricity usage. Nonetheless, energy auditing encounters some limitations (Cooremans, 2013). Firstly, conducting extensive audits is impractical due to the diverse and large volume of electricity consumers across domestic, industrial, and agricultural sectors. Secondly, non-technical factors such as social and cultural influences impact the optimal technical solutions derived from electricity audits. Therefore, to achieve reduced electricity consumption and control based on macro and national strategies, soft and qualitative approaches used in analyzing socio-economic systems through system dynamics should be considered. Consequently, this study aims to analyze the impact of various socio-cultural policies on reducing electricity consumption using a system dynamics approach.

The article's structure to address the research objective is as follows: the second part will delve into previous studies related to system dynamics of energy, followed by the presentation of the research method of system dynamics in the third part. The fourth section will present the research results, and the fifth section will conclude with management recommendations.

2 Literature review

The following studies delve into system dynamics within the electricity and energy industry. Firstly, the Turkish electricity market was scrutinized through a system dynamics model, incorporating factors such as electricity generation, consumption, exports, imports, GNP, GNP per capita, and inflation rates, all of which impact electricity costs (Öner & Kayıkçı, 2002). Furthermore, the impact of economic and environmental constraints on the German electricity market was examined through system dynamics (Jäger, Schmidt, & Karl, 2009). Another study utilized system dynamics to model energy consumption trends under various urban growth scenarios over a 50-year period, focusing on transportation and industry sectors (Fong, Matsumoto, Lun, & Kimura, 2007). In the British natural gas industry, a system dynamics model was employed, encompassing three sub-models related to exploration, production, and consumption (Chi, Nuttall, & Reiner, 2009). Additionally, the influence of energy efficiency intervention policies on household subscribers was modeled through system dynamics, considering factors such as electricity cost, comfort and convenience of electrical appliance usage, and the environmental impact of consumption (Davis & Durbach, 2010).

In the realm of socio-cultural strategies for reducing electricity and energy consumption, several studies have been conducted. Gleerup et al. (Gleerup, Larsen, Leth-Petersen, & Togeby, 2010) examined the impact of SMS and email feedback on home electricity consumption in Denmark, aiming to enhance consumers' awareness of their electricity usage. Their findings indicated that notifications containing information about peak household consumption periods led to an average annual electricity consumption reduction of approximately 3%. Carico and Reimer also investigated the impact of a workplace feedback system on electricity consumption, revealing that peer feedback and training reduced energy consumption by 7% and 4%, respectively (Carrico & Riemer, 2011). Another study highlighted the efficacy of a feedback system, emphasizing the importance of continuity and presentation over an extended period, device-specific analysis, clear and engaging displays, and the utilization of computer and interactive tools. It was concluded that feedback systems contributed to energy savings, particularly in electricity, ranging from 1.1% to 20% (Fischer, 2008).

A study in Denmark investigated the impact of providing accurate feedback to households on power consumption, employing LCD screens. Over a five-month period, twenty Danish families participated, leading to an average estimated saving of 8.1% in electricity consumption (Grønhøj & Thøgersen, 2011). Direct feedback has the potential to save electricity consumption by 5 to 15%, while indirect feedback typically leads to savings of about 0-10% (Darby, 2006). Another study examined the effects of implementing a campaign message strategy on energy consumption, revealing reductions in peak demand and total energy consumption in California (Moezzi, Gossard, & Lutzenhiser, 2002). In Spain, researchers explored various policies for the photovoltaic energy market using a system dynamics approach, concluding that current electricity generation systems and solar energy offer limited short-term benefits (Movilla, Miguel, & Blázquez, 2013). Similarly, in China, a 2013 study utilized system dynamics to predict and optimize energy consumption, focusing on minimizing carbon emissions in industries (Wu & Xu, 2013).

In 2014, the role of renewable energy development policies in Finland's energy independence was scrutinized using a system dynamics model. Results indicated that implementing energy action plans to establish new renewable energy capacities could save $4 billion in natural gas imports in the country (Aslani, Helo, & Naaranoja, 2014). Another 2014 study in Ecuador employed a system dynamics approach to assess how renewable energy and GDP changes impact CO_2 emissions, highlighting the need to reduce reliance on fossil fuels and enhance productivity (Robalino-López, Mena-Nieto, & García-Ramos, 2014). Subsequently, a 2015 study simulated electricity demand for forestry, timber, and lumber industries in South Africa, emphasizing the necessity for new electricity sources to address future energy supply uncertainties (Koegelenberg & Pillay, 2015). Additionally, a dynamic systems-based simulation model was developed for electricity pricing in the household sector in China, encompassing subsystems such as subsidized prices, clean energy tariffs, and electricity distribution prices (Luo, Huang, & Chen, 2015). Researchers also explored the minimum carbon emission development strategy for the West African power system using a system dynamics approach, emphasizing the need for balanced infrastructure development considering economic growth and environmental impact (Momodu, Addo, Akinbami, & Mulugetta, 2017).

Researchers also conducted a comprehensive review of electricity access and its impact on rural socio-economic development, utilizing causal loop diagrams of system dynamics to illustrate the complexity of the nexus (Riva, Ahlborg, Hartvigsson, Pachauri, & Colombo, 2018). Another literature review focused on reinforcement learning and its applications in sustainable energy and electric systems, highlighting the demand for reinforcement learning in the sustainable energy sector (Yang, Zhao, Li, & Zomaya, 2020). Moreover, a system dynamics model incorporating the generalized bass model was developed to model renewable energy technology adoption in the hotel sector in Queensland, Australia, outlining conditions under which adoption rates follow S-curve growth (Dhirasasna, Becken, & Sahin, 2020). Likewise, multiple factors influencing energy consumption in aging residential buildings were investigated using a system dynamics model, encompassing meteorology, architecture, resident behavior, and energy-use behavior (Li, Wang, Wang, Hu, & Sun, 2021). Furthermore, the relationship between renewable energy penetration and energy security indicators was explored using a system dynamics approach, indicating a sharp increase in energy consumption alongside marginal improvements in energy efficiency and economic growth (Shadman et al., 2022). In Iran, the impact of renewable energy development on carbon dioxide emissions was studied across five distinct scenarios, revealing potential reductions in carbon emissions (Mostafaeipour, Bidokhti, Fakhrzad, Sadegheih, & Mehrjerdi, 2022).

Conclusively, the reviewed literature underscores the need for further research into the impact of socio-cultural policies on electricity consumption rates, emphasizing the necessity to study these policies for individual regions due to their specific characteristics. Therefore, this study aims to analyze the impact of various socio-cultural policies on electricity consumption reduction.

3 Methodology

System dynamics, as a method for studying complexities in a transdisciplinary approach, facilitates learning within complex systems and aids in identifying the causes of policy resistance, thereby enabling the design of more effective policies (Brenner, 2013; Gallati & Wiesmann, 2011). Moreover, it empowers decision-makers to craft improved policies by comprehending how structures lead to behaviors (Forrester, 1993). The steps of system dynamics, as outlined, encompass: (1) problem definition, (2) modeling cause and effect loops, (3) dynamic modeling, (4) model validation, (5) results and program scenario design, and (6) implementation and organizational learning (Maani & Cavana, 2000). This research specifically focuses on the initial five steps of system dynamics, detailing the results of each stage thereafter.

4 Results

The results of each step of the presented research methodology are stated as follows:

4.1 Definition of the problem

This study seeks to analyze the electricity consumption behavior of household subscribers in a case study of the North Kerman Electricity Distribution Company in Iran, including the cities of Kerman, Rafsanjan, Zarand, Shahrbabak, Ravar, Kuhbanan, and Anar.

4.2 Modeling the diagrams of cause-and-effect loops

The variables of the cause-and-effect loop model that affect household electricity consumption are population growth and the number of subscribers, per capita consumption, community welfare level, technology and number of electrical appliances, energy prices and weather conditions. Policies aimed at reducing electricity consumption encompass:

4.2.1 Education

Education encompasses a range of activities designed to foster learning and raise awareness among the audience (Parsizadeh & Ghafory-Ashtiany, 2010). In the context of energy consumption control, educational initiatives can impart knowledge about the significance of optimal consumption and its societal impact in the short and long term. It also emphasizes the correct usage of electrical appliances, the need to monitor the consumption of various electrical devices, and the importance of energy labels. Various visual, audio, and electronic tools can be utilized for educational purposes. This includes dissemination through books, magazines, brochures, as well as organizing seminars, meetings, and conferences tailored to different segments of society. Leveraging cyberspace and messaging platforms are also pivotal educational tools. Community education should encompass all strata of society, including clergy, educators, students, employees, managers, laborers, industry proprietors, athletes, and artists.

4.2.2 Advertising

Advertising serves as a means to communicate with the audience and convey a message (Schwartz, Bruine de Bruin, Fischhoff, & Lave, 2015). It can be executed through mediums such as posters, leaflets, brochures, or various media channels. Similar to educational initiatives in cyberspace, messaging platforms are emerging tools for advertising. Advertising targets all segments of society and can be tailored to influence specific societal groups. Effective advertising methods include TV commercials in the form of animations, teasers, or short films, establishing online platforms and channels in cyberspace, and utilizing short messages. Advertising efforts should emphasize the importance of optimal consumption, fostering a culture of awareness, and articulating its effects.
Based on the identified factors, the cause-and-effect loop diagram (current situation) is depicted in Figure 1.

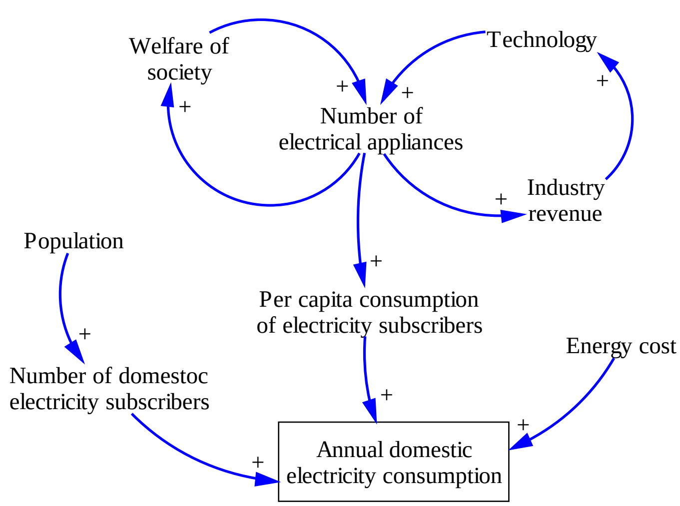

Figure 1: Diagram of cause-and-effect loops (current status)

Owing to the absence of statistics and data on the quantity of electrical appliances, community welfare, technology, and industrial income, these variables have not been incorporated into the model. However, the trajectory of household electricity consumption from 2009 to 2017, influenced by the aforementioned factors, has been extrapolated into the future. The cause-and-effect loop diagram, based on the framework of cultural policies, is illustrated in Figure 2.

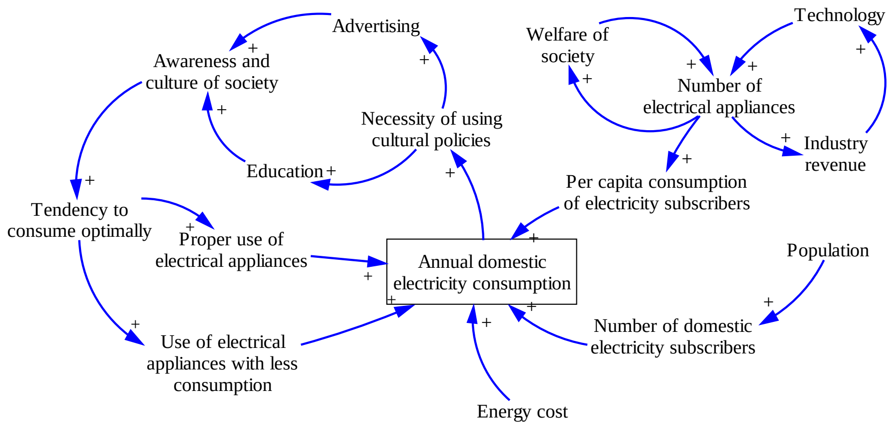

Figure 2: Chart of cause-and-effect loops (policy structure)

4.3 Dynamic modeling (modeling and formulation)

The following figure shows the stock and flow diagram of the current power consumption situation.

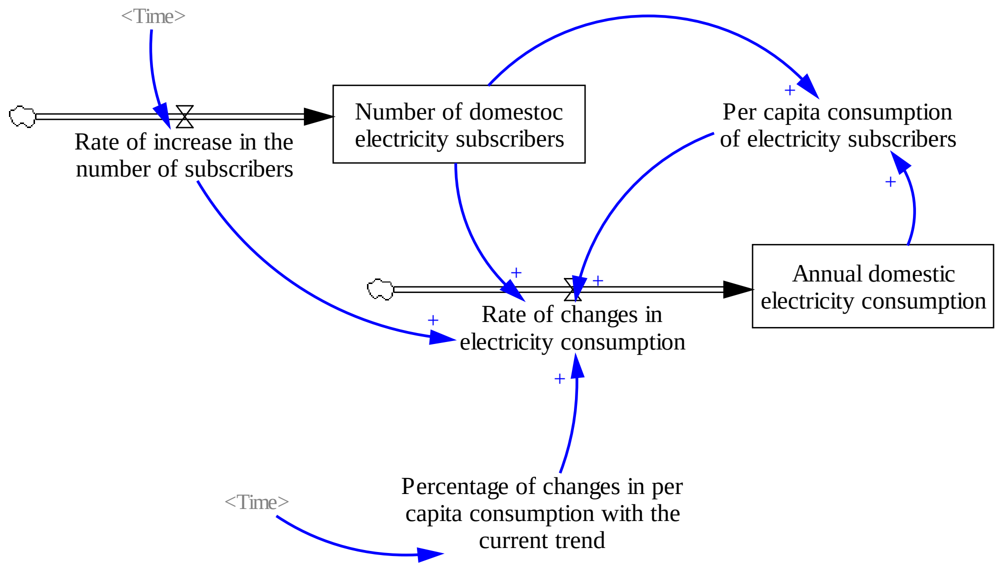

Figure 3: Stock-flow diagram (current status)

Figure 4 also shows the stock-flow diagram with the structure of cultural policies to reduce electricity consumption.

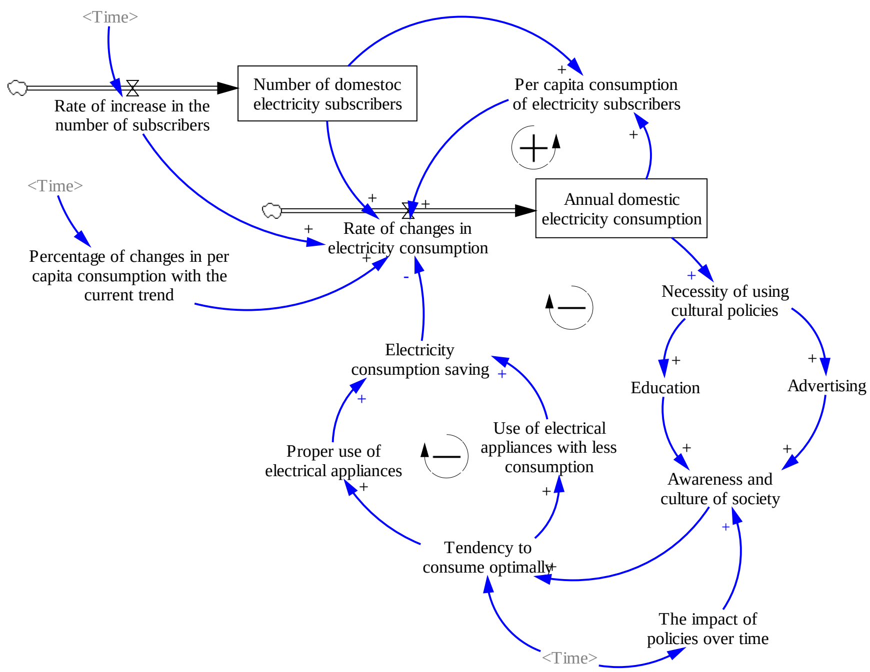

Figure 4: Stock-flow diagram (policy structure)

4.4 Model validation

Several tests and methods are available to demonstrate the validity of the model. The initial model, which depicts the current scenario and forecasts future behavior, was validated by comparing the subscriber numbers and annual household electricity consumption values generated by the model up to 2017 with the distribution company's statistics. The results indicated a close similarity between the model-derived values and the company's actual data.

The validation of the second model is depicted in Figure 5, illustrating the impact of the implemented policies on the initial model. To achieve this, Monte Carlo sensitivity analysis was employed using Vensim DSS software. The education policy's value was varied from 0 to 1, while the advertising policy's value was set to zero. Additionally, the policies' effectiveness percentage over time was excluded from the model. When the education variable is set to zero, signifying no policy effectiveness, the annual electricity consumption remains unchanged. Conversely, a value of 1 for the education variable indicates a 100% reduction in annual electricity consumption, effectively reducing it to zero. Intermediate values between 0 and 1 represent varying degrees of policy impact. Similarly, the policies can be adjusted accordingly.

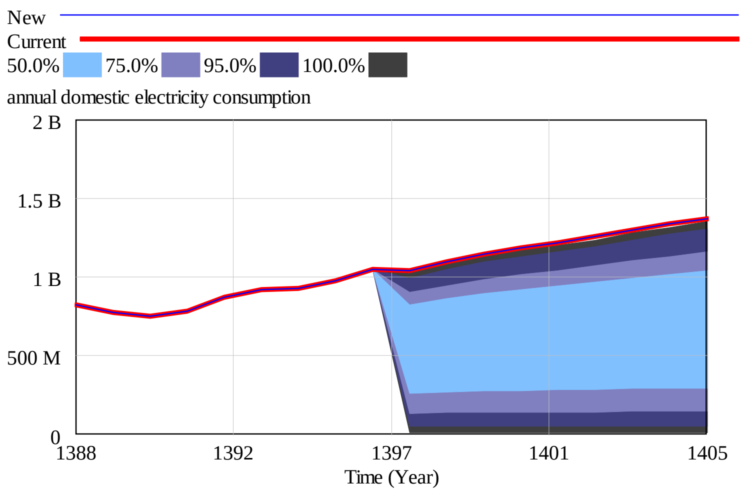

Figure 5: The result of Monte Carlo sensitivity analysis

4.5 Model results

By concurrently implementing education and advertising policies, along with the stated assumptions, the anticipated electricity consumption savings from 2018 to 2026 are estimated to range between 69 million kWh to 274 million kWh (Figure 6).

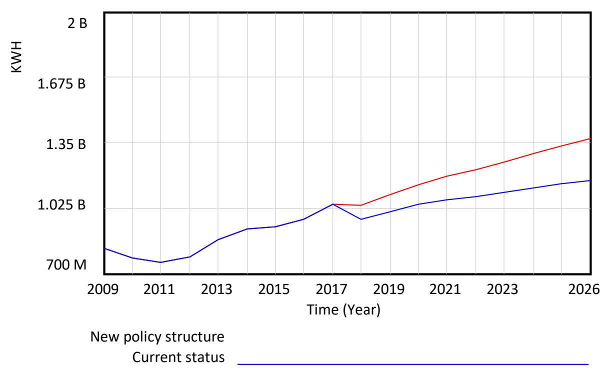

Figure 6: Annual household electricity consumption

4.5.1 Sensitivity analysis

In this section, alterations in model outcomes are assessed concerning policy adjustments in various scenarios. For instance, the advertising policy is kept constant with previous values, while the training policy is assigned fixed values ranging from 5 to 15 percent. Figure 7 illustrates the timeframe during which variations in annual electricity consumption occur when the training policy is implemented under its weakest and most stringent conditions.

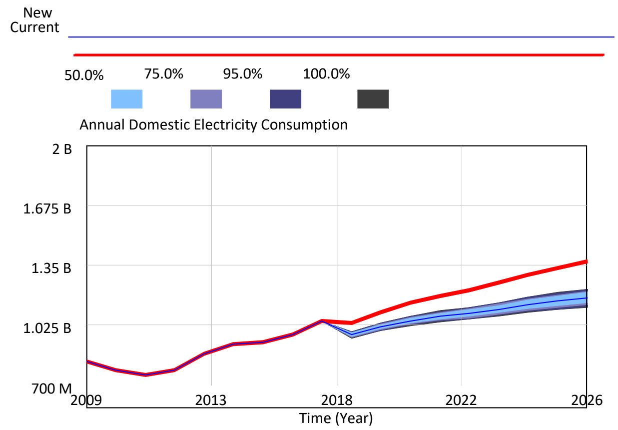

Figure 7: Sensitivity analysis

5 Conclusion

Based on the findings, while the implementation of individual policies leads to a reduction in electricity consumption, the overall consumption trend continues to rise. The sensitivity analysis and scenario results indicate that educational policies hold greater significance than advertising. This is because education not only emphasizes the importance of optimal consumption but also focuses on the practical aspects of achieving it. To enhance outcomes, simultaneous implementation of training and advertising is essential to exert a more substantial influence on electricity consumption. Given the interconnected nature of these approaches, drawing a clear boundary between them may prove challenging. Advertising can serve as a means of educating the community, and vice versa.

Insights from studies in Denmark and the United States reveal that tools such as SMS, email, phone calls, and other electronic and non-electronic methods can effectively communicate peak consumption times to subscribers (Røpke, Christensen, & Jensen, 2010). This feedback system serves to raise awareness and serve as a reminder. Future research should explore the economic implications of different policies on electricity consumption. Furthermore, electricity distribution companies should tailor a portfolio of educational and advertising tools based on their budget and the efficacy of these tools.

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Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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About the Author

Seyed Hamed Moosavirad received his PhD in Manufacturing Engineering and Management from University of New South Wales, NSW, Australia. He also received the B.Sc. and M.Sc. degrees in industrial engineering from the Shahid Bahonar University of Kerman and Iran University of Science and Technology, respectively. He is currently working as an Associate Professor at the Department of Industrial Engineering in Shahid Bahonar University of Kerman, Iran. His research interests include maintenance management, supply chain management, data mining, project management, multiple-criteria decision analysis. He currently serves as an Associate Editor for International Journal of Applied Industrial Engineering and an editorial board member in the Journal of Organizational and End User Computing.

Amirreza Torabi received his B.Sc. and M.Sc. in Industrial Engineering from Shahid Bahonar University of Kerman, Kerman, Iran in 2017 and 2020, respectively. His research interests include value engineering, multi attribute decision making and system dynamics.

Mitra Mirhosseini received the B.Sc. and M.Sc. in electrical engineering from Shahid Bahonar University of Kerman (SBUK), Kerman, Iran, in 2007 and 2010, respectively, and the Ph.D. degree in electrical engineering from the University of New South Wales (UNSW), Sydney, Australia, in 2015. From 2016 to 2017, she was an Academic Member with the Central Laboratory of Applied Research, SBUK. She is currently working an Assistant Professor in Energy and Environment Research Center at SBUK. Her current research interests include modeling and control of grid-connected photovoltaic systems, energy storage system, power quality and their grid integration performance improvement**.**