VOL. 19, NO. 8, APRIL 2024 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

www.arpnjournals.com

EXPLORING THE POTENTIAL FOR HOUSEHOLD REFRIGERATOR REPLACEMENT IN MEXICO CITY

M.A. Escobedo-Izquierdo[1], S. Zamora-Muñoz[1], S. Quezada-García[1] and E.G. Espinosa-Martínez[2]
[1]Departamento de Sistemas Energéticos, Facultad de Ingeniería, Universidad Nacional Autónoma de México, México
[2]Department of Engineering, CIIDETEC-Coyoacán, Universidad del Valle de México, Coyoacán, México
E-Mail: erick.espinosa@uvmnet.edu

ABSTRACT

Many studies have focused on improving the energy performance of household refrigerators and finding out their performance under different operating conditions. However, there seems to be a gap regarding the potential for electrical energy savings due to retrofitting household refrigerators. This study focuses on the replacement potential of household refrigerators eight or more years old in poor households in Mexico City. The study uses a stratified sampling methodology. The results show that it is advisable to replace 77.75% of the household refrigerators that are in operation in poor households in Mexico City. The replacement of household refrigerators with energy-efficient equipment represents 36% of the electrical energy consumption for food refrigeration in the domestic sector in Mexico City.

Keywords: energy savings; energy efficiency, domestic sector.

Manuscript Received 21 February 2024; Revised 18 May 2024; Published 30 June 2024

1. INTRODUCTION

The main obstacles to achieving a sustainable society are the negative environmental impact caused by fossil fuel energy sources and the rapid increase in global energy consumption. Renewable energy sources are considered a solution to reduce greenhouse gas emissions and achieve energy security (Jacobson, 2009). Renewable energies can bring societies closer to sustainability; however, renewable sources cannot often produce enough energy to meet society's needs, making it necessary to reduce energy consumption. The use of energy-efficient technology, as well as the adoption of new consumption habits and policy regulations to manage energy consumption, are measures that can reduce the consumption of fossil fuel energy sources, thereby reducing greenhouse gas emissions.

In 2020, 48% of global electricity consumption was due to commercial and residential buildings, which accounted for 29% of the total final energy consumption. This percentage is expected to grow to 30%, representing 25% of total CO_2 emissions related to energy (DNV, 2023) by 2050. Specifically, commercial and residential buildings consume about 25% of primary energy in Brazil, around 30% in China, and over 40% in the United States and Europe (Deng *et al*., 2014; Gerhardt *et al*., 2021). Over the past decade, researchers have focused on energy-efficient technology to reduce buildings' dependence on primary energy and achieve zero-energy buildings, which are considered integrated solutions to address energy saving, environmental protection, and greenhouse gas emission reduction issues (Deng *et al*., 2014).

Residential buildings have received particular attention because they are an important target group for energy saving and efficient energy use, accounting for 25% of total energy consumption in the United States, 26% in Japan, and up to 50% in Saudi Arabia (Brounen *et al*., 2013; Wang *et al*., 2011).

The increasing use of appliances in residential buildings has led to rapid growth in electricity demand and consumption (Zhang *et al*., 2020; Zhang and Tao, 2020; Zou and Mishra, 2020). Energy-efficient appliances can significantly contribute to reducing the dependence of residential buildings on primary energy (Atasoy *et al*., 2022). Their widespread adoption saves energy resources and promotes the development of a low-carbon economy (Zhang et al., 2020). Therefore, the importance of guiding consumers in choosing energy-efficient appliances (Zhang and Tao, 2020).

Some influential factors in consumers' purchase of energy-efficient appliances include regulations, environmental awareness, and price (Zhang *et al*., 2020; Zhang and Tao, 2020). The price of energy-efficient appliances is a barrier to widespread adoption (Zhang *et al*., 2020). Galarraga *et al*. (2011) estimated that in Spain, the premium paid for an energy-efficient household refrigerator (HR) accounts for nearly 9% of the final price and represents one-third of the energy savings obtained by the consumer over the refrigerator's lifespan. However, a study by Zou and Mishra (2020) on rural households in China demonstrated that subsidies encourage the acquisition of energy-efficient appliances.

New regulations have been created to promote the acquisition of energy-efficient appliances, and higher awareness efforts among users have been made about the importance of environmental protection. For example, since 2004, China has implemented energy efficiency policies and initiatives such as voluntary and mandatory energy labeling, enabling consumers to make informed decisions when purchasing appliances (Zhou *et al*., 2010). Another example is the European Union, whose member countries have developed policies focused on the efficient use of electricity to enhance households' energy savings (Ek and Söderholm, 2010). The use of information on energy consumption and other resources in European appliances has been regulated since the early 1990s

VOL. 19, NO. 8, APRIL 2024 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

(Galarraga *et al*., 2011). Other countries that have enacted minimum energy efficiency standards for appliances include Australia, Brazil, Canada, Japan, Korea, the Philippines, Russia, and Mexico (Mahlia *et al*., 2004).

Among the most common appliances are HRs, with approximately one HR for every six people worldwide (Marques *et al*., 2013). The number of new HRs sold is around 150 million annually (Harrington *et al.,* 2018). HRs account for just over 7% of the average energy consumption in American households (Bansal *et al*., 2011), although this figure can vary significantly for other countries. For example, in Brazil, HRs account for 18.3% of residential electricity consumption (Gerhardt *et al*., 2021), while in Turkey, they represent 32% (Gürel *et al*., 2020). In 1995, in China, due to a lack of attention to energy efficiency, the energy consumption of HRs accounted for over 32% of the country's total residential electricity consumption (Tao and Yu, 2011). HRs are estimated to consume up to 6% of global electricity (Negrão and Hermes, 2011). Therefore, improving HR efficiency is an important aspect of future climate change mitigation.

Many studies currently focus on improving the energy performance of HRs and examining their performance under different operating conditions (e.g., Cheng *et al*., 2017; Fatouh and Abou-Ziyan, 2018; Gürel *et al*., 2020; Jeong *et al*., 2021; Pirvaram *et al*., 2019). Some of these studies have proposed improvements to heat exchange systems (Cheng *et al*., 2017; Doğan *et al.,* 2021; Pirvaram *et al*., 2019), while others have suggested changing refrigerants (Babarinde *et al*., 2020; Fatouh and Abou-Ziyan, 2018), and some have focused on user interaction with these appliances (Harrington *et al*., 2019). However, there seems to be a gap regarding the potential energy savings resulting from HRs modernization, possibly because energy data collected in households is often complex and difficult to interpret. The most recent study found was conducted in China in 2011; the results by Tao and Yu (2011) show that replacing HRs with more energy-efficient ones has the potential to reduce residential energy consumption significantly.

This paper explores the potential for replacing HRs currently in operation with more modern HRs that comply with the energy efficiency standards in force in Mexico; it also presents the potential for saving electricity due to their replacement. The study is among the population living in poverty in the residential sector of Mexico City. With the methodology applied, it is possible to identify the areas of greatest impact where a HR replacement program can be implemented to reduce electricity consumption and thereby reduce greenhouse gas emissions.

2. BACKGROUND

Energy efficiency became part of Mexico's energy policy in the 1990s, and one of the most important lines of action was energy savings in the residential sector.

In 2000, the Trust Fund for Electric Energy Savings (FIDE) began implementing pilot programs for energy efficiency in the residential sector to test new financing mechanisms and evaluate user response.

In early 2002, the "Pilot Program for Household Refrigerators" was implemented in six cities in Mexico. This program involved replacing energy-inefficient HRs with new, more efficient ones. The pilot program concluded in 2003 with the replacement of 2,386 units. Subsequently, the "Financing Program for Electric Energy Savings" was implemented. This program aimed to replace inefficient HRs over eight years old in the residential sector with new HRs with higher energy efficiency. The program utilized financing mechanisms to conserve the environment and reduce greenhouse gas emissions. The program began at the end of 2002 and ended in 2006, with 623,317 HRs replaced.

The latest program implemented in Mexico was the "Appliance Replacement Program for Electric Energy Savings." This program involved replacing HRs over ten years old with new appliances that had energy efficiency labels complying with the Mexican standard (NOM-015-ENER-2002 "Energy Efficiency of Household Refrigerators and Freezers: Limits, Test Methods, and Labeling"). This program started in March 2009 and concluded in 2013, benefiting 1,682,802 families, 5.5% of residential sector users. The costs of the HRs were covered by the savings they generated, estimated to be $356 per year for users.

3. METHODOLOGY

The proposed methodology in this study consists of the following basic steps:

a) Characteristics of the population
b) Sample size
c) Application and survey results
d) Calculation of energy savings

The methodology followed in this study is described below as follows,

3.1 Characteristics of the Population

The HR replacement or modernization program must have a clear target population’s characteristic. Since the cost of energy-efficient appliances is a barrier to their acquisition, a focus on support programs for the poverty-living population is recommended.

In this study, the number of beneficiaries corresponds to poverty-living households that would replace their HRs, which are eight years old or older, with a new and more energy-efficient model.

3.2 Sample Size

For large populations, it is advisable to determine the size of a statistically representative sample for study purposes. In other words, a feasible sample size to extrapolate the results to the total population.

A simple random sampling technique can be applied to determine the sample size, commonly used due to its simplicity and ease of implementation. This technique involves selecting elements from a population randomly and uniformly, ensuring that each element has

ARPN Journal of Engineering and Applied Sciences
©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

an equal probability of being selected to be part of the sample.

For heterogeneous subpopulations, simple random sampling is not an appropriate technique. In such cases, stratified sampling is a better option, which provides greater precision and representativeness of the results obtained. However, the total sample size required is usually larger compared to simple random sampling.

Stratified sampling is performed separately within each stratum and the sample size for each stratum (n_h) is calculated based on (Cochran, 1977):

$$n_h = n\frac{N_h}{N}; \qquad h = 1,2,3,...,L \tag{1}$$

where N is the number of elements in the total population, L is the number of strata into which the population is divided, N_h is the number of elements in stratum h, and n is the sample size of the population. For values close to a 95% confidence level, with P_h and Q_h being constant for each stratum, the sample size of the population can be calculated using (Lohr, 2019):

$$n = \frac{Z^2 P_h Q_h}{d^2} \tag{2}$$

where d is the desired precision for the estimation, which represents the maximum acceptable margin of error for estimating the population proportion. Z is the critical value of the normal distribution corresponding to the desired confidence level, P_h is the estimated proportion of the population that has the characteristic of interest, and Q_h is the proportion of the population that does not have the characteristic of interest; i.e., $Q_h = 1 - P_h$.

3.3 Survey Application and Results

To understand the characteristics of the HRs owned by the population targeted by the support program, a questionnaire must be designed to be administered to the sample.

For this case, the questionnaire consists of the following questions:

a) Do you have access to electricity service?

b) Is your HR in working condition?

c) What is the manufacturing year of your HR?

d) What is the capacity (volume) of your HR?

Subsequently, the results obtained from the survey administered to the sample are analyzed to determine the number of HRs that has the necessary characteristics to be replaced. These results are then scaled up to the population targeted by the support program.

3.4 Energy Savings Estimate

Knowing the number of HRs that can be replaced in the population and their characteristics, the energy saving potential can be determined since the energy consumption of energy-efficient HRs is known.

Energy and economic savings are determined by:

$$E_s = \sum_{i=7}^{w=30} k_i \left(E_b - E_p\right)_i \tag{3}$$

where k_i represents the number of HRs in operation with volume i; with i = 7, 8, 9..., 28, 29, 30; representing the volume in ft^3 of equipment entering the replacement program. E_b represents the base or current energy consumption per unit of time and E_p represents the projected energy consumption per unit of time through energy saving mechanisms, in this case the Mexican energy efficiency standard for HRs.

Next, the methodology is applied to the case study, which focuses on the population living in poverty in Mexico City.

4. MEXICO CITY CASE STUDY AND RESULTS

Mexico City is divided into 16 town halls (A. Obregón, Azcapotzalco, B. Juárez, Coyoacán, Cuajimalpa, Cuauhtémoc, G.A. Madero, Iztacalco, Iztapalapa, M. Contreras, Milpa Alta, Tláhuac, V. Carranza, and Xochimilco), and there are 2,386,605 households with electricity, of which 91% have a HR (INEGI, 2017).

4.1 Characteristics of the Population

Figure-1 reports the total households and the households in poverty in each town hall. As seen, the number of households differs significantly for each town hall, as well as the number of households in poverty. Therefore, the town halls are considered heterogeneous, and it is necessary to use stratified sampling.

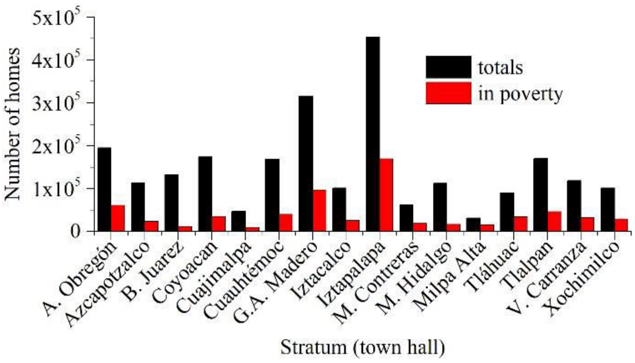

Figure-1. Total number of households and those in a situation of poverty by town hall.

4.2 Sample Size

The study conducted a stratified sampling with proportional allocation to the size of each town hall that divides Mexico City. Each town hall is considered a stratum, with L = 16. The household is the sampling unit. The population is composed only of poverty households,

ARPN Journal of Engineering and Applied Sciences
©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

with N = 664,132. Since the proportion of HRs aged 8 years or more is unknown, P_h = 0.5 is taken, as this proportion ensures that the sample size is the largest possible, covering any potential scenario. The level of precision chosen is d = 0.02, and the confidence level is set at 95%, corresponding to Z = 1.96. Table-1 presents a summary of these parameters. Meanwhile, Figure-2 displays the sample size for each stratum, resulting in a total sample size of 2,392.

Table-1. Parameters used to determine the sample size and the size of each stratum.

Parameter	Value
N	664132
L	16
d	0.02
P_h	0.5
Q_h	0.5
Z	1.96

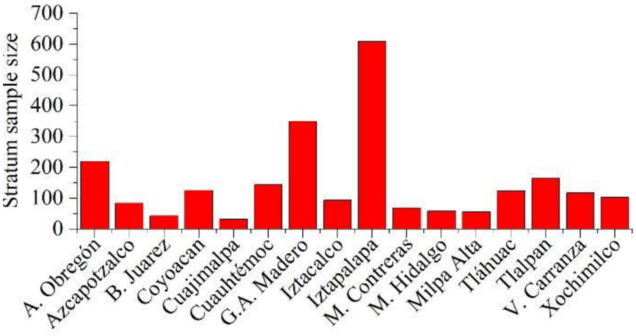

Figure-2. Sample size for each stratum.

4.3 Survey Application and Results

The survey found that 100% of the households have access to electricity. 0.8% of them do not have a HR, 91.2% have a functioning HR, and 8% have a HR that is not working. The percentage of households with more than eight years old HRs is 77.75%, which means that slightly more than three-quarters of the HRs can be considered energy inefficient. The year of manufacture of the HRs is in more detail in Figure-3.

This study focuses solely on HRs between 7 ft^3 to 30 ft^3. The percentage of HRs within this range is 95.53% of the total. The volume of the HRs is presented in Figure-4.

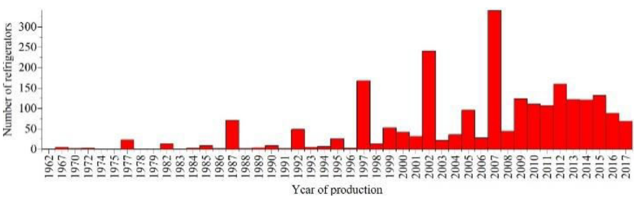

Figure-3. Year of manufacture of HRs for Mexico City according to the results of the survey.

Thus, based on the survey results, it is found that 1,860 HRs are aged 8 years or older, in operation, and have a volume between 7 ft^3 and 30 ft^3. Therefore, this is the number of HRs that can be replaced due to their energy saving potential. This number represents 77.75% of the sample; thus, the total number of HRs that can be replaced in households in poverty in Mexico City is 516,025.

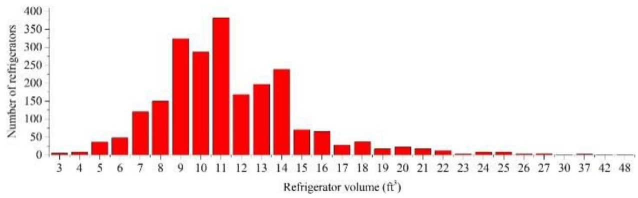

Figure-4. Volume of HRs for Mexico City according to the survey results.

4.4. Energy Savings Estimate

From the results of the survey and using Eq. (3), the possibility of electrical energy saved by the implementation of a new HR replacement program in Mexico City is 98,861,388 kWh/year, which represents 36% of the energy consumed for food refrigeration in Mexico City. It is important to mention that the value of the current electric energy consumption, E_b, is obtained from past Mexican energy efficiency standards; and the value of the projected electric energy consumption, E_p, was obtained from the Mexican energy efficiency standard for HRs in force in 2012.

5. DISCUSSIONS

From the evolution of the Mexican standard for energy efficiency in HRs, the average consumption was 1,200 kWh/year in 1993. With the most recent revision of the standard in 2018, the energy consumption of new equipment should be around 250 kWh/year. From this arises the need to replace the old energy-inefficient HRs. This study focused on determining the potential for the replacement of HRs for households living in poverty located in Mexico City. Poverty-stricken households were selected because they are targeted by the social programs implemented by the Mexican government; additionally, they are the largest population (see Figure-1). The programs are directed to this population sector because the price premium for energy-efficient appliances is one of the barriers.

If a new HR replacement program was implemented, the government would promote energy-efficient technologies in the domestic sector, since it is advisable to replace 516,025 HRs in use and operate with low efficiencies. This represents an energy saving of approximately 98,900 MWh/year; that is, it represents a saving of 36% of the energy consumption for food refrigeration in the domestic sector in Mexico City.

The results show that despite the programs implemented to replace HRs from 2000 to 2013, there is still great potential for the replacement and modernization of this appliance.

©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

Additionally, the results suggest that government programs and incentives to support poor households to purchase energy-efficient HRs should be periodic, since time and use decrease efficiency, further aggravated with each HR repair. On the other hand, manufacturers constantly improve the energy efficiency of their new equipment. Therefore, the difference in energy consumption between "old" and new equipment increases. At this point, the question arises, how often is it prudent to replace a HR to save electricity during its operation without having a negative life cycle energy balance? In other words, how often should a HR be replaced sustainably?

A life-cycle study of HRs is needed to consider how the equipment is disposed of, and how this waste is treated. This is beyond the scope of this paper but can be future research.

6. CONCLUSIONS

This study focused on determining the replacement potential of eight or more years old household refrigerators for poor homes in Mexico City. For this purpose, we propose a methodology based on stratified sampling that can be applied to other case studies, for example, for other regions and household appliances.

The results show that despite the programs implemented to substitute household refrigerators, there is still great potential for the replacement and modernization of this appliance. Specifically, it is possible to replace 77.75% of the household refrigerators operating in poor households in Mexico City.

The replacement of household refrigerators with energy-efficient equipment represents 36% of electricity consumption for food refrigeration in the domestic sector in Mexico City.

REFERENCES

Atasoy E., Çetin B., Bayer Ö. 2022. Experiment-based optimization of an energy-efficient heat pump integrated water heater for household appliances. Energy 245, 123308. https://doi.org/10.1016/j.energy.2022.123308

Babarinde T.., Akinlabi S.., Madyira D. 2020. Energy performance evaluation of R600a/MWCNT-nanolubricant as a drop-in replacement for R134a in household refrigerator system. Energy Reports 6, 639-647. https://doi.org/10.1016/j.egyr.2019.11.132

Bansal P., Vineyard E., Abdelaziz O. 2011. Advances in household appliances- A review. Appl. Therm. Eng. 31, 3748-3760. https://doi.org/10.1016/j.applthermaleng.2011.07.023

Brounen D., Kok N., Quigley J. M. 2013. Energy literacy, awareness, and conservation behavior of residential households. Energy Econ. 38, 42-50. https://doi.org/10.1016/j.eneco.2013.02.008

Cheng W., Ding M., Yuan X., Han B.-C. 2017. Analysis of energy saving performance for household refrigerator with thermal storage of condenser and evaporator. Energy Convers. Manag. 132, 180-188. https://doi.org/10.1016/j.enconman.2016.11.029

Cochran W. G. 1977. Sampling Techniques, 3rd ed. John Wiley & Sons, New York.

Deng S., Wang R.Z., Dai Y.J. 2014. How to evaluate performance of net zero energy building - A literature research. Energy 71, 1-16. https://doi.org/10.1016/j.energy.2014.05.007

DNV. 2023. Energy Transition Outlook 2022, A global and regional forecast to 2050.

Doğan B., Ozturk M. M., Tosun T., Tosun M., Erbay L.B. 2021. A novel condenser with offset strip fins on a mini channel flat tube for reducing the energy consumption of a household refrigerator. J. Build. Eng. 44, 102932. https://doi.org/10.1016/j.jobe.2021.102932

Ek K., Söderholm P. 2010. The devil is in the details: Household electricity saving behavior and the role of information. Energy Policy 38, 1578-1587. https://doi.org/10.1016/j.enpol.2009.11.041

Fatouh M., Abou-Ziyan H. 2018. Energy and exergy analysis of a household refrigerator using a ternary hydrocarbon mixture in tropical environment - Effects of refrigerant charge and capillary length. Appl. Therm. Eng. 145, 14-26. https://doi.org/10.1016/j.applthermaleng.2018.09.008

Galarraga I., Heres D. R., Gonzalez-Eguino M. 2011. Price premium for high-efficiency refrigerators and calculation of price-elasticities for close-substitutes: a methodology using hedonic pricing and demand systems. J. Clean. Prod. 19, 2075-2081. https://doi.org/10.1016/j.jclepro.2011.06.025

Gerhardt F. L. C., Salvo R. de V., Marchi Neto I. de, Lima R.S. de, Silva R.C. da. 2021. Computational modeling of a thermal energy storage tank coupled to a water-cooled household refrigerator. J. Energy Storage 41, 102961. https://doi.org/10.1016/j.est.2021.102961

Gürel A. E., Ağbulut Ü., Ergün A., Ceylan İ. 2020. Environmental and economic assessment of a low energy consumption household refrigerator. Eng. Sci. Technol. an Int. J. 23, 365-372. https://doi.org/10.1016/j.jestch.2019.06.003

Harrington L., Aye L., Fuller B. 2018. Impact of room temperature on energy consumption of household refrigerators: Lessons from analysis of field and laboratory data. Appl. Energy 211, 346-357. https://doi.org/10.1016/j.apenergy.2017.11.060

©2006-2024 Asian Research Publishing Network (ARPN). All rights reserved.

Harrington L., Aye L., Fuller B., Hepworth G. 2019. Peering into the cabinet: Quantifying the energy impact of door openings and food loads in household refrigerators during normal use. Int. J. Refrig. 104, 437-454. https://doi.org/10.1016/j.ijrefrig.2019.05.040

INEGI. 2017. Censo de Población y Vivienda 2017 [WWW Document]. Inst. Nac. Estadística y Geogr. URL https://cuentame.inegi.org.mx/monografias/informacion/df/poblacion/vivienda.aspx?tema=me&e=09#:~:text=Distrito Federal&text=En 2020%2C en Ciudad de,número de viviendas particulares habitadas

Jacobson M. Z. 2009. Review of solutions to global warming, air pollution, and energy security. Energy Environ. Sci. 2, 148-173. https://doi.org/10.1039/B809990C

Jeong H., Byun S., Kim D. R., Lee K.-S. 2021. Power optimization for defrosting heaters in household refrigerators to reduce energy consumption. Energy Convers. Manag. 237, 114127. https://doi.org/10.1016/j.enconman.2021.114127

Lohr S. L. 2019. Sampling: Design and Analysis, 3rd ed. Cengage Learning, Boston, MA.

Mahlia T. M.., Masjuki H.., Saidur R., Amalina M.. 2004. Cost-benefit analysis of implementing minimum energy efficiency standards for household refrigerator-freezers in Malaysia. Energy Policy 32, 1819-1824. https://doi.org/10.1016/S0301-4215(03)00169-1

Marques A. C., Davies G. F., Evans J.A., Maidment G.G., Wood I.D. 2013. Theoretical modelling and experimental investigation of a thermal energy storage refrigerator. Energy 55, 457-465. https://doi.org/10.1016/j.energy.2013.03.091

Negrão C. O. R., Hermes C. J. L. 2011. Energy and cost savings in household refrigerating appliances: A simulation-based design approach. Appl. Energy 88, 3051-3060. https://doi.org/10.1016/j.apenergy.2011.03.013

Pirvaram A., Sadrameli S. M., Abdolmaleki L. 2019. Energy management of a household refrigerator using eutectic environmental friendly PCMs in a cascaded condition. Energy 181, 321-330. https://doi.org/10.1016/j.energy.2019.05.129

Tao J., Yu S. 2011. Implementation of energy efficiency standards of household refrigerator/freezer in China: Potential environmental and economic impacts. Appl. Energy 88, 1890-1905. https://doi.org/10.1016/j.apenergy.2010.11.015

Wang Z., Zhang B., Yin J., Zhang Y. 2011. Determinants and policy implications for household electricity-saving behaviour: Evidence from Beijing, China. Energy Policy 39, 3550-3557. https://doi.org/10.1016/j.enpol.2011.03.055

Zhang Y., Tao W. 2020. Will energy efficiency affect appliance price? An empirical analysis of refrigerators in China based on hedonic price model. Energy Policy 147, 111818. https://doi.org/10.1016/j.enpol.2020.111818

Zhang Y., Xiao C., Zhou G. 2020. Willingness to pay a price premium for energy-saving appliances: Role of perceived value and energy efficiency labeling. J. Clean. Prod. 242, 118555. https://doi.org/10.1016/j.jclepro.2019.118555

Zhou N., Levine, M. D., Price L. 2010. Overview of current energy-efficiency policies in China. Energy Policy 38, 6439-6452. https://doi.org/10.1016/j.enpol.2009.08.015

Zou B., Mishra A. K. 2020. Appliance usage and choice of energy-efficient appliances: Evidence from rural Chinese households. Energy Policy 146, 111800. https://doi.org/10.1016/j.enpol.2020.111800