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Environmental and economic assessment of a low energy consumption household refrigerator

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ABSTRACT

Energy consumption is the biggest obstacle in the economic growth of a country. In recent years, Turkey has imported around at the rate of three-quarters of its total energy demand. Upon the past 10-years running, Turkey paid nearly half a trillion dollars for its total energy bill. The big share of energy consumption has emerged from buildings. Therefore, energy savings have great importance, particularly in the buildings. A refrigerator is responsible for the most dominant electrical energy consumption rate with 32% in a house. Therefore, this paper proposes a novel household refrigerator design for reducing energy consumption. In the proposed design, the necessary air for the cooling process will be provided from outdoor ambient in appropriate weather condition. The compressor work will, thus, be decreased via this way, and contribute to a reduction in energy consumption. The results indicated that this system in 63 provinces can be effectively used between 1 and 4 months and help to reduce 36 million $ in Turkish electric energy bill with the use of only 1 year period. Additionally, a reduction of approximately 850,000 tons of CO_2 annually in Turkey can be achieved by applying the proposed design in this study. Hereby, Turkey can contribute not only to be sustained economic growth but also to reduce harmful gas emissions arising from electricity generation methods in the country.

1. Introduction

Over recent years, rapidly developing technology and growing population have caused enormous increases in global energy consumption and energy demand [1]. In parallel to this, the world primary energy consumption increased averaged 1.7% per year in the last 10 years running. Today, fossil fuels are frequently used as the most dominant energy source by the rate of approximately 85% [2]. On the other hand, fossil fuels are similarly the most dominant energy source in electricity production worldwide. According to the World Energy Outlook 2017 report (WEO) of the International Energy Agency (IEA), the world electricity production in the year 2017 was provided by the rate 65% by fossil fuels as shown in Fig. 1 [3].

As shown in Fig. 1, the most frequently used energy source was coal at a rate of 38% in the year 2017. Indeed, coal generally has the largest share in electricity production all across the world. However, McLeish (2008) reported that coal-fired electricity production was responsible for 90% carbon emissions in the United States whilst coal-fire electricity production accounted for only 52% of total electricity production in the United States [4]. Just as in many other countries, Turkey is also dependent on fossil fuels in electricity production since the very beginning. Fig. 2 shows electricity production by sources in 2017 for Turkey.

The dominant use of fossil fuels has also led to emerging risks of global warming, the greenhouse effect and ozone depletion [6]. According to IEA, the use of primary energy sources has, on the other hand, showed an upward trend in the past 20 years running. For instance, the world population increased by 27% whilst energy consumption per capita increased by 10%. Therefore, the consumption of primary energy sources increased by 49%, while CO_2 (carbon dioxide) emissions increased by 43% [7,8]. Increase in electricity production is directly related to the increase in CO_2 emissions and greenhouse gas emissions as well. For example, the changes in electricity production between the year 1970 and 2017 is given in Fig. 3.

Clearly, electricity production in Turkey has increased in nearly all year compared the previous year. This increase has negatively influenced not only the electricity bill and economic growth of the country but also emitting harmful gas emissions arising from the burning of fossil fuels. For instance, the total energy consumption of Turkey in the year 2008 increased by 86% compared to

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Nomenclature

TES	total energy saving, kWh
TCS	total cost saving, $
W_{comp}	daily energy consumption of the compressor, kWh
EEP	unit price of electric energy, $/kWh
DN	number of day
$N_{ref.}$	total number of refrigerator
ψ_{CO_2}	the average CO_2 emission for power production by coal, $kgCO_2/kWh$
Z_{CO_2}	the enviro-economic cost, $
z_{CO_2}	international carbon price, $\$/tCO_2$
ϕ_{CO_2}	CO_2 mitigation per annum, $kgCO_2$

1990, reaching 74 Million ton of oil equivalent (Mtoe). Industry and residences are one of the largest shares in energy consumption [10]. On the other hand, Turkey has imported much more energy from foreign countries and ranked among the most importing countries in the world. Table 1 shows the Turkish energy import percentages and ranking in energy importing list.

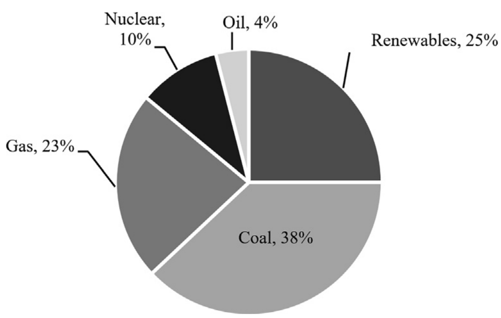

Fig. 1. Global electricity production shares by sources in 2017.

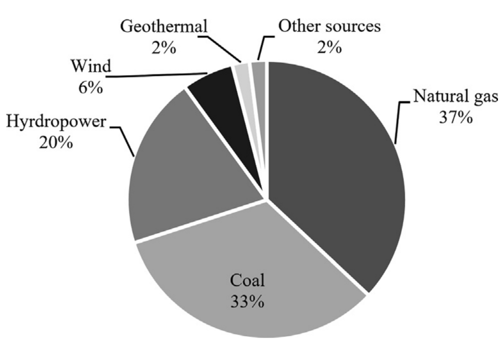

Fig. 2. Turkey electricity production by sector in 2017 [5].

Table 1
Turkey's energy imports as a per cent and ranked in the world from 2000 to 2015 [11].

Years	Energy import as a per cent, %	Ranked in the world
2000	65.96	26
2001	65.24	27
2002	67.51	25
2003	69.71	25
2004	70.13	24
2005	71.58	24
2006	71.71	25
2007	72.73	24
2008	70.64	26
2009	69.04	25
2010	69.62	27
2011	71.61	25
2012	74.02	23
2013	73.07	24
2014	74.21	23

As clearly seen in Table 1, Turkey has paid much more for its energy bill. Today, energy import is the biggest obstacle to Turkey's economic development [12]. Actually, it paid nearly half of a trillion dollar for total energy import in the last 10-years running [11]. Additionally, Table 2 shows the Turkish energy import bill between the years 2008 and 2017.

In a line parallel to this, Turkey is able to meet 45–55% of its electrical energy demand and 26% of its total energy demand by using the domestic sources of the country [6].

According to the Turkish Statistical Institute (Turkstat), approximately 22% of the electricity consumed in Turkey was used in housing in the year 2016 [14]. Of the electrical energy consumption sources in the house, the refrigerators are responsible for 32% of total energy consumption. This ratio is followed by lighting with 12%, heater with 9%, and a washing machine with 8% [15]. A regulation has been drafted by the Turkish Industry and Trade

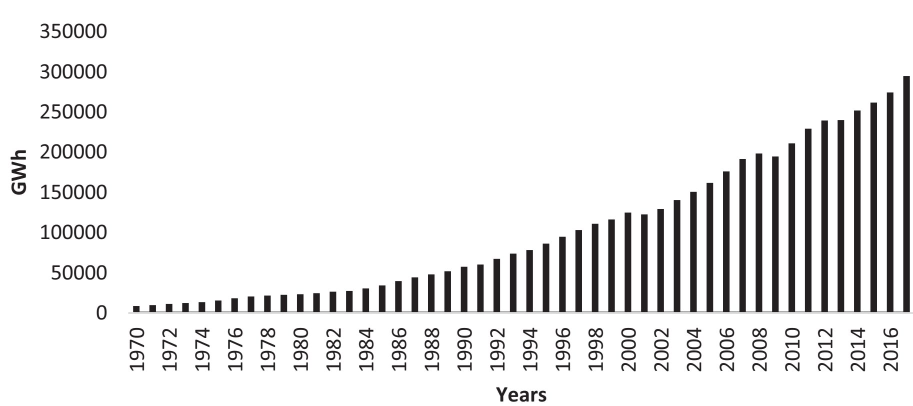

Fig. 3. Turkey electricity generation by years (graph generated from data on [9]).

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Table 2
Turkey's energy import bill by years [11,13].

Years	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Import (Billion dollars)	48.3	29.9	38.5	54.1	60.1	55.9	54.9	37.8	27.2	37.2	443.9

Ministry in 2010 in order to reduce this consumption and to enable consumers to tend refrigerators with energy-efficient [16]. According to this regulation, refrigerators and freezers are divided into 7 different energy efficiency classes according to their energy consumption [17].

There are some studies on energy saving in household refrigerators in the literature. For example, Yusufoğlu et al. (2015) investigated four different phase change materials (PCMs) by two different refrigerator models. In the related study, the authors focused on the on/off time of compressor and tried to optimize this times. They achieved to obtain better energy efficiency. Additionally, PCMs effect was enhanced with increasing condenser surface area [18]. Sonnenrein et al. (2015) studied the influence of latent heat storage elements on the temperature of the condenser for a commercial household refrigerator. The obtained results in the related study showed that particularly PCMs applications caused the lower condenser temperature. Also, this approach gave a significant reduction on the power consumptions [19]. Ghadiri and Rasti (2014) focused on the effect of some parameters such as condenser air cooling increment, hot-wall condenser removal, compressor cooling capacity effect, capillary tube diameter effect, changes of R134a charge amount and ambient temperature on the energy consumption in a household refrigerator. Results indicated that by hot-wall condenser removal, condenser air cooling increment and decreasing compressor cooling capacity, energy consumption and refrigerators charge amount reduced by 23.6% and 19.3%, respectively [20]. Cheng and Yuan (2011) focused on the dynamic model of a new design household refrigerator with SSPCM (shape-stabilized phase change material) HSC (heat storage condenser) [21]. In another study, Saidur et al. (2000) carried out the effect of temperature, relative humidity, setting the position of the thermostat, door opening/closing factors, and loading on energy consumption of a household refrigerator freezer [22]. Kim et al. (2006) have studied optimal lifetimes of mid-sized refrigerator models in the United States by using a life cycle optimization model by the aid of dynamic programming. The model operates were governed to find optimal lifespan that global warming potential, minimize energy, and cost objectives upon a time horizon from 1985 to 2020 [23].

This paper mainly focused on the household refrigerator design to be operated in the outdoor temperature value for 81 provinces of Turkey. The designed system will be able to use the outdoor air when it has the potential for product-cooling and it will, therefore, be aimed to save not only the compressor work but also to reduce harmful gas emissions arising from the burning of fossil-based fuels. Once the outdoor temperature is higher or lower than the design temperature, the refrigerator will continue to operate normally. The usability of the designed system will be investigated for 81 provinces and the regions where the system can be used will be determined. Energy savings by using the proposed system will be calculated and discussed in this study.

2. Methodology

In this paper, the monthly average outdoor temperature values of Turkey's 81 provinces were obtained from the General Directorate of Meteorology (GDM). Also, these values are given in Table 3 [24,25]. The provinces where monthly average outdoor temperature values are less than or equal to 6 °C are marked in Table 3. Since these values are average, it should be noted that the temperatures on a monthly basis will be above these values. Therefore, it is assumed that the temperatures will be 6 °C and below half of the relevant month.

In this study, some assumptions must be made in order to evaluate the study mathematically. These assumptions are listed as follows:

- The design temperature of the refrigerator has been accepted as average 4 °C (between 2 and 6 °C). In this paper, 4 °C is preferred not to spoil the foods in the cooling part of the conventional household refrigerators under the proposed operating conditions by manufacturers.
- There is a risk of freezing of foods in the case the average indoor temperature of the refrigerator is at 0 °C and below. Therefore, the average indoor temperatures at 0 °C and below were excluded from the calculation.
- Energy consumption per year of a conventional household refrigerator has been accepted as 385 kWh.
- The total number of refrigerators has been accepted as equal to the number of households [26].
- The dollar exchange rate is accepted as equal to 5.35 Turkish Lira (1 Dollar = 5.35 TL).
- For a more accurate result, it was assumed that the outdoor temperature would be between 0 and 6 °C in half of the marked months.
- The number of households in the provinces where the design will be implemented is obtained by dividing the number of people living in that province by 4. In other words, it is assumed that 4 people live in each household in these provinces [27].

2.1. Operation procedure

For this study, Fig. 4 briefly shows flow-chart of the proposed operating model and conditions as well.

The operation procedure of the proposed design was given step by step as follows.

1-. Basically, the proposed design in this paper is able to work as different two operation modes, that is, normal operation mode and proposed operation mode.
2-. In the cases that the outdoor temperature is 6 °C or above, the refrigerator will work at normal mode. The reason why this temperature selected is not to allow the products in the refrigerator to spoil.
3-. Similarly, in the cases that the outdoor temperature is lower than 2 °C, the refrigerator will work at normal mode. The reason why this temperature selected is not to allow the products in the refrigerator to freeze.
4-. On the other hand, in the cases that the outdoor temperature is between 2 and 6 °C, the refrigerator will work at the proposed mode in this paper.
5-. In the proposed mode, the required air to cool the foods will be provided from the outdoor air, and so it is aimed to save a great deal of compressor work and to reduce the emissions from electricity consumption.

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Table 3
Acceptable months for the system and monthly average outdoor temperatures by region (°C).

Province	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
Monthly Average Outdoor Temperatures in the Mediterranean Region (°C)												
Antalya	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Burdur	2.6	3.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.3
Isparta	1.9	2.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	3.5
Mersin	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Adana	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Hatay	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Osmaniye	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Kahramanmaraş	4.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Monthly Average Outdoor Temperatures in Eastern Anatolia Region (°C)												
Erzincan	AT.NOA.	AT.NOA.	4.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.2	0.1
Elazığ	AT.NOA.	0.5	5.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1.9
Tunceli	AT.NOA.	AT.NOA.	5.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1
Bingöl	AT.NOA.	AT.NOA.	3.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	0.5
Erzurum	AT.NOA.	AT.NOA.	AT.NOA.	5.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	0.6	AT.NOA.
Muş	AT.NOA.	AT.NOA.	0.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.5	AT.NOA.
Bitlis	AT.NOA.	AT.NOA.	1.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.7	AT.NOA.
Kars	AT.NOA.	AT.NOA.	AT.NOA.	5.3	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	0.3	AT.NOA.
Ağrı	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1.4	AT.NOA.
Ardahan	AT.NOA.	AT.NOA.	AT.NOA.	4.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Van	AT.NOA.	AT.NOA.	1.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.3	AT.NOA.
Iğdır	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.7	AT.NOA.
Hakkari	AT.NOA.	AT.NOA.	1.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.1	AT.NOA.
Malatya	0.1	1.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.4
Province	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
Monthly Average Outdoor Temperatures in Southeastern Anatolia Region (°C)												
Gaziantep	3	4.2	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.9
Kilis	5.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Adıyaman	4.5	5.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Şanlıurfa	5.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Diyarbakır	1.8	3.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4
Mardin	3	4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.3
Batman	2.7	4.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.6
Şırnak	1.8	2.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	3.7
Siirt	2.7	4.2	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.9
Monthly Average Outdoor Temperatures in Central Anatolia Region (°C)												
Eskişehir	AT.NOA.	1.3	5.1	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.1
Konya	AT.NOA.	1.2	5.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1.8
Ankara	0.3	1.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.7
Çankırı	AT.NOA.	0.9	5.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.6	1.6
Aksaray	0.4	1.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.5
Kırıkkale	0.4	2.1	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.5
Kırşehir	AT.NOA.	1.1	5.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2
Yozgat	AT.NOA.	−1	2.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.6	0.5
Niğde	AT.NOA.	0.8	5.2	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1.8
Nevşehir	AT.NOA.	0.6	4.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	1.9
Kayseri	AT.NOA.	0	0.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5	0.5
Karaman	0.4	1.6	6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.6
Sivas	AT.NOA.	AT.NOA.	3	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.6	AT.NOA.
Monthly Average Outdoor Temperatures in Black Sea Region (°C)												
Bolu	0.7	2	5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	3.1
Düzce	3.7	5.1	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.9
Zonguldak	6	6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Karabük	2.9	4.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Bartın	4.1	4.6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	6
Kastamonu	AT.NOA.	0.6	4.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5	1
Çorum	AT.NOA.	0.9	5.1	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5.9	1.9
Sinop	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Samsun	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Amasya	2.6	4.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.7
Tokat	1.7	3.3	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	3.9
Ordu	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Giresun	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Gümüşhane	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5	0.5
Trabzon	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Bayburt	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.6	AT.NOA.
Rize	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Artvin	2.6	3.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.4
Monthly Average Outdoor Temperatures in Marmara Region (°C)												
Çanakkale	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Balıkesir	4.7	5.7	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Edirne	2.6	4.3	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.

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Table 3 (*continued*)

Province	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
Tekirdağ	4.8	5.1	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Kırklareli	2.8	3.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	5
İstanbul	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Bursa	5.2	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Yalova	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Kocaeli	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Bilecik	2.4	3.5	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.7
Sakarya	5.9	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Monthly Average Outdoor Temperatures in Aegean Region (°C)												
İzmir	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Denizli	5.8	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Manisa	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Kütahya	0.4	1.7	5.2	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.6
Aydın	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Uşak	2.3	3	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	4.2
Muğla	5.5	6	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.
Afyon	0.2	1.5	5.4	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	AT.NOA.	2.5

*AT.NOA.: Ambient temperature is not appropriate.

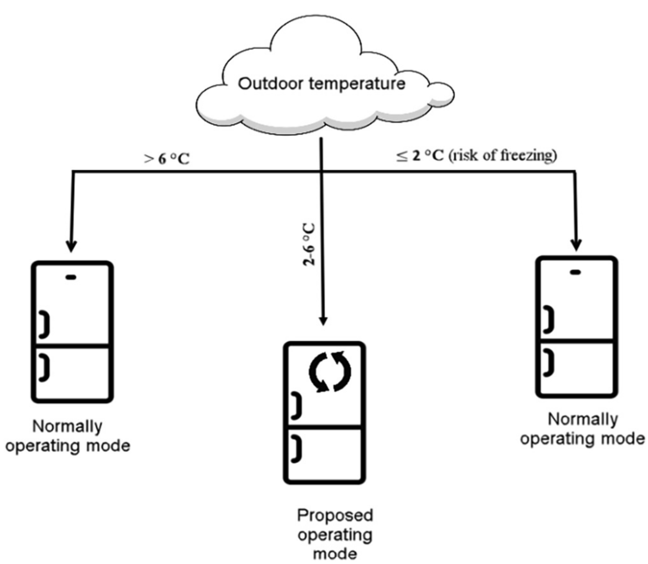

Fig. 4. Flow charts of normally and proposed operating modes for different temperature.

2.2. Economic analysis

In accordance with the acceptance in this paper, the refrigerator compressor consumes 385 kWh of energy annually. This value corresponds to approximately 1 kWh of energy consumption as calculated per day. In this study, it was assumed that half of the daily energy consumption was met by the compressor and the other half by the outdoor air. The reason for this acceptance is the possible changes in the outdoor air temperatures.

Total energy saving (TES) can be calculated by using Eq. (1)

$$TES = W_{comp}.N_{ref.}.DN \tag{1}$$

Based on the assumptions in this study, the total cost saving (TCS) was calculated by the following equation including energy price and refrigerator number.

$$TCS = W_{comp}.EEP.N_{ref.}.DN \tag{2}$$

where, W_{comp} is the daily energy consumption of the compressor (kWh), EEP is the unit price of electric energy, (accepted as 0.088 $/kWh), and $N_{ref.}$ is the total number of refrigerator. Finally, DN in the equation is also the number of day that can be saved [28].

2.3. Enviro-economic (environmental cost) analysis

In every period of history, fossil fuels, which are used predominantly use across the world, have increased the amount of CO_2 released into the atmosphere. With an increasing amount of CO_2 emissions, some problems such as environmental pollutions and global warming broke out. A number of countries have already taken some measures to reduce CO_2 emissions and solve these problems as well.

Depending on TES, the reduction on CO_2 emissions was calculated by using enviro-economic (environmental cost) analysis. In this study, CO_2 emission reduction (ϕ_{CO_2}) was calculated with the following equation.

$$\phi_{CO_2} = \psi_{CO_2} \times TES \tag{3}$$

In the equation, ψ_{CO_2} represents CO_2 emission per kWh arising from electricity production in a power plant using coal as fuel. As the studies in the literature are examined, it is seen that this value can be taken as 980 gCO_2/kWh [29]. Considering the transmission losses (40%), distribution losses (20%) and other losses, this value can be taken as approximately 2.08 kg CO_2/kWh [30]. The international carbon price (z_{CO_2}) ranges from 13 $/t CO_2 to 16 CO_2 $/t [31,32]. In the calculations, this value is taken as 14.5 $/ t CO_2. Thus, the environmental cost value can be calculated using Eq. (4) [33].

$$Z_{CO_2} = z_{CO_2} \times \phi_{CO_2} \tag{4}$$

3. Results and discussion

In this study, a refrigerator design with low energy consumption is investigated by using climate data in Turkey. Table 3 shows both appropriate provinces and months to be utilized in these provinces depending on the outdoor temperature values for the designed refrigerator. TES values were calculated by Eq. (1), the population information, the number of household refrigerator, appropriate month numbers, TCS, CO_2 mitigation and environmental cost are given in Table 4.

Table 4 shows that this designed system was can be applied in certain months for 63 provinces in Turkey. It is seen that the number of provinces where the average outside temperature is 6 °C and below is quite high.

Temperature values shown in the table are monthly average temperature values, and outside temperatures that are higher than

Table 4
Achieving total energy saving and enviro-economic analysis results by provinces.

Provinces	Population	$N_{ref.}$ Refrigerator number	Appropriate month number	TES ($)	ϕ_{CO_2} CO_2 mitigation (tons/annum)	Z_{CO_2} Environmental Cost ($/annum)
Adıyaman	615,076	153,769	2	405,950	9595	139,130
Afyonkarahisar	715,693	178,923	4	944,713	22,330	323,779
Ağrı	536,285	134,071	1	176,974	4183	60,654
Aksaray	402,404	100,601	3	398,380	9416	136,536
Amasya	329,888	82,472	3	326,589	7719	111,931
Ankara	5,445,026	1,361,257	3	5,390,578	127,414	1,847,498
Ardahan	97,096	24,274	1	32,042	757	10,982
Artvin	166,143	41,536	3	164,483	3888	56,373
Balıkesir	1,204,824	301,206	2	795,184	18,795	272,531
Bartın	193,577	48,394	3	191,640	4530	65,680
Batman	585,252	146,313	3	579,399	13,695	198,576
Bayburt	80,417	20,104	1	26,537	627	9095
Bilecik	221,693	55,423	3	219,475	5188	75,220
Bingöl	273,354	68,339	2	180,415	4264	61,833
Bitlis	341,474	85,369	2	225,374	5327	77,242
Bolu	303,184	75,796	4	400,203	9459	137,160
Burdur	264,779	66,195	3	262,132	6196	89,840
Bursa	2,936,803	734,201	1	969,145	22,907	332,153
Çankırı	186,074	46,519	4	245,620	5806	84,181
Çorum	528,422	132,106	4	697,520	16,487	239,059
Denizli	1,018,735	254,684	1	336,183	7946	115,219
Diyarbakır	1 699,901	424,975	3	1,682,901	39,778	576,776
Düzce	377,610	94,403	3	373,836	8836	128,124
Edirne	406,855	101,714	2	268,525	6347	92,031
Elazığ	583,671	145,918	3	577,835	13,658	198,040
Erzincan	231,511	57,878	3	229,197	5417	78,552
Erzurum	760,476	190,119	2	501,914	11,863	172,020
Eskişehir	860,620	215,155	3	852,014	20,139	292,008
Gaziantep	2,005,515	501,379	3	1,985,461	46,929	680,472
Gümüşhane	170,173	42,543	2	112,314	2655	38,493
Hakkari	275,761	68,940	2	182,002	4302	62,377
Iğdır	194,775	48,694	1	64,276	1519	22,029
Isparta	433,830	108,458	3	429,494	10,152	147,199
Kahramanmaraş	1,127,623	281,906	1	372,116	8795	127,534
Karabük	244,453	61,113	2	161,338	3813	55,295
Karaman	246,672	61,668	4	325,607	7696	111,594
Kars	287,654	71,914	2	189,853	4487	65,068
Kastamonu	372,373	93,093	4	491,531	11,618	168,461
Kayseri	1,376,722	344,181	4	1,817,276	42,954	622,830
Kırıkkale	278,749	69,687	3	275,961	6523	94,579
Kırklareli	356,050	89,013	3	352,491	8332	120,808
Kırşehir	234,529	58,632	3	232,183	5488	79,575
Kilis	136,319	34,080	1	44,986	1063	15,418
Konya	2,180,149	545,037	3	2,158,347	51,015	739,724
Kütahya	572,256	143,064	4	755,378	17,854	258,889
Malatya	786,676	196,669	3	778,809	18,408	266,919
Mardin	809,719	202,430	3	801,623	18,947	274,738
Muğla	938,751	234,688	2	619,576	14,645	212,346
Muş	404,544	101,136	2	266,999	6311	91,508
Nevşehir	292,365	73,091	3	289,440	6841	99,199
Niğde	352,727	88,182	3	349,201	8254	119,681
Sakarya	990,214	247,554	1	326,771	7724	111,993
Siirt	324,394	81,099	3	321,152	7591	110,068
Sivas	621,301	155,325	2	410,058	9692	140,538
Şanlıurfa	1,985,753	496,438	1	655,298	15,489	224,589
Şırnak	503,236	125,809	3	498,204	11,776	170,748
Tekirdağ	1,005,463	251,366	2	663,606	15,685	227,436
Tokat	602,086	150,522	3	596,067	14,089	204,288
Tunceli	82,498	20,625	2	54,450	1287	18,662
Uşak	364,971	91,243	3	361,322	8540	123,835
Van	1,106,891	276,723	2	730,549	17,268	250,379
Yozgat	418,650	104,663	3	414,465	9796	142,049
Zonguldak	596,892	149,223	2	393,949	9312	135,017
Total	**44,047,577**	**11,011,902**	**160**	**35,936,911**	**849,417**	**12,316,561**

6 °C are not included in the calculations. However, even on days when the outside temperature is higher than 6 °C, temperatures may drop below 6 °C. This case clearly shows that the proposed design can also be applied on these days.

As shown in Table 4, significant savings are possible by such a simple design. In Eastern Anatolia and Central Anatolia region, where the outdoor temperatures are low, the amount of energy savings also increases significantly. Another parameters affect the saving amount that are undoubtedly the population and the number of household, as well. In other words, with the proposed design in the crowded-provinces, a great of energy saving can be achieved. Besides the economic aspect of the proposed design, the more important issue is the environmental impacts. Environmental impacts were analyzed according to the environmental cost

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method using Eq. (4), and the results are given in Table 4 by the provinces.

As a result of the calculations, the first five provinces with the most savings were shown together with TCS in Fig. 5. The most important parameters in this graph are the number of people living in the provinces and how many months of this design can be used in the year.

As shown in Fig. 5, the highest savings for Turkey is obtained in Ankara by using this proposed design. It is possible to provide energy cost savings of approximately 5.4 million $ during a three months period in Ankara.

Only the amount of energy cost savings were provided by these five provinces is approximately 13 million $. This value constitutes 31% of the saving amount of all provinces participating in the calculation. On the other hand, the total amount of savings from all provinces is approximately 36 million $.

As a result of applying the proposed design in Turkey, the reduction in energy consumption is clearly shown in Fig. 6.

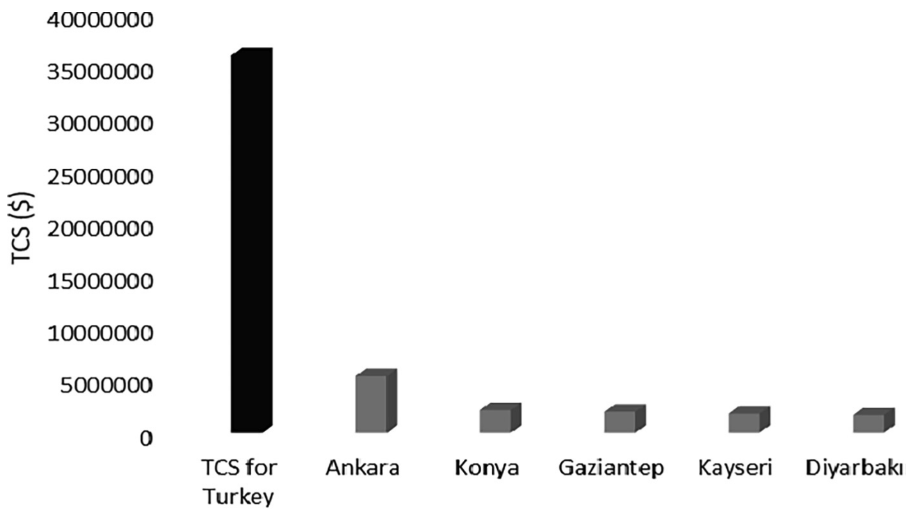

Fig. 5. TCS for Turkey and the first five provinces in the most energy saving.

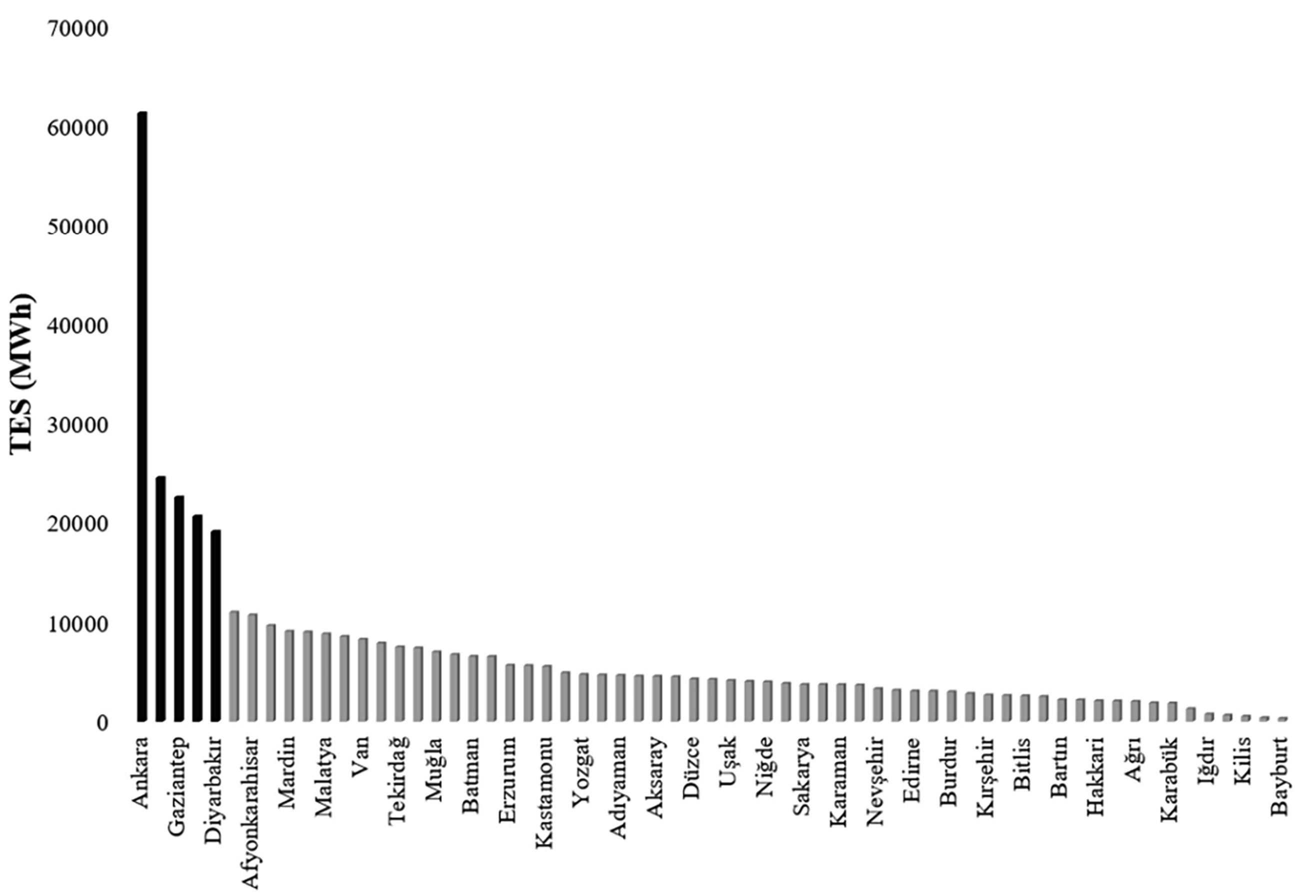

Fig. 6. The reduction in annual energy consumption for Turkey.

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Approximately 409,000 MWh energy saving is possible using by this proposed design annually. The decrease amounts in energy consumption of the first 5 provinces were calculated as 148,000 MWh annually. Considering the environmental impacts of energy costs and energy generation, these outputs have great importance in the short and long run. As a result of the environmental cost analysis, a reduction of approximately 850,000 tons of CO_2 per year can be achieved with the proposed design in this study. In addition, an annual gain of 12.3 million $ will be obtained based on the CO_2 cost.

4. Conclusion and recommendations

This study investigated a household refrigerator system that can benefit from the outdoor temperature. This system has low energy-consumption and aims to save energy in Turkey. This study investigated how to affect the energy efficiency of using this proposed design. The following results, conclusions and recommendations are drawn based on this paper;

- Considered the system and outputs, ensuring significant energy savings are likely to scale in Turkey. This system presents more appropriate results particularly for the provinces where have less outdoor temperature and more utilization-time. It is seen that there is a significant saving opportunity even in the regions where the usage period is short but the population density is high. An important factor to be considered in this design is that the outside temperature falls far below the design temperature. In such a case, the products in the refrigerator may freeze. In order to avoid this problem, the air taken from outside can be increased by mixing with indoor (mostly kitchen) air.
- In this study, only household refrigerators were considered and calculated. If this proposed design applied to commercial type coolers or/and cold stores including, the amount of energy savings will be much higher than calculated in this study. In these systems, it should be noted that the compressor power consumption and operating times of these systems are much higher than the household refrigerators.
- Monthly average temperature data were used in the study. When using instantaneous temperature data, the amount of savings can be determined more clearly. It is anticipated that the amount of savings to be achieved in such a calculation will be much more.
- The proposed system in this study can contribute to the economic growth and reduce harmful gas emissions arising from the burning of fossil fuels Turkey. Briefly, the proposed system is both an economic system and environmentally friendly.
- It is clear that the use of this system in other countries will help to reduce electricity consumption, drive economic development and reduce harmful gas emissions from electricity generation.
- It is clear that the proposed design will have the initial investment cost. The response of users and manufacturers to this cost has great importance.
- This proposed design can need filtering to reduce the pollutant particles because of directly using outdoor air. This will also increase the initial investment cost.

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