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# Pathways Toward Improving the Energy Efficiency of Residential Air-Conditioning Systems in Saudi Arabia

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*In Saudi Arabia, the residential electricity consumption approaches 50%, primarily driven by air conditioners (AC). This study explores the potential energy savings and carbon dioxide ($CO_2$) emission reductions up to 2030 through three scenarios: business as usual (BAU), continuous improvement scenario (CIS), and accelerated improvement scenario (AIS). BAU scenario assumes that the current energy efficiency ratio (EER) of 11.8 BTU/Wh is maintained until 2030. CIS considers a 5% EER improvement in new AC stock every two or five years, while AIS assumes a 10% improvement in the EER at the same intervals. Additionally, energy savings and emission reductions possible from varying adoption levels of a new refrigerant (R32) are estimated for three scenarios. Finally, the $CO_2$ emission reduction under each scenario is computed for two extreme cases of grid emission factor. BAU scenario predicts energy savings of up to 17.7 TWh in 2030 compared to 2020 energy consumption figures. AIS with two-year intervals results in additional energy savings of 10.1 TWh in 2030 and cumulative energy savings of 37.1 TWh over a decade compared to the BAU scenario. Even CIS with five-year intervals yields additional energy savings of 1.69 TWh in 2030 and 5.1 TWh cumulatively compared to the BAU scenario. In comparison, the introduction of the new refrigerant results in cumulative energy savings of 10.2 TWh in the best-case scenario. These findings emphasize the importance of enhancing the EER of residential AC systems as a priority in energy efficiency policy.*
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## 1 Introduction

Globally, HVAC systems consume around 15% of electricity, while air conditioners use about 20% of electricity generated in developing countries [1]. Due to its hot and dry climate, air conditioning is widely used in buildings in Saudi Arabia to maintain comfortable temperatures. The energy demand for cooling has increased significantly in recent years due to the growing population coupled with improving living standards. In fact, according to IEA [2], energy used for cooling spaces has tripled in the past three decades. Several factors have contributed to this dramatic rise in cooling demand including increased household income levels, increased urbanization, as well as global warming with cooling accounting for nearly 50% of total energy consumption in buildings [3]. As income levels, population, and urbanization continue to rise globally, the energy demand for cooling is expected to increase as well. This, in turn, will have a continued adverse impact on the environment.

In Saudi Arabia, air conditioners (ACs) in residential buildings are the primary consumers of electricity [4,5], accounting for about 66% of the total residential electricity demand (Fig. 1). The country is also experiencing one of the fastest population growth and urbanization rates globally, with further increase in urbanization expected in the coming years. Consequently, the demand for room AC units remains strong with over 1 million units projected to be needed in 2021 [7]. However, until 2011, Saudi Arabia did not have a minimum energy performance standard (MEPS) for AC units. This lack of regulation has resulted in a substantial number of old and inefficient AC units with low energy efficiency ratios (EERs) of 7.8 BTU/Wh. To tackle the low efficiency of these AC units, the Saudi Arabian Standards Organization (SASO) has been regularly updating the MEPS for the ACs sold in the Saudi market since 2012 [8]. Figure 2 shows the minimum EER for ACs from 2010 onwards with the last updated EER reaching 11.8 in 2018. It is important to note that the SASO has adhered to the international standard ISO 5151 [9] for calculating the EER of AC units, using the T1 test condition which corresponds to outdoor dry bulb temperature of 35 °C and indoor dry bulb temperature of 27 °C.

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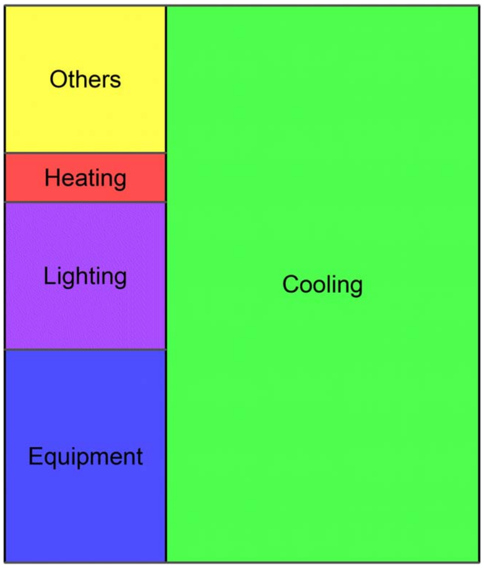

**Fig. 1 Electrical energy consumption of residential sector in Saudi Arabia (adopted from Ref. [6]).**

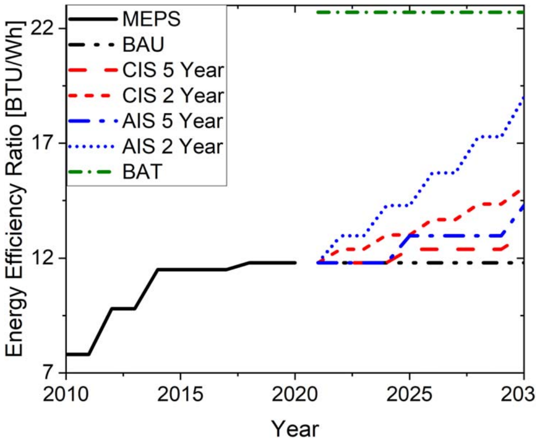

**Fig. 2 EER since 2010 (adopted from Ref. [8]) and predictions for future**

Few studies have examined the air conditioning landscape in Saudi Arabia. Howarth et al. [8] investigated the correlation between temperature and electricity generation over specific time periods in Saudi Arabia, concluding that the energy demand for ACs has plateaued since 2016. Similar research has been conducted in other countries to offer policy recommendations for improving the energy efficiency in residential cooling sector. For instance, Karali et al. [10] assessed the effects of recently updated standards on reducing energy usage by ACs in China. The authors examined the payback period for implementing new and more efficient cooling technologies in China. They found that ACs with variable speed drives have significant potential for improving efficiency. Moreover, the updated MEPS, effective from 2020, is projected to reduce accumulative $CO_2$ emissions from air conditioning use by 12.8% between 2020 and 2050. For medium-efficiency and high-efficiency scenarios considered by the authors, it is predicted that the $CO_2$ emissions attributed to air conditioning usage will reduce by 15–53% compared to their proposed MEPS. Ali et al. [11] examined the energy savings, emissions reduction as well as economic benefits of improving the MEPS at two-year and five-year intervals for Pakistan. They concluded that energy savings of 11.6 TWh with an associated reduction of 7 million barrels of imported oil can be achieved in the best-case scenario of implementing MEPS revision at two-year intervals.

Limited studies have examined the benefits and cost-effectiveness of improving the energy efficiency of AC systems in Saudi Arabia. Mokheimer [12] found that enhancing MEPS for AC systems in villas to an EER of 13.0 could save 24.9 TWh of electricity and reduce $CO_2$ emissions by 15.1 Mt annually. A study by Al-Musa [13] suggested that replacing 25% of 2016 AC units with energy-efficient ones by 2025 could potentially save 17.1 TWh of electricity and reduce $CO_2$ emissions by 7.5 Mt. However, both studies used simplified analysis approaches and did not evaluate the impact of varying operating hours due to climate conditions. Krarti and Howarth [6] assessed the benefits and cost-effectiveness of expanding Saudi Arabia's high-efficiency AC (HEAC) program. The HEAC program incentivizes consumers with a 900 Saudi Riyals subsidy for purchasing split system units with an EER of 13.0 or higher. Their study considered three distinct scenarios, with two scenarios involving the replacement of varying numbers of existing units with new units having EER of 11.8. The third scenario considered replacing all existing AC units with high-efficiency AC units featuring EER of 13 or higher. Their analysis revealed that upgrading all existing AC units to EER of 11.8 would result in annual electricity savings of 20 TWh, accompanied by a reduction in $CO_2$ emissions of 14.3 Mt. If all the existing AC units were to be replaced with high-efficiency AC units with a minimum EER of 13, then the annual electricity savings would increase to 33 TWh with a corresponding reduction of 24 Mt of $CO_2$ emissions. The authors concluded that upgrading the AC units to EER of 13 would yield a simple payback period ranging from 4.6 to 5.7 years while the subsidy implemented as part of the HEAC initiative can be recovered by the Saudi Government within two years. The authors also recommended implementing structured policies, including upgrading the MEPS to an EER of 13 and altering the refrigerant requirements, to enhance the benefits of the HEAC initiative. However, despite the comprehensive nature of the study, the authors did not explore the effects of gradually increasing the MEPS and the corresponding savings expected in electricity consumption. The study primarily focused on evaluating the maximum potential improvements achievable through a step-change in the efficiency of AC units which is challenging to implement in the real world.

Selected studies have also examined how refrigerant selection impacts the energy consumption of ACs. Shah et al. [14] focused on the energy usage of various refrigerants, particularly hydrofluorocarbons (HFCs) of two reasons. First, HFCs are primarily used as refrigerants in air conditioning and refrigeration equipment. Second, HFCs have global warming potential (GWP) several thousands of times greater than that of $CO_2$. The study concluded that shifting the global stock of room ACs and refrigeration equipment to the BAT energy efficiency levels and low GWP refrigerants by 2030 could prevent up to 373 Gt $CO_2$ equivalent emissions.

In this context, the present study addresses a crucial research gap by conducting a comprehensive assessment of potential energy savings and $CO_2$ reduction possible by separately considering the impact of energy efficiency measures and transition to low GWP refrigerants in Saudi Arabia. A detailed AC stock for Saudi Arabia is estimated till 2030 and multiple scenarios are considered to calculate the potential energy savings and corresponding environmental benefits under each scenario. To the best of the author's knowledge, this is the first study that provides detailed insights into various pathways available for reducing the energy consumption of the residential AC sector in Saudi Arabia at the granular level. The detailed analysis is expected to be instrumental in guiding the formulation of future minimum energy performance standards for the Saudi market.

## 2 Model Framework and Methods

The first step involves the estimation of the AC stock in Saudi Arabia for the year 2020, followed by extrapolation to the year 2030 based on rational assumptions. To predict the AC stock, we used data pertaining to estimated AC demand from the Japan Refrigeration and Air Conditioning Industry Association for the period 2000–2021 [7,15] along with projected sales figures from Statista Market Insights [16] since 2018. Considering that the estimated sales figures were about 90% of the estimated demand for the years 2018–2020, we assumed that the sales figures for each calendar year from 2000 to 2020 would also be 90% of the estimated demand for those calendar years. In order to forecast the AC stock for the period from 2020 to 2030, we assumed an average annual stock growth of 4.8%. The assumed growth rate has been derived from an analysis of the growth forecast for the Saudi Arabian Air conditioner market [16–19]. The total annual stock of ACs is subsequently computed by the summation of the sales for the current year and the previously existing ACs that have remained operational over a ten-year period. The annual stock for year "$i$" is therefore calculated as follows:

$$\text{Stock}_i = S_i + \sum_{i-10}^{i-1} S_i \times \text{Survival}_i \tag{1}$$

where $S$ is the annual sales figure for the AC units. The survival profile for ACs is calculated using a logistic curve as follows:

$$\text{Suvival}_i = 1 - \frac{1}{1 - e^{-\alpha(i-t)}} \tag{2}$$

where $i$ is the AC's age, $t$ is the estimated median lifespan of 15 years, and $\alpha$ is a growth parameter that determines how quickly ACs retire around their median lifespan. Due to a lack of data on survival profiles for the Saudi market, the growth parameter was set to 0.85 which is similar to a previous work on estimating the residential air conditioner (RAC) survival profile in China [10]. The survival profile of AC units is shown in Fig. 3.

The annual energy consumption by ACs in kilowatt-hour is calculated as follows:

$$\text{Energy consumption} = \frac{\text{h} \times \text{cooling power(kW)}}{\text{EER}/3.41} \times 0.6 \tag{3}$$

where h is the estimated annual working hours for ACs in Saudi Arabia and EER is the energy efficiency ratio in BTU/Wh. A factor of 3.41 is used in the equation to convert BTU/h to Watts (W) for consistency in units. Due to predominantly hot climate and relatively low energy costs, AC units are typically run for extended periods, especially during summer. In the summer months from May to September, it is assumed that the AC units are operated for 16 h per day while in the remaining three months outside of winter, the operating hours are assumed to be 12 h per day. Thus, based on an average summer season length of about five months, the total annual operating hours are estimated to be 3480. The estimated operating hours align well with survey data indicating that over 70% of participants in Saudi Arabia use their ACs for 10–24 h per day, with 20% running their AC units for more than 20 h daily [20].

A vast majority of the AC units sold in the Middle East, including Saudi Arabia, are non-inverter types [21]. These AC units have compressors that switch on and off at regular intervals to maintain the desired indoor temperature. Since the EER is calculated for peak load operation of the compressor [22], it is assumed that the compressor operates at full load for 60% of the annual operating hours. Therefore, a factor of 0.6 is used in Eq. (3) to appropriately estimate the energy consumption.

To validate the 60% assumption, the energy consumption of a non-inverter AC with 1.5 ton of refrigeration cooling capacity was compared with its measured energy consumption. Over 108 days from mid-July to the end of October, the non-inverter AC with an EER of 12.15 BTU/Wh had an average electrical energy consumption of 20.8 kWh/day [23]. Using the 0.6 factor in Eq. (3), the estimated energy consumption for 24-h operation was 21.3 kWh, closely matching the measured value. Further validation was done by comparing the total electricity consumption for AC units in Saudi Arabia in 2020 with electrical energy consumption data from the General Authority of Statistics for 2020 [24]. The total electricity consumption in Saudi Arabia in 2020 was 289.3 TWh, with the residential sector accounting for 47.58% of the total electrical energy consumption. Considering that air conditioning accounts for 66% of the total residential electricity demand [6], the total electrical energy consumption by AC units was calculated as 90.85 TWh. This compares very well with the calculated electrical energy consumption in the year 2020 of 90.45 TWh using the bottom-up method used in this study.

In Eq. (3), EER is the average energy efficiency ratio of the applicable stock which is calculated by combining survival profiles with annual EERs of new AC stock under three different policy scenarios (Fig. 2). For the purpose of this study, the entire AC stock in Saudi Arabia is represented by the most common cooling capacity of 1.5 ton of refrigeration (5.275 kW). A limited market survey of major manufacturers in the Saudi market was performed to identify the common EER values and cooling capacities for split-type AC units and is shown in Fig. 4.

From the limited dataset presented here, Zamil and LG offer the highest EERs of 13.1 or greater for cooling capacities of 1.5 and 2 ton of refrigeration. The Gree split-type AC with 1.0-ton cooling capacity was the least efficient model, though Gree also sells more efficient models at other cooling capacities. R410A refrigerant was used in all three ACs mentioned above. Furthermore, many currently available ACs exceed SASO's targeted minimum EER of 11.8 suggesting a possibility of improving the

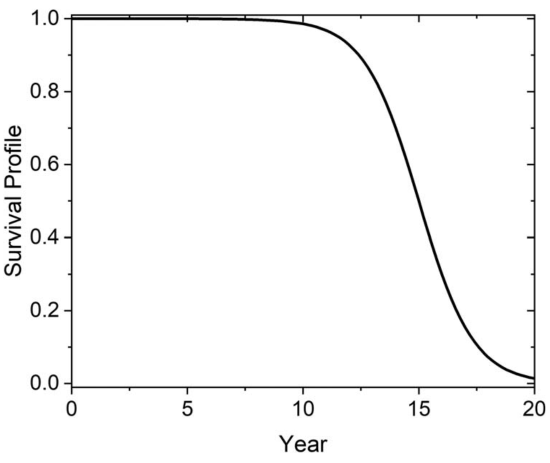

**Fig. 3 The assumed survival rate of AC units in Saudi Arabia**

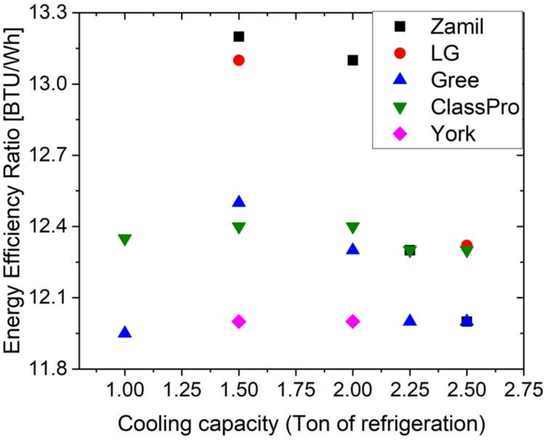

**Fig. 4 Selected AC brands with common cooling capacities in Saudi Arabia**

minimum EER in the next version of minimum energy performance standards.

Energy savings (ES) and emission reduction (ER) for various scenarios, such as continuous improvement (CIS) and accelerated improvement (AIS), are determined by comparing them to the energy consumption of the business as usual (BAU) scenario. The calculation of energy savings for different scenarios is as follows:

$$\mathrm{ES_{CIS}} = \mathrm{BAU}_i - \mathrm{CIS}_i \tag{4}$$

$$\mathrm{ES_{AIS}} = \mathrm{BAU}_i - \mathrm{AIS}_i \tag{5}$$

The scope of this study is confined to the indirect $CO_2$ emissions resulting from electricity generation to power the AC units. Consequently, direct $CO_2$ emissions from refrigerant leaks and disposal of old RACs are not considered here. The calculation of emission reductions for each scenario follows the same methodology as the energy savings:

$$\mathrm{ER_{CIS}} = \mathrm{ES_{CIS}} \times \mathrm{EF} \tag{6}$$

$$\mathrm{ER_{AIS}} = \mathrm{ES_{AIS}} \times \mathrm{EF} \tag{7}$$

where EF is Saudi Arabia's grid emission factor including transmission and distribution losses of 7% [25]. To account for the increased penetration of renewables in the coming years, the following two cases are considered to demonstrate the two extremes for Saudi Arabia's grid emission factor:

(1) Baseline case: This case assumes that the grid emission factor remains constant from 2020 to 2030 at 0.622 kg $CO_2$/kWh.
(2) Net zero 2060 case: This case applies constraints on the $CO_2$ emissions from electricity generation following the model of Kamboj et al. [26]. The model predicts the grid emission factor trajectory at five-year intervals to meet the net zero green house gas (GHG) emissions target for 2060.

The $CO_2$ emissions for the net zero 2060 case deviate from the baseline case beyond 2020. Details of the predicted grid emission factors from 2020 to 2030 for the two cases considered here are listed in Table 1.

Further in-depth discussion regarding the formulation of multiple scenarios is presented in two distinct subsections. The first subsection discusses the scenarios that explore different rates of improvement in EER for new AC units while the second subsection addresses scenarios involving various adoption rates of a new low GWP refrigerant in the new AC stock.

**2.1 Effect of Increasing Energy Efficiency Ratio.** This section focuses on the influence of varying rates of EER improvement in new AC units on energy consumption and associated $CO_2$ emissions. From Fig. 2, we have adopted the current EER of 11.8 BTU/Wh as a baseline till 2021. Five distinct scenarios have been defined to elucidate the varying rates of increasing EER for the new stock as depicted in Fig. 2:

- BAU: The baseline scenario maintains a constant EER value of 11.8 until the year 2030.
- AIS—2 years: This scenario involves a 10% EER enhancement every two years.
- AIS—5 years: This scenario involves a 10% EER enhancement every five years
- CIS—2 years: This scenario involves a 5% EER enhancement every two years.
- CIS—5 years: This scenario involves a 5% EER enhancement every five years.

The EER peaks at 19 BTU/Wh in the most optimistic scenario (AIS—2 years). Remarkably, the EER of 19 BTU/Wh is still lower than the EERs between 20.8 BTU/Wh and 22.7 BTU/Wh reported in Refs. [27–29] for the best available technology in 2021 or earlier. Therefore, there appear to be no technical barriers to implementing AIS at two-year intervals as well.

**Table 1 Predicted grid emission factor (kg/kWh) for baseline and net zero 2060 scenarios [26]**

| Scenarios | 2020 | 2025 | 2030 |
|---|---|---|---|
| Baseline | 0.622 | 0.622 | 0.622 |
| Net zero 2060 | 0.622 | 0.502 | 0.291 |

**2.2 Effect of Transitioning to a Low Global Warming Potential Refrigerant.** This section defines and discusses the multiple scenarios that explore different transition rates to a low GWP refrigerant in new AC units. In this study, we have chosen two non-ozone-depleting HFC refrigerants (R32 and R410a) to analyze the effect of refrigerant alteration on the AC units. AC units utilizing R32 as the refrigerant are more efficient than AC units employing R410a. Moreover, R32 exhibits higher latent heat at both evaporator and condenser pressures, thus requiring a smaller mass flowrate for the same cooling capacity. Additionally, R32 has slightly higher density than R410a and thereby requires a smaller volume flowrate for a given mass flowrate. Consequently, among the two refrigerants considered, R32 offers zero ODP and very low GWP, along with superior performance [30]. Considering the prevalent use of R410a as the refrigerant of choice in the majority of AC units sold in the Saudi market, we explore various scenarios to understand the impact of different levels of R32 penetration in the market.

Three different scenarios are examined to ascertain the maximum potential energy savings and emission reduction based on varying levels of R32 penetration into the market:

(1) BAU: This baseline scenario assumes a constant EER value of 11.8 till 2030 with no alteration in refrigerant used.
(2) AIS refrigerant (AISR)—2 years: This scenario examines an increment in the penetration of R32 refrigerant in new AC stocks by 20% every two years, with 100% of new AC stocks adopting R32 by 2030.
(3) CIS refrigerant (CISR)—2 years: This scenario examines an increment in the penetration of R32 refrigerant in new AC stocks by 10% every two years, with half of the new AC stock adopting R32 by 2030.

## 3 Results and Discussion

This section has also been bifurcated into two subsections to separately investigate the impact of enhanced EER and the utilization of low GWP refrigerant.

**3.1 Effect of Increasing Energy Efficiency Ratio.** With the applicable AC stock calculated up to 2030, the energy consumption is determined for multiple scenarios using Eq. (3) and is graphically represented in Fig. 5. Under the baseline scenario (BAU), the energy consumption is expected to decrease by 19.6%, from 90.45 TWh in 2020 to 72.7 TWh in 2030. While the baseline scenario is promising, augmenting regulatory policies is imperative to further bolster the efficiency of ACs in the Saudi market.

The most aggressive policy scenario, AIS with two-year intervals, yields remarkable energy savings of 10.1 TWh in 2030 compared to the BAU scenario. However, evaluating cumulative energy consumption and energy savings over the decade from 2020 to 2030 offers a more comprehensive view of the benefits brought about by policy interventions. As anticipated, AIS with two-year intervals presents the most significant cumulative energy savings of 37.1 TWh over the ten-year period compared to BAU (Fig. 6). Interestingly, CIS with two-year intervals achieves greater cumulative energy savings of 20.2 TWh when compared to the cumulative energy savings of 9.7 TWh for AIS with five-year intervals. The huge gap in energy savings for these two scenarios suggests small

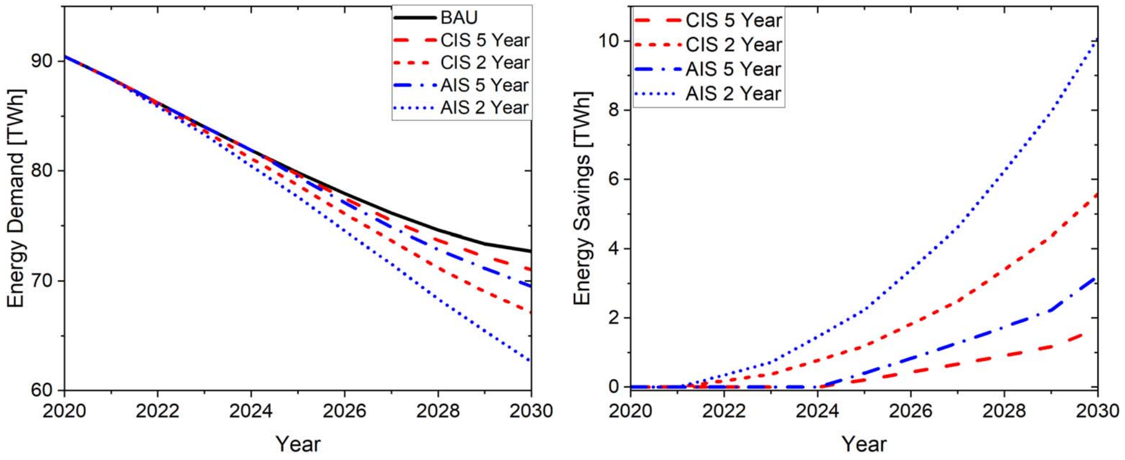

**Fig. 5 Evolution of energy demand and energy savings for five different scenarios until 2030 (cooling capacity: 1.5 ton of refrigeration (5.275 kW))**

but frequent updates in EER are a better option over less frequent updates mandating relatively large enhancement of 10% in EER. CIS with five-year intervals delivers the lowest cumulative energy savings of 5.1 TWh over the ten-year period compared to BAU.

Figure 7 depicts the indirect $CO_2$ emissions for the considered scenarios. As $CO_2$ emissions are directly linked to electrical power consumption, they mirror the trends observed in energy demand. To illustrate the impact of increasing penetration of renewables into the grid, $CO_2$ emissions corresponding to the same energy demand have been plotted for two extreme cases of grid emission factors (Figs. 7(*a*) and 7(*b*)). In the BAU scenario for the baseline case (Fig. 7(*a*)), $CO_2$ emissions are expected to decrease by 19.6% over the decade, from 56.3 MMt in 2020 to about 45.2 MMt in 2030. Aligning with energy savings results, AIS with two-year intervals demonstrates the most substantial cumulative $CO_2$ emission reduction of 23.1 $MtCO_2$ compared to BAU over the ten-year period. Conversely, CIS with five-year intervals presents the lowest cumulative emission reduction of 3.2 $MtCO_2$ over the same period compared to BAU. Furthermore, CIS with two-year intervals and AIS with five-year intervals showcase cumulative emission reductions of 12.6 $MtCO_2$ and 6 $MtCO_2$, respectively, over the decade.

For all scenarios, $CO_2$ emission reductions are significantly smaller in the net zero 2060 case, as it assumes a 53.3% reduction in the grid emission factor from 2020 to 2030 due to increased renewable energy penetration. Under the BAU scenario, $CO_2$ emissions decrease by 62.4% over the decade, reflecting the substantial impact of the grid emission factor. Although the overall trends remain the same in terms of the influence of different scenarios on $CO_2$ emissions, the difference between the BAU and other scenarios is smaller. Over the ten-year period, CIS with five-year intervals shows the lowest $CO_2$ reduction of 1.8 $MtCO_2$ compared to BAU. However, this reduction still equates to avoiding the combustion of more than 4 million barrels of oil [31]. Finally, it is important to note that the grid emission factors for net zero 2060 scenario assume 45 TWh of annual electrical energy generation from solar PV and wind by 2025, increasing to 151 TWh by 2030 [26]. Considering that the total annual electrical production from solar PV and wind reached 2.5 TWh in 2022 [32], the grid emission factors predicted for net zero 2060 case are very optimistic.

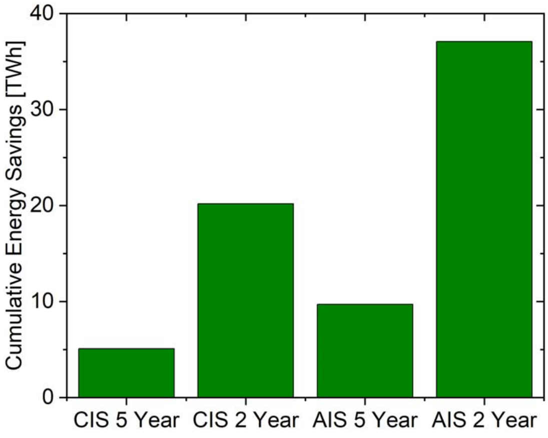

**Fig. 6 Cumulative energy savings for different scenarios compared to BAU scenario over the ten-year period from 2020 to 2030 (cooling capacity: 1.5 ton of refrigeration (5.275 kW))**

### 3.2 Effect of Transitioning to a Low Global Warming Potential Refrigerant.

The adoption of new AC units with refrigerant R32 results in an increase in energy savings attributed to more than 6% improvement in energy efficiency [30,33]. In this study, the theoretical increase in energy efficiency for R32 as compared to R410A was calculated at fixed evaporator and condenser temperatures corresponding to the T1 test condition. Assuming a 15 °C difference between the condenser and outdoor dry bulb temperatures, and between the evaporate and indoor dry bulb temperatures, the EER was calculated for condenser temperature of 50 °C and evaporator temperature of 12 °C. An isentropic efficiency of 85% was assumed for the compressors of both refrigerants and the compressor inlet was set as saturated vapor state and condenser exit as saturated liquid state. Thermophysical properties for the two refrigerants were calculated at different states using EES code. The theoretical increase in EER was calculated to be 6.4% which compares well with reported values in the literature.

The energy consumption and indirect $CO_2$ emissions are then computed using Eq. (3) for three distinct scenarios as outlined in Sec. 2.2 for a fixed improvement in EER of 6.4%. Implementing AISR with two-year intervals yields relatively modest energy savings of 3.3 TWh in 2030 compared to the BAU scenario (Fig. 8). Over the ten-year period, AISR demonstrates cumulative energy savings of 10.2 TWh compared to the BAU scenario (Fig. 9). The CISR scenario with two-year intervention intervals results in cumulative energy savings of 5.2 TWh over the decade compared to the BAU scenario. Overall, transitioning to a new refrigerant yields modest energy savings, with the cumulative energy savings for the best-case scenario of AISR being comparable to the cumulative savings for AIS with five-year intervals.

Figure 10 illustrates the indirect $CO_2$ emissions associated with electricity production for the three scenarios considered here. The

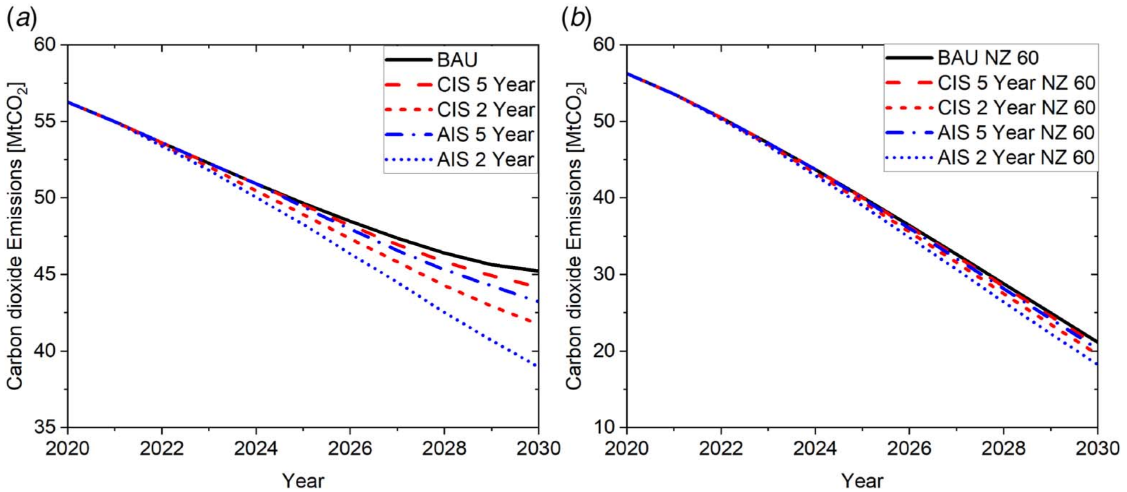

**Fig. 7** Comparison of the emission reduction for five different scenarios until 2030: (*a*) $CO_2$ emissions for baseline case and (*b*) $CO_2$ emissions for net zero 2060 case

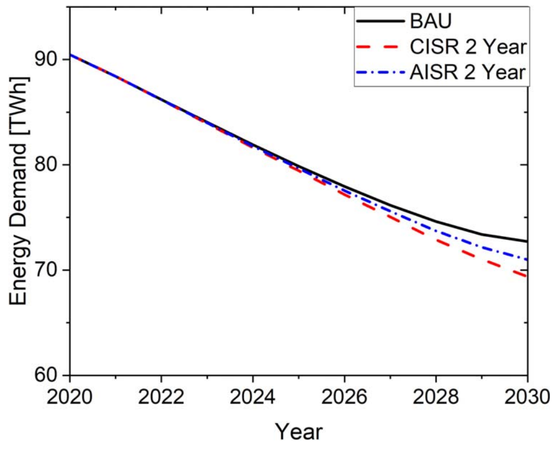

**Fig. 8** Evolution of energy demand for the refrigerant transition under three different scenarios until 2030 (cooling capacity: 1.5 ton of refrigeration (5.275 kW))

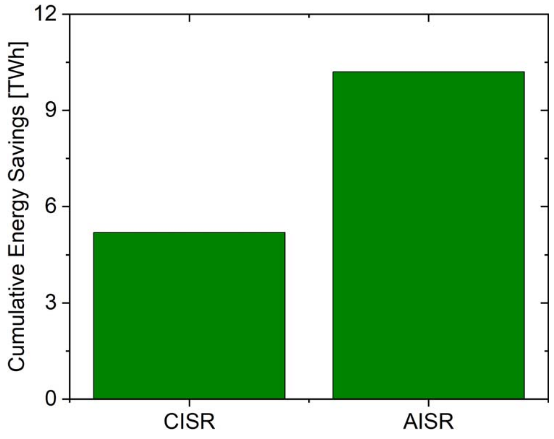

**Fig. 9** Cumulative energy savings for two scenarios of refrigeration transition compared to BAU scenario over the ten-year period from 2020 to 2030 (cooling capacity: 1.5 ton of refrigeration (5.275 kW))

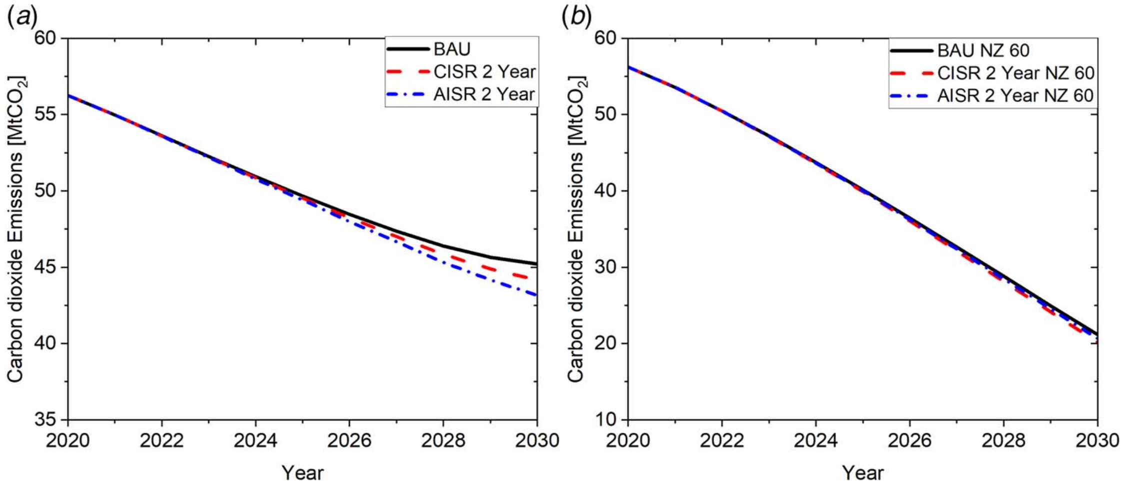

**Fig. 10** Comparison of the emission reduction for the refrigerant transition under three different scenarios until 2030: (*a*) $CO_2$ emissions for baseline case and (*b*) $CO_2$ emissions for net zero 2060 case

$CO_2$ emissions for each scenario have been plotted for the baseline case (Fig. 10(*a*)) and net zero 2060 case (Fig. 10(*b*)). As expected, $CO_2$ emission trends closely follow energy demand. The largest cumulative $CO_2$ emission reduction of 6.3 MMt is achieved for AISR with two-year intervals. In the net zero 2060 case, a similar pattern is observed, but the largest cumulative $CO_2$ emission reduction decreases to 3.7 MMt for AISR with two-year intervals.

Overall, the AC market in Saudi Arabia showcases unique trends in terms of reduction of $CO_2$ emissions even in the BAU scenario with no further improvement in EER. This implies that accelerating the replacement of old AC stock through the high-efficiency AC initiative and through educational campaigns can also contribute toward reaching the net zero $CO_2$ goal in terms of reducing GHG emissions. However, improvement in the EER of the new AC units in the market will accelerate the transition toward a more efficient AC stock in Saudi Arabia. Although the current study focuses on the influence of increasing the EER on reducing $CO_2$ emissions, it is imperative to point out that other options exist to reduce the energy requirement for cooling and are actively being pursued. Mandatory insulation of walls and roofs as required in the revised Saudi Building code [34], increased public awareness of energy conservation methods, and capacity building for conducting energy audits and building retrofits through the National Energy Services Company (Tarshid) [35] are some of the measures being implemented to reduce the energy usage and environmental impact of cooling. Finally, alternate cooling methods including various solar cooling technologies are also garnering research interest as potential options to complement the current electricity-powered vapor compression refrigeration-based cooling systems [36].

## 4 Conclusion

The current study predicts the applicable stock of ACs in Saudi Arabia over a ten-year time period from 2020 to 2030. The annual AC stock is calculated using a 4.8% annual growth rate for new AC units and a median lifespan of 15 years for phasing out old AC stock. Various scenarios are examined to forecast potential energy savings and emission reductions, with a focus on either improvement in EER or transition to low GWP refrigerant. Through a comprehensive evaluation of three distinct scenarios—BAU, CIS, and AIS up to 2030—we have estimated the substantial energy savings and $CO_2$ emission reductions achievable with varying levels of energy efficiency enhancements. For each scenario, the $CO_2$ emission reductions are predicted for two extreme cases of grid emission factor represented by baseline case and net zero 2060 case. Although the BAU scenario is promising, the accelerated improvement scenario can result in significant cumulative energy savings of 37.1 TWh when EER of incoming AC stock is improved at two-year intervals. Even the intermediate scenario under CIS with two-year intervals predicts cumulative energy savings of 20.2 TWh. These energy savings correspond to cumulative emission reduction of 12.6 $MtCO_2$ and 7.7 $MtCO_2$ compared to BAU scenario for the baseline case and net zero 2060 case respectively. These findings underscore that even incremental improvements in EER can significantly contribute to energy conservation and reduction of carbon footprint.

The evaluation of multiple scenarios for introducing new refrigerant (R32) revealed a more modest impact on energy savings compared to the improvements in EER. For the best-case scenario (AISR), cumulative energy savings of 10.2 TWh are achieved when only the refrigerant transition is implemented aggressively. This suggests that while transitioning to low GWP refrigerants is important, focusing on enhancing the energy efficiency of residential AC systems should be a primary policy objective to achieve substantial energy savings and reduce carbon emissions.

To summarize, the current study fills a critical gap by providing a comprehensive understanding of potential energy savings and environmental benefits achievable through strategic policy interventions and technological advancements in the residential AC sector of Saudi Arabia. The insights and recommendations presented in this study can inform and guide the development of robust minimum energy performance standards, thereby reducing the environmental footprint of the residential sector.

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## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

## Nomenclature

$t$ = estimated median lifespan (year)
h = estimated annual working hours for ACs
$S$ = annual sales figure for AC units
EER = energy efficiency ratio (BTU/Wh)
EF = emission factor (kg $CO_2$/kWh)
ER = emission reduction (kg $CO_2$)
ES = energy savings (kWh)

### Greek Symbol

$\alpha$ = growth parameter

### Subscripts

AIS = accelerated improvement scenario
CIS = continuous improvement scenario

### Abbreviations

AC = air conditioning
AIS = accelerated improvement scenario
AISR = accelerated improvement scenario for the refrigerant transition
BAT = best available technology
BAU = business as usual
CIS = continuous improvement scenario
CISR = continuous improvement scenario for the refrigerant transition
EES = engineering equation solver
GWP = global warming potential
HEAC = high-efficiency air conditioner
HFC = hydrofluorocarbon
HVAC = heating, ventilation, and air conditioning
IEA = International Energy Agency
MEPS = minimum energy performance standard
$MtCO_2$ = million tons of carbon dioxide
ODP = ozone depletion potential
SASO = Saudi Arabian Standards Organization

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