Energy Reports 8 (2022) 6101–6109

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Energy conservation and climate change mitigation potential of improving efficiency of room air conditioners in Pakistan

Waqas Ali [a], Muhammad Bilal Sajid [a,*], Awad B.S. Alquaity [b], Shujaat Abbas [c,d,*], Muhammad Asaad Iftikhar [a], Jamsheed Sajid [a], Akhtar Abbas [a]

[a] US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, Islamabad, Pakistan
[b] Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[c] Graduate School of Economics and Management, Ural Federal University, Russian Federation
[d] Institute of Business Management, Department of Economics, Karachi, Pakistan

ARTICLE INFO

Article history:
Received 21 January 2022
Received in revised form 31 March 2022
Accepted 12 April 2022
Available online xxxx

Keywords:
Energy efficiency
GHG emissions
Energy labeling
Climate change
Pakistan

ABSTRACT

The present study predicts the energy savings, carbon emissions reduction and economic benefits for Pakistan through energy efficiency improvements for room air conditioners under different policy scenarios. The simulation model assumes that room air conditioner stock will increase from 2.7 million for year 2020 to 4.9 million for year 2030. A market average energy efficiency ratio of 2.95 is assumed for year 2020. The impact of improvement in energy efficiency ratio is analyzed for business as usual and four other different scenarios: continuous improvement (5-years and 2-years cycles) and accelerated improvement (5-years and 2-years cycles). The model dynamically incorporates the retiring of old stock and addition of new stock every year. Our results show that annual national electricity consumption for this sector is projected to increase from 7.3 TWh in 2020 to 12.6 TWh in 2030 under the business as usual scenario. The cumulative energy consumption and carbon emissions are 103.5 TWh and 63.1 $MtCO_2$. However, implementing energy efficiency policies can result in electricity savings of 11.6 TWh over the ten years or savings nearly 7 million barrels of oil import. Policy recommendations aimed at promoting energy labeling, minimum energy performance standards, regulatory policies, and further country-specific studies for variety of appliances are provided.

1. Introduction

Global energy demand for space cooling has tripled in the last 30 years (IEA, 2018). Buildings account for more than 30% of worldwide energy consumption (Eyre et al., 2018), which is expected to rise further with increasing prosperity, urbanization, rising temperatures, legislation, user behavior, and technological availability across the globe (Berardi and Jafarpur, 2020). The heating and cooling of buildings has emerged as one of the largest sources of energy consumption (Li et al., 2021) and accounts for 28% of CO_2 emissions throughout the world (Li and Yao, 2021). The energy consumption for heating and cooling is expected to increase by 28% between 2015 and 2040 in non-OECD nations (US Energy Information Administration, 2016). Due to increase per capita income levels, easy installment plans, and rapid urbanization, room air conditioners (RACs) ownership has risen dramatically in emerging nations during the past ten years. As a result, it is essential to quantify increased energy consumption to evaluate climate change impact. Policies based on the energy efficiency of air conditioners (van Ruijven et al., 2019) are essential in constructing a sustainable future and are now being examined in new research (Karali et al., 2020a; Vieira et al., 2018).

Enhancing energy efficiency has become a cornerstone of energy strategies. The fundamental goal of these measures is to minimize energy usage and hence the carbon footprint of buildings (Belussi et al., 2019). (Economidou et al., 2020) examined European Union energy policies throughout the last 50 years, focusing on policy tools to stimulate energy efficiency measures in new and existing buildings. Energy consumption in residential and commercial buildings proliferates to achieve indoor thermal comfort (Goldsworthy and Poruschi, 2019). (Chen et al., 2020) examined the influences on building attributes, occupant behavior, and equipment and technology, and concluded that efficient building design is required to identify underlying concerns. Both occupant behavior intervention and technological improvements must be updated promptly to assist building users make in-

* Corresponding authors.
E-mail addresses: mbilalsajid@uspcase.nust.edu.pk (M.B. Sajid), Shujaat.abbas@urfu.ru (S. Abbas).

https://doi.org/10.1016/j.egyr.2022.04.040

Nomenclature

RAC	Room air conditioner
OECD	Organization for Economic Co-operation and Development
Mtoe	Million ton of oil equivalent
RMB	Ren Min Bi
MEPS	Minimum energy performance standards
IECC	International Energy Conservation Code
ISEER	Indian Seasonal Energy Efficiency Ratio
BAU	Business as usual
LEAP	Low Emissions Analysis Platform
EER	Energy efficiency ratio
NEECA	National Energy Efficiency & Conservation Authority
ES&L	Energy Efficiency Standards and Labeling
JRAIA	Japan Refrigeration and Air Conditioning Industry Association
ES	Energy savings
BAU	Business As Usual
CIS	Continuous improvement scenario
AIS	Accelerated improvement scenario
ER	Emission reduction
EF	Grid emission factor (kg/kWh)
COVID	Coronavirus disease
SDG	Sustainable development goals

formed choices. Pakistan's domestic sector accounts for 48% of total energy demand with an average annual energy consumption per household of 2401 kWh/a and a capita of 391 kWh/a (Awan and Knight, 2020). Refrigeration and air conditioning systems consume around 15% of global electricity, while air conditioners use about 20% of electricity in developing countries (Chen et al., 2018). In Pakistan, split-type RACs with a cooling capacity of 1.5 tons constitute most RACs produced/assembled domestically. The most efficient RAC in this cooling capacity category has an EER of 4.0, and the least efficient has an EER of 2.6. While highly efficient RAC units manufactured are currently available, historical sales data has shown that customers prefer low-cost and less-efficient models (IEA, 2020). Therefore, the market average EER tends to be slightly skewed towards the lower efficiency models, as seen in several countries across the globe. Using the data available for maximum, minimum and average EER across 12 global markets (Shah et al., 2013), the market average EER was calculated to be about 10% lower than the mean EER. Using a similar criterion, the market average EER in Pakistan for new stock in 2020 is 2.95.

Improving the efficiency of room air conditioners (RACs) can provide considerable energy savings to satisfy cooling demand in developing countries with hot climates (Shah et al., 2021). Park et al. (2019) identified benefits and improvement opportunities of RAC energy efficiency. Karali et al. (2020a) calculated the cost and minimum energy performance standards (MEPS) of Chinese RACs, concluding that MEPS can save 12.8% of CO_2 and 2620 billion RMB in bills between 2019 and 2050. Kwong et al. (2017) analyzed radiant cooling systems in Malaysia and concluded that it could save up to 34% of energy and is cost-effective to be implemented. Mcneil et al. (2019) examined the effect of energy-efficient appliances on Indonesia's peak load. They found that 26.5 GW of power can be saved by 2025, with air conditioners being the primary driver of peak increase. Lee and Tsai (2020) utilized a cloud-based artificial intelligence system to enhance the energy efficiency of room air conditioners. The HVAC system retrofitted for greater energy efficiency in existing buildings, resulting in a 50% decrease in energy usage while maintaining acceptable indoor thermal comfort (Liu et al., 2018). Abd-ur Rehman et al. (2018) studied energy conservation measures for Saudi residential buildings by integrating the International Energy Conservation Code (IECC) design standards, concluding that IECC standardized buildings can save 56% on cooling and 25% on heating. Dioha and Emodi (2019) used LEAP software to analyze household energy consumption, local air pollutant emissions, and CO_2 emissions until 2030, and concluded that a poor country like Nigeria needs to look into local and foreign funding sources, as well as seriously engage in energy access programs to achieve 100% modern energy access. Tian et al. (2019) uses the LEAP and ARIMA models to investigate the energy consumption and carbon emissions of building heating in the Liaobin coastal economic zone from the perspectives of rules, legislation, energy consumption, and CO_2 emissions. It is concluded that policy interventions to boost clean energy can remove 45% of CO_2 emissions.

Electricity demand almost doubles during summer compared to the winter months, and RACs and other space cooling systems such as fans are significant contributors. RACs are also among the primary drivers of peak load in summer worldwide (IEA, 2018). Energy efficiency programs mandating improvements in sales-weighted fleet average EERs have been successful in several markets such as Japan and South Korea earlier (Abhyankar et al., 2017). Building energy efficiency improvements can minimize energy consumption and greenhouse gas emissions in the environment . Abbas et al. (2021) utilized the LEAP model to propose the solution to minimize emissions from the environment by low-carbon sustainable energy technologies for construction materials of buildings. Phadke et al. (2016) performed an economic analysis to evaluate the costs associated with efficiency improvements of RACs in developing countries like India and calculated the payback period to be less than 9 months for about 25% improvement in ISEER (Indian Seasonal EER). Kim et al. (2020) used the LEAP model and bass diffusion methods to predict energy consumption and GHG emissions in residential and commercial buildings, and found that renewable technology has the upper hand in reducing GHG emissions (24.5%), followed by building energy savings systems with a GHG emissions reduction potential of 19.81%.

It is evident from the literature review that no previous research study has investigated the energy conservation and greenhouse gas mitigation potential of improving energy efficiency standards of residential air conditioners in Pakistan.

The main objectives of this research study are:

1. Assessment of current annual electricity consumption and associated greenhouse gas emissions pertaining to use of residential air conditioners in Pakistan
2. Identification of appropriate scenarios for improvement in energy efficiency standards by considering the technological advancements and best practices in other developing economies
3. Evaluation of annual and cumulative (2020–2030) energy conservation, fuel import bill reduction, and climate change mitigation impact of above-mentioned scenarios
4. Quantification of the impact of uncertainty in input parameters of the model on energy conservation and greenhouse gas mitigation results through sensitivity analysis
5. Identification of suitable recommendations to help policy makers in implementing energy efficiency standards for residential air conditioners and other appliances

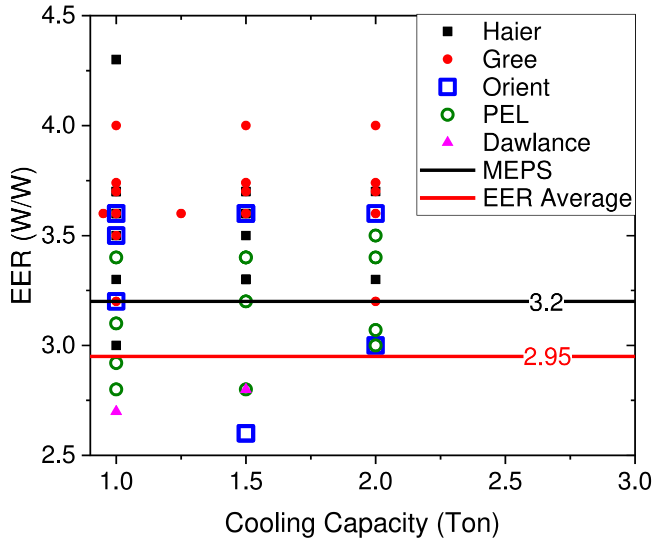

Fig. 1. Cooling capacity and EER data for current RACs in Pakistan along with the MEPS.

This rest of the research study is divided into three sections. Section 2 provides a detailed explanation of the proposed model, RAC stocks, energy consumption estimation, energy savings, and indirect CO_2 emission reduction. Section 3 discusses the findings, potential electricity savings, CO_2 emission reduction potential, and sensitivity analysis, while Section 4 covers conclusion and recommendations.

2. Materials and methods

The bottom-up approach enables to build a detailed model using inputs for the equipment's annual production, vintage percentage, survival profile, and energy intensity. In this study, the energy demand and related CO_2 emissions for Pakistan are projected from 2020 to 2030, using 2020 as the base year. The data collected is fed to LEAP (Low Emissions Analysis Platform) software to predict the energy consumption and indirect CO_2 emissions under different policy scenarios over the next decade. This section discusses details on the RAC market in Pakistan, data sources, and scenarios development based on the annual stock, energy consumption, energy-saving, and emission reduction potential.

2.1. RAC market in Pakistan

A detailed catalog survey of dominant manufacturers has been performed to identify most RACs currently sold in Pakistan and is represented in Fig. 1. The energy efficiency ratio (EER) has been plotted against the cooling capacity (in tons) for representative RACs currently available in Pakistan. The most efficient models are the inverter split-type ACs offered by Haier and Gree with cooling capacities of 1 and 1.5 tons of refrigeration. The least efficient model was Orient's fixed speed split-type AC with a cooling capacity of 1.5 tons, although Orient also sells more efficient models. All the three RACs mentioned above used the refrigerant R410 A. Additionally, many currently available RACs exceed the highest targeted MEPS of 3.2 set by NEECA in 2014, indicating an urgent need to update the MEP standards.

With growing energy demand, there exists a dire need for Pakistan to update its outdated energy efficiency regulatory policies to achieve energy savings through the gradual removal/replacement of inefficient RAC stock and the adoption of new energy-efficient appliances. Minimum Energy Performance Standard (MEPS) for window and split ACs with cooling capacity under 14 kW (4 Tons of Refrigeration (TR)), shown in Table 1, has been developed for voluntary compliance in 2014 (National Energy Efficiency & Conservation Authority (NEECA), 2016).

Table 1
Pakistan MEPS 2014 in terms of EER for air conditioners using air cooling condenser (National Energy Efficiency & Conservation Authority (NEECA), 2016).

System type	Cooling capacity (W)	Targeted EER (W/W)	Minimum EER (W/W)
Window	3517–4499 (1–1.28 Ton)	2.90	2.75
Split	≤4500 (≤1.28 Ton)	3.20	3.04
	4500–7099 (1.28–2 Ton)	3.10	3
	7100–14 000 (2–4 Ton)	3.00	2.94

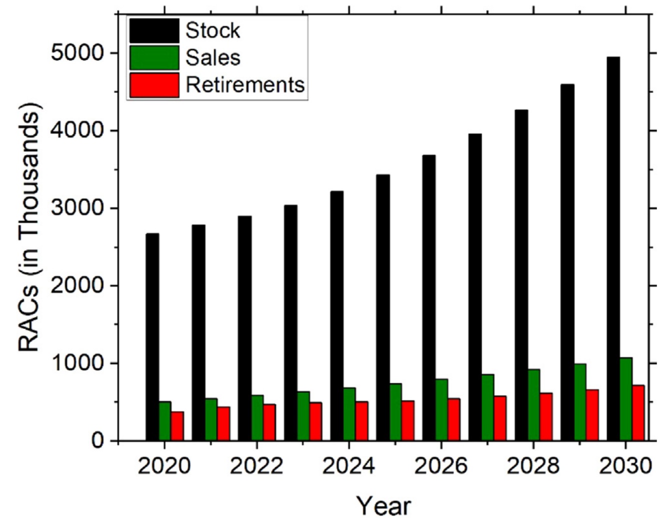

Fig. 2. Predicted total RAC stock (in Thousand units), sales, and retirements over the entire decade (2020–2030).

2.2. Applicable stock

About 10% of households in Pakistan owned a RAC in 2018 (National Institute of Population Studies - NIPS/Pakistan, 2019). Significant potential for growth exists due to an ever-growing population and large number of cooling degree days. The growth rate for the next decade is estimated to be 7.76% for the years 2011 to 2019. Annual device sales, retirements, and total stock up to 2030 are presented in Fig. 2. Overall, RAC stock in Pakistan is expected to double from about 2.7 million in 2020 to about 4.9 million in 2030. Based on the projected population of 263 million in 2030 (World Development Indicators, 2020) and assuming that the ratio of households to the total population remains the same as in the 2017 census (Pakistan Bureau of Statistics, 2017), the number of households will increase to about 41 million. RAC ownership per household will increase marginally to reach about 12% in 2030, indicating a strong potential for continued growth until 2030 and beyond. The total applicable stock presented in Fig. 2 is an estimate since the retirement profile estimates a median lifetime of 5 years and RAC lifetime of 10 years, which may increase due to increased device robustness in recent years.

2.3. Data sources

One of the significant challenges in current work is the scarcity of data for Pakistan. It is obtained by combining the data from

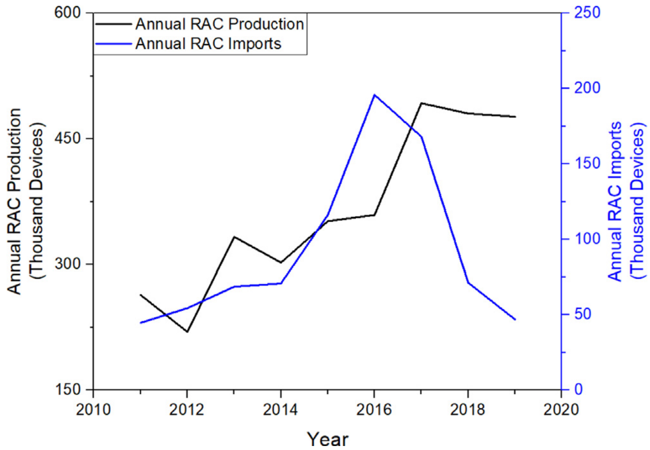

Fig. 3. Annual RAC stock (Thousand Devices) of local production and imports.

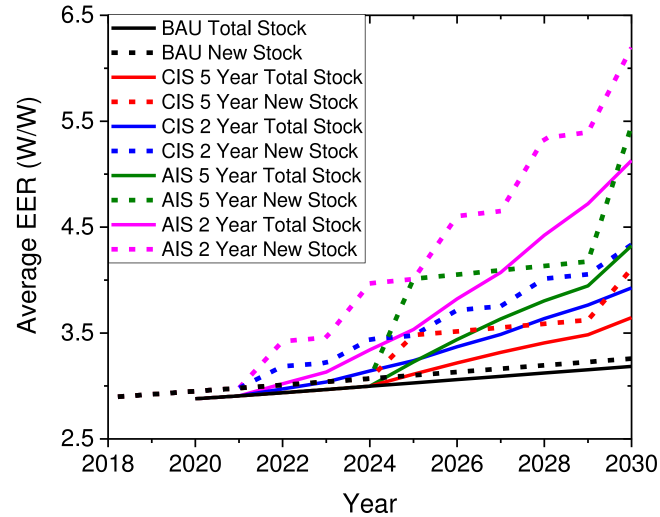

Fig. 4. New stock and total stock average EER (W/W) under different scenarios pertaining to BAU, CIS and AIS (2, 5 years cycles).

multiple reliable sources. Pakistan's RAC stock analysis is performed using data for domestic production of RACs available from the Pakistan Bureau of Statistics (PBS) and the data for RAC imports into Pakistan obtained from the United Nations Comtrade Database (Comtrade, 2020; Pakistan Bureau of Statistics, 2020). Estimated demand for RACs in Pakistan is obtained from Japan Refrigeration and Air Conditioning Industry Association (JRAIA), which consistently reported higher demand for RACs than annual domestic production and imports. The number of annually imported and locally produced RACs is shown in Fig. 3. Due to the unavailability of official sales data and since estimated demand for RACs is much greater than supply, it is assumed that 90% of RACs produced or imported into Pakistan are sold in the same calendar year. Additionally, the JRAIA report provided a breakdown of RAC demand for 2016–2018, which attributed over 95% of RAC demand to split-type RACs ("World Air Conditioner Demand by Region", 2019). Therefore, EER data for split-type RACs have been used to represent energy demand for the entire RAC stock in Pakistan.

2.4. Scenarios development

In this study, business as usual (BAU) or reference scenario, continuous improvement scenario (CIS), and accelerated improvement scenario (AIS) have been considered for forecasting the energy consumption and related in-direct CO_2 emissions for RACs in Pakistan.

A market average EER of 2.95 is estimated for 2020 and has been used to extrapolate EER values of RAC stock. The average EER of new stock is assumed to increase by 1% annually due to technological improvements and customer preference to purchase more efficient RACs to decrease electricity costs (Yu et al., 2015). Market average EER for the preceding years 2011–2019 is predicted using the same assumption of a progressive annual increase in EER by 1%, with the average EER in 2020 set as 2.95. Average EER for annual new stock (dashed lines) and average EER corresponding to total applicable stock (solid lines) is presented in Fig. 4 for the different scenarios used in the study.

In the accelerated improvement scenarios (AIS), the market average EER of 2025 RAC models is assumed to match the EER value of the most efficient RAC currently available (EER = 4.0 in 2020). EER of incoming new stock is assumed to continue improving at the same rate from 2020-to 2030 (dashed line in Fig. 4). In CIS, the rate of improvement of EER is assumed to be half of the improvement rate needed to achieve stated EER goals under AIS. Additionally, the policy intervention cycle of 2 and 5 years is investigated for both scenarios, with the EER growth rate remaining at 1% in intervening years between policy updates. Assuming a regulatory cycle of 2 years under AIS results in a new stock average EER of 6.2 in 2030, while a regulatory cycle of 5 years under CIS results in a new stock average EER of 4.11 in 2030. Considering that RACs with an EER of 6.67 was available in the Japanese market in 2011 (Shah et al., 2013), it is safe to assume that no technical barriers exist in achieving an average EER of 6.2 in 2030.

2.5. Annual RAC stock

The production and imports data for RACs are available for 2011 to 2019. Due to the estimated demand for RACs being much greater than the supply, 90% of the RACs produced/imported in Pakistan are assumed to be sold in the same calendar year. An average annual stock growth of 7.8% has been projected for RACs from 2020 to 2030 using historical production and import data from January 2011 to December 2019.

The survival profile for RACs is predicted using a logistic curve as follows (Heaps, 2005):

$$Survival_i = 1 - 1/\left(1 + e^{-\alpha(i-t)}\right) \quad (1)$$

where α is the growth rate (%), i is the age (years) of RACs, and t is the median lifetime (years).

Due to the lack of data on survival profiles, the growth parameter was considered 0.85, similar to the work on estimating the RAC survival profile in China (Karali et al., 2020b).

The total annual stock of RACs is the summation of current year sales and previous surviving RACs over its lifetime of 10 years. The annual stock for the year 'i' is given as:

$$Stock_i = S_i + \sum_{i-10}^{i-1} S_i \times Survival_i \quad (2)$$

where S is the sale of the product.

For the base year 2020, the sales data for the calendar year 2010 was not available and was therefore not considered in the stock calculation as the maximum error was negligible (0.12%). The error was calculated by assuming that sales in 2010 will be the same as 2011, which is a reasonable assumption to calculate maximum error as estimated demand in 2011 was 6.6% higher than in 2010 (Shah et al., 2017).

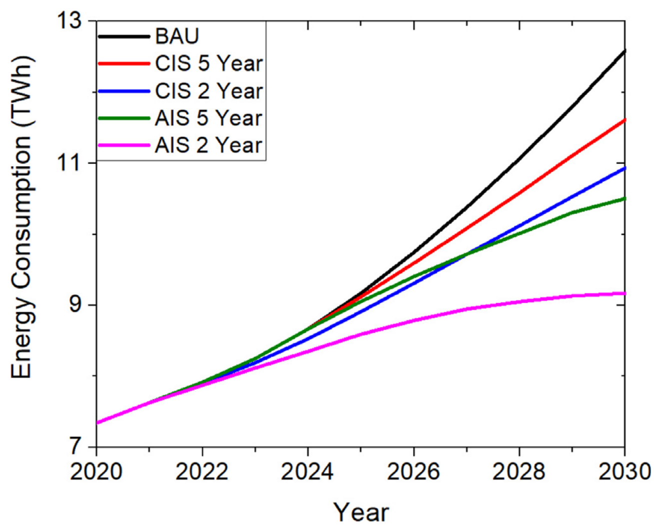

Fig. 5. Annual energy consumption (TWh) under BAU, CIS, and AIS scenarios for Pakistan's RACs sector.

2.6. Energy consumption estimation

The annual energy consumption by RACs in kWh is calculated as:

$$E = Annual\ Operating\ Hours \times \frac{Cooling\ capacity\ (\mathrm{kW})}{EER_{Average}} \quad (3)$$

Eq. (3) shows that energy consumption is directly proportional to the annual operating hours (assumed as 1500 h) and cooling capacity of air conditioner unit. Furthermore, energy consumption is inversely proportional to EER value which shows that an improvement in EER value will have a direct effect on decreasing the energy consumption without any change in operating hours or cooling capacity.

The most common cooling capacity of 1.5 Ton of refrigeration (5.275 kW) represents the entire RAC stock in Pakistan.

2.7. Energy saving and indirect CO_2 emission reduction

The potential energy savings and emission reduction are calculated from the difference between business as usual scenario (BAU) versus continuous improvement scenario (CIS) and accelerated improvement scenario (AIS) cases:

$$ES_{CIS} = BAU_i - CIS_i \quad (4)$$

$$ES_{AIS} = BAU_i - AIS_i \quad (5)$$

Eqs. (4) and (5) show that to estimate the total annual energy saving for entire stock, first we calculate the annual energy consumption under business-as-usual scenario and the specific scenario under consideration. The total energy saving for scenario will difference of the two annual energy consumption values. It is worth noting that BAU energy consumption value for each year will be different due to difference in stock size and gradual improvement in EER value.

The study focuses only on indirect CO_2 emissions produced due to the electricity usage by the appliances. Direct emissions from refrigerant leaks and scrappage of old RACs have not been considered here. Therefore, the emissions reduction for each case is calculated similarly to the energy savings as:

$$ER_{CIS} = ES_{CIS} \times EF \quad (6)$$

$$ER_{AIS} = ES_{AIS} \times EF \quad (7)$$

Eqs. (6) and (7) show that emissions reduction is directly proportional to the energy savings for any scenario. The emissions factor (EF) is assumed to be 0.6 kg CO_2/kWh for the whole study. This weighted average value shows the total carbon footprint of power sector of the country. This study assumes that energy mix for power generation would remain the same for entire time period of the simulation model (2020–2030)

3. Results and discussion

This section presents the energy consumption and savings potential by incorporating applicable stock, potential electricity savings, and emission reduction. Furthermore, a sensitivity analysis is performed at the end of the section to investigate the effect of three independent parameters on energy savings and associated emission reduction.

3.1. Potential electricity savings

Under the reference scenario (BAU), energy consumption is projected to increase by 71%, from 7.3 TWh in 2020 to 12.6 TWh in 2030 (Fig. 5). Considering that Pakistan currently suffers from chronic power supply shortages, it is essential to implement regulatory policies to avoid further supply–demand gaps. It is considered that CIS and AIS are being evaluated for policy update intervals of 2 years and 5 years to visualize the effect of possible policy interventions on energy demand. The most competitive scenario (AIS with 2-year intervals) corresponds to an average annual increase of 7.7% in the EER of new stock. In comparison, the most relaxed policy intervention scenario (CIS with 5-year intervals) corresponds to a 3.4% average annual increase in EER, which is comparable to the efficiency increase (∼3%) achieved in India between 2006–2016 (Abhyankar et al., 2017).

Implementing energy efficiency requirements under AIS with both 2 year and 5-year intervals provides significant energy savings in place of a more efficient RAC stock than CIS. AIS implementation with 2-year update intervals ensures that the energy consumption curve grows at a much slower pace before flattening out near 2030 despite increasing sales over the next decade compared to BAU. Only AIS with a regulatory cycle of 2 years results in flattening of energy consumption curve in 10 years, with energy consumption continuing to increase under all other scenarios even in 2030. Implementing AIS with 2-year update intervals will result in cumulative energy savings of 11.6 TWh by 2030 and is equivalent to eliminating almost 11% of incremental energy demand under the BAU scenario. Energy savings are equivalent to the energy content of 6.8 million barrels of crude oil. They will result in a corresponding import bill reduction upwards of $ 272 million on oil imports (assuming energy content of 1700 kWh/barrel and an average import price of USD 40/barrel). The cumulative equivalent barrels of crude oil saved and resulting financial savings over 10 years are presented in Fig. 6 for multiple scenarios. However, with the world going through a severe recession due to the COVID-19 pandemic, implementing an ambitious energy reform plan like AIS with 2-year update intervals may prove challenging.

If the energy efficiency program under CIS is implemented, cumulative energy savings over 10 years compared to BAU vary between 2.7 to 5.5 TWh for 5-year and 2-year regulatory update intervals, respectively; equivalent to import bill reductions of $ 62 to 128 million in terms of crude oil imports. Energy savings of 5.5 TWh is achieved under CIS with 2-year update intervals are comparable to savings of 5.8 TWh under AIS with 5-year frequency intervals; however, implementing a gradual increase in efficiency ratings under CIS is recommended. Energy savings of 2.7 TWh, equivalent to eliminating 2.6% of energy demand

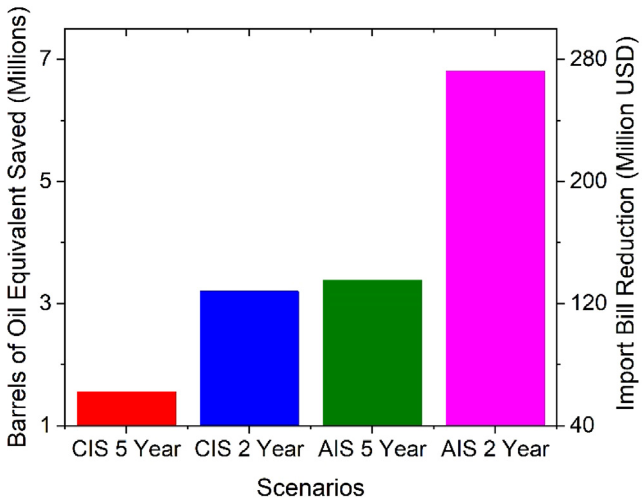

Fig. 6. Cumulative equivalent barrels of oil (in millions) saved and import bill reduction (in million USD) in oil imports by 2030.

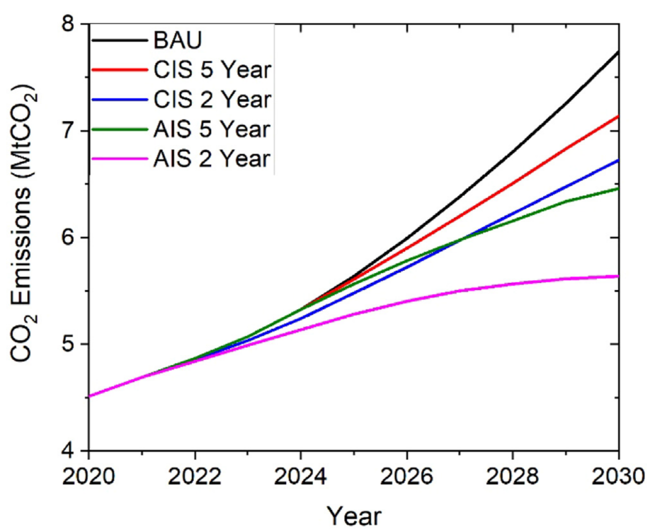

Fig. 7. Indirect annual CO_2 emissions (in million tons of CO_2) under BAU, CIS, and AIS scenarios.

under the BAU scenario, is still possible under CIS with 5-year intervals. Potential cumulative energy savings of 2.7 to 5.5 TWh are also equivalent to 513 to 1046 MW in peak power demand considering an average system capacity factor of 60% for Pakistan. The electricity deficit in peak power stood at 1062 MW for 2019. Implementing energy policy interventions under CIS or AIS can significantly reduce the energy supply–demand gap in Pakistan.

3.2. CO_2 emissions reduction potential

CO_2 emissions are directly proportional to electrical power consumption and follow the same trends as energy demand under the scenarios considered here. CO_2 emissions are expected to increase by 71% in ten years, from 4.5 million metric tons in 2020 to 7.7 million metric tons in 2030. Indirect CO_2 emissions associated with electricity production have been plotted for different scenarios in Fig. 7. In CIS and AIS, the increase in CO_2 is limited to 58% and 24% concerning 2020 emissions for worst (5-year interval) and best cases (2-year interval) of two scenarios, respectively.

3.3. Sensitivity analysis

The results obtained for the prediction of estimated energy demand and associated greenhouse gas emissions are based on various modeling assumptions and input parameters. Any uncertainty in the input parameters would directly affect the accuracy of the results reported in this study. Hence, to quantify this impact, we have performed sensitivity analysis for the energy consumption. It is important to note that greenhouse gas emissions are directly proportional to the energy consumption as evident from Eqs. (6) and (7). Therefore, no separate sensitivity analysis is performed for greenhouse gas emissions.

The results of our analysis are based on three main input parameters, (i) operating hours (ii) average EER value for new stock for year—2020 (iii) growth rate for annual sales of RACs. The effects of these parameters on cumulative as well as normalized annual energy consumption (with respect to the base case for year—2020) are discussed below. The findings of sensitivity analysis are summarized in Table 2 and Fig. 8.

Table 2 lists the values of the parameters used in base case, as well as the new values considered for the sensitivity analysis. The base case has been computed using 7.76% growth rate, 1500-hour operation and EER value of 2.95 for new stock of year 2020. The cumulative energy consumption (2020–2030) for BAU is 104.6 TWh. For performing sensitivity analysis, the value of each parameter has been varied to two new values which are 25% above and below the initial value. The resultant values of BAU cumulative energy consumption corresponding to each varied parameter have been reported in the table. The cumulative energy consumption values for these BAU cases vary between 78.4 TWh and 139.6 TWh.

$$\textit{Normalized Energy Consumption} = \frac{\textit{Annual Energy wrt Scenario}}{\textit{Annual Energy Year } 2020} \quad (8)$$

Fig. 8 shows the effect of varying growth rate, EER value and operating hours on annual normalized energy consumption. Eq. (8) shows that normalized energy consumption is calculated by taking the ratio between annual energy consumption of any scenario e.g., AIS 2-year and annual energy consumption for year—2020.

Effect of Operating Hours: The previously presented results (Figs. 5–7) for cumulative energy consumption and greenhouse gas emissions are based on 1500 h of annual operation. In the sensitivity analysis, we have varied this parameter by ±25% to 1125 h and 1875 h. The cumulative energy consumption for the base case (1500 h) is 104.5 TWh which increases to 130.7 TWh for 1875 h and decreases to 78.4 TWh for reduced annual operations of 1125 h. As evident from the Eq. (3), the energy consumption is directly proportional to operating hours. Hence, the cumulative energy consumption also linearly varies with operation hours and shows ±25% change. The variation of normalized energy consumption with respect to annual operating hours is presented in Fig. 8(a). For the BAU Base Case, the normalized energy consumption increases to nearly 1.75 for the year—2030. The variation of normalized energy consumption for 'BAU Annual operating hours = 1125' follows the same pattern. This trend can be explained by understanding that any Base Case and its corresponding scenario would assume same value of annual operating hours for the year—2020. The variation of cumulative energy consumption and normalized energy consumption for AIS 2-year and CIS 5-year can be explained in similar manner.

Effect of EER Value: In the results reported earlier (Figs. 5–7), we had assumed an average EER value of 2.95 for the new stock of year—2020. The values of EER for future years are computed from this value for different scenarios. Eq. (3) shows that

Table 2
Sensitivity analysis of energy consumption w.r.t. annual growth rate, operating hours and EER value.

Sensitivity parameters		Base case	Operating hours		EER		Growth rate	
Annual growth rate (%)		7.76	7.76		2.95		5.8	9.7
Annual operating hours		1500	1125	1875	1500		1500	
New stock's EER in 2020			2.95		2.21	3.69	2.95	
Cumulative energy consumption for BAU (TWh)		104.6	78.4	130.7	139.6	83.7	96.7	113.3
Percentage change in cumulative energy consumption w.r.t. base case (2020)	BAU						−7.5%	8.4%
	CIS 5 year	0	−25%	25%	33.5%	−20%	−7.3%	8.1%
	AIS 2 year						−6.7%	7.3%
Cumulative energy savings w.r.t. BAU (TWh)	CIS 5 year		2	3.3	3.5	2.1	2.2	3.15
	AIS 2 year		8.7	14.5	15.5	9.3	9.9	13.5

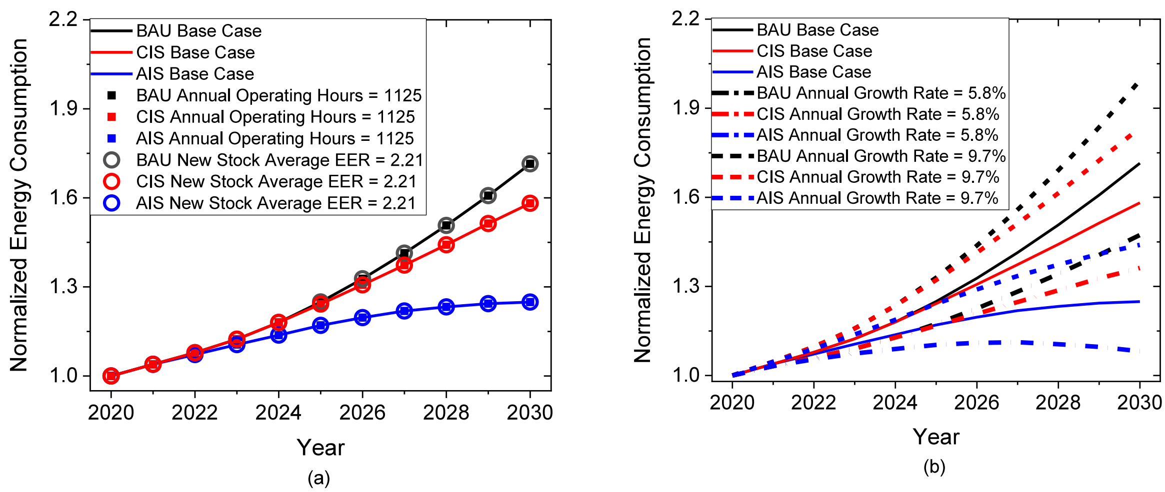

Fig. 8. Normalized energy consumption for multiple scenarios with perturbation in three independent parameters (operating hours, EER value and annual growth rate).

energy consumption is inversely proportional to EER value. The cumulative energy consumption for Base Case (EER value of 2.95) is 104.6 TWh which increases to 139.6 for lower EER of 2.21 while in decreases to 83.7 TWh for higher EER of 3.69. Hence, it can be observed that a 25% improvement in EER value results in 20% energy savings while 25% decrease in EER value corresponds to 33.5% additional energy consumption for the BAU cases. The cumulative energy savings for CIS 5-year are 3.5 TWh and 2.1 TWh while for AIS 2-year, the savings are 15.5 TWh and 9.3 TWh. It can be observed that highest potential for energy conservation (15.5 TWh) occurs when initial EER value is lowest and then EER is rapidly increased in shorter cycle i.e., AIS 2-year for initial EER of 2.21. The effect of EER on normalized energy consumption follows similar pattern as that of annual operating hours and can be explained in similar manner.

Effect of Growth Rate: This study assumes an annual growth rate of 7.76% for RAC sales. For sensitivity analysis, we have varied its values to 5.8% and 9.7%. As shown in Table 2, the cumulative energy consumption for 7.76% growth rate is 104.6 TWh. For 5.8% growth rate, the cumulative energy consumption reduces to 96.7 TWh, while for 9.7% growth rate this value increases to 113.3 TWh. For BAU cases, an increase of 25% in growth rate results in 8.4% increase in energy consumption while 25% reduction in growth rate results in 7.5% decrease in energy consumption when compared with base case of 7.76% growth rate. This trend can be explained by examining the effects of growth rate on sales of new RACs and change in proportion of high efficiency RACs. The increase in growth rate results in sales and adoption of more RAC units which results in increase in energy consumption. Although, these newer RACs decrease the proportion of older, in-efficient RACs but marginally contributes to energy conservation, but cumulative effect is the increase in energy consumption. On the other hand, decrease in growth rate results in net decrease in cumulative energy consumption due to existence of small stock of relatively in-efficient RAC units.

For the improved scenarios, the highest energy savings emerge for the case of AIS 2-year which offer 13.5 TWh for growth rate of 9.7% while these savings reduce to 9.9 TWh for the lower growth rate of 5.8%. For CIS 5-year scenario, the energy savings vary from 3.15 TWh to 2.2 TWh for the growth rate of 9.7% and 5.8% respectively. These trends can be explained in the same manner as those for the variation of cumulative energy consumption for BAUs under different growth rates.

The variation of normalized energy consumption with respect to the annual growth rate is presented in Fig. 8(b). It is evident that effect of growth rate is different from those of other parameters under consideration, i.e., operating hours and EER value. We can observe that variation in growth rate affects any Base Case and the corresponding improvement scenarios differently. The BAU Base Case (for growth rate of 7.78%) reaches a value of nearly 1.75 of normalized energy consumption for the year 2030. The BAU for 5.8% growth reaches the value of nearly 1.45 for normalized energy consumption. On the other hand, the growth rate of 9.7% increase the normalized energy consumption to nearly 2.0.

Hence, it can be concluded that any uncertainty in the value of growth rate will exponentially affect the increase in cumulative energy consumption as well as the normalized energy consumption. The primary reason behind this huge variation is the difference in calculation of total size of RAC stock due to uncertainty in annual growth rate.

4. Conclusion and recommendation

The study provides a quantitative assessment of energy savings potential, GHG emissions mitigation, and economic benefits that can be obtained by improving the energy efficiency of new residential air conditioners being sold in Pakistan. The analysis covers a period of 10 years.

1. Year 2020 is considered as the start of the simulated period with the stock of 2.7 million units and market average energy efficiency ratio of 2.95 is assumed. A annual growth rate of 7.76% is assumed for forecasting future stock size.
2. Applicable stock is subsequently used to forecast energy consumption under three primary scenarios: business as usual (BAU), continuous improvement scenario (CIS), and accelerated improvement scenario (AIS) while considering the frequency of regulatory updates.
3. AIS with 2-year update intervals can provide cumulative energy savings of 11.6 TWh associated emission reduction of 7.1 million metric tons of CO_2 compared to the BAU scenario.
4. CIS with 5-year update intervals can provide energy savings of 2.7 TWh which is equivalent to eliminating the need to build at least one 500 MW peaking power plant.
5. AIS with 5-year update intervals and CIS with 2-year update intervals provide comparable energy savings of 5.8 TWh and 5.5 TWh, respectively.
6. Only AIS with 2-year update intervals results in flattening of energy consumption curve by 2030, with the energy consumption continuing to increase under all other scenarios even in 2030.

The following policy recommendations are provided in the light of this research study:

1. Improvement in energy efficiency of residential air conditioner offers attractive opportunity for climate change mitigation and can significantly contributes to meeting Paris Agreement goals of the country.
2. Gradual improvements in minimum energy performance standards of new RAC units should be first introduced for voluntary compliance and then be transformed to mandatory requirement after a gap of 3–5 years.
3. The indigenous manufacturing industries should be provided with technological as well as financial support (in the form of subsidies or tax incentives) for improvement energy efficiency of their products.
4. Awareness about green buildings technologies, energy efficient products, climate change mitigation, green building standards etc. can increase awareness and market demand for energy efficient air conditioners and other appliances.
5. Further detailed, country-specific studies for other appliances and technologies such electric motors, ceiling fans, pumps etc. building envelop, should be carried out to quantify cumulative energy, economic and environmental benefits of energy efficiency standards upgradation.

CRediT authorship contribution statement

Waqas Ali: Conceptualization, Investigation, Writing – original draft, Data curation, Software, Formal analysis. **Muhammad Bilal Sajid:** Conceptualization, Supervision, Methodology, Formal analysis, Writing – review & editing. **Awad B.S. Alquaity:** Formal analysis, Writing – review & editing, Software, Data curation, Validation. **Shujaat Abbas:** Supervision, Writing – review & editing, Methodology, Validation. **Muhammad Asaad Iftikhar:** Methodology, Formal analysis, Writing – review & editing. **Jamsheed Sajid:** Writing – review & editing, Data curation. **Akhtar Abbas:** Software, Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abbas, A., Sajid, M.B., Iftikhar, M.A., Khoja, A.H., Ahmad, M.M., Shahid, M., Ullah, K., 2021. Assessment of long-term energy and environmental impacts of the cleaner technologies for brick production. Energy Rep. 7, 7157–7169. http://dx.doi.org/10.1016/J.EGYR.2021.10.072.

Abhyankar, N., Shah, N., Park, W.Y., Phadke, A.A., 2017. Accelerating Energy Efficiency Improvements in Room Air Conditioners in India: Potential, Costs-Benefits, and Policies. Lawrence Berkeley National Laboratory, pp. 1–39.

Awan, U., Knight, I., 2020. Domestic sector energy demand and prediction models for Punjab Pakistan. J. Build. Eng. 32, 101790. http://dx.doi.org/10.1016/j.jobe.2020.101790.

Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I., Salamone, F., Scamoni, F., Scrosati, C., 2019. A review of performance of zero energy buildings and energy efficiency solutions. J. Build. Eng. 25, 100772. http://dx.doi.org/10.1016/j.jobe.2019.100772.

Berardi, U., Jafarpur, P., 2020. Assessing the impact of climate change on building heating and cooling energy demand in Canada. Renew. Sustain. Energy Rev. 121, 109681. http://dx.doi.org/10.1016/j.rser.2019.109681.

Chen, W.-H., Mo, H.-E., Teng, T.-P., 2018. Performance improvement of a split air conditioner by using an energy saving device. Energy Build. 174, 380–387. http://dx.doi.org/10.1016/j.enbuild.2018.06.055.

Chen, S., Zhang, G., Xia, X., Setunge, S., Shi, L., 2020. A review of internal and external influencing factors on energy efficiency design of buildings. Energy Build. 216, 109944. http://dx.doi.org/10.1016/j.enbuild.2020.109944.

Comtrade, U.N., 2020. UN comtrade| international trade statistics database. https://comtrade.un.org/data/.

Dioha, M.O., Emodi, N.V., 2019. Investigating the impacts of energy access scenarios in the Nigerian household sector by 2030. Resources 8, 127. http://dx.doi.org/10.3390/RESOURCES8030127.

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L., 2020. Energy & buildings review of 50 years of EU energy efficiency policies for buildings. Energy Build. 225, 110322. http://dx.doi.org/10.1016/j.enbuild.2020.110322.

Eyre, N., Darby, S.J., Grünewald, P., Mckenna, E., Ford, R., 2018. Reaching a 1.5 °C target: socio-technical challenges for a rapid transition to low-carbon electricity systems. Phil. Trans. R. Soc. A 376, 20160462. http://dx.doi.org/10.1098/RSTA.2016.0462.

Goldsworthy, M., Poruschi, L., 2019. Air-conditioning in low income households; a comparison of ownership, use, energy consumption and indoor comfort in Australia. Energy Build. 203, 109411. http://dx.doi.org/10.1016/j.enbuild.2019.109411.

Heaps, C., 2005. User Guide for LEAP 2005. Stockholm Environment Institute, https://leap.sei.org/.

IEA, 2018. The Future of Cooling. IEA, Paris, https://www.iea.org/reports/the-future-of-cooling.

IEA, 2020. World Energy Outlook 2020. IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2020.

Karali, N., Shah, N., Park, W.Y., Khanna, N., Ding, C., Lin, J., Zhou, N., 2020a. Improving the energy efficiency of room air conditioners in China: Costs and benefits. Appl. Energy 258, 114023. http://dx.doi.org/10.1016/j.apenergy.2019.114023.

Karali, N., Shah, N., Park, W.Y., Khanna, N., Ding, C., Lin, J., Zhou, N., 2020b. Improving the energy efficiency of room air conditioners in China: Costs and benefits. Appl. Energy 258, 114023. http://dx.doi.org/10.1016/j.apenergy.2019.114023.

Kim, S., Lee, S., Han, S., Kim, J., 2020. Scenario analysis for GHG emission reduction potential of the building sector for new city in South Korea. Energies 13, 5514. http://dx.doi.org/10.3390/en13205514.

Kwong, Q.J., Kho, S.J., Abdullah, J., Raghava, V.R., 2017. Evaluation of energy conservation potential and complete cost–benefit analysis of the slab-integrated radiant cooling system: A Malaysian case study. Energy Build. 138, 165–174. http://dx.doi.org/10.1016/j.enbuild.2016.12.014.

Lee, D., Tsai, F.-P., 2020. Air conditioning energy saving from cloud-based artificial intelligence: Case study of a split-type air conditioner. Energies 13, 2001. http://dx.doi.org/10.3390/en13082001.

Li, Y., Wang, W., Wang, Y., Xin, Y., He, T., Zhao, G., 2021. A review of studies involving the effects of climate change on the energy consumption for building heating and cooling. Int. J. Environ. Res. Public Health 18, 1–18. http://dx.doi.org/10.3390/ijerph18010040.

Li, X., Yao, R., 2021. Modelling heating and cooling energy demand for building stock using a hybrid approach. Energy Build. 235, 110740. http://dx.doi.org/10.1016/j.enbuild.2021.110740.

Liu, Y., Liu, T., Ye, S., Liu, Y., 2018. Cost–benefit analysis for energy efficiency retrofit of existing buildings : A case study in China. J. Cleaner Prod. 177, 493–506. http://dx.doi.org/10.1016/j.jclepro.2017.12.225.

Mcneil, M.A., Karali, N., Letschert, V., 2019. Forecasting Indonesia's electricity load through 2030 and peak demand reductions from appliance and lighting efficiency. Energy Sustain. Dev. 49, 65–77. http://dx.doi.org/10.1016/j.esd.2019.01.001.

National Energy Efficiency & Conservation Authority (NEECA), 2016. Energy efficiency standard & labeling (EES & L) programs. https://neeca.gov.pk/SiteImage/Misc/files/PakistanEnergyLabellingScheme_RegisteredManufacturers_7_21.pdf.

National Institute of Population Studies - NIPS/Pakistan, 2019. Pakistan Demographic and Health Survey 2017-18. NIPS/Pakistan and ICF; NIPS/Pakistan and ICF, http://dhsprogram.com/pubs/pdf/FR354/FR354.pdf.

Pakistan Bureau of Statistics, 2017. Compendium on Environmental Statistics of Pakistan. Pakistan Bureau of Statistics, http://www.pbs.gov.pk/content/pakistan-statistical-year-book-2017.

Pakistan Bureau of Statistics, 2020. Quantum index of large scale manufacturing industries (QIM) | Pakistan bureau of statistics. https://www.pbs.gov.pk/qim.

Park, W.Y., Shah, N., Ding, C., Qu, Y., 2019. Challenges and recommended policies for simultaneous global implementation of low-GWP refrigerants and high efficiency in room air conditioners. https://escholarship.org/uc/item/07j5f74s.

Phadke, A., Shah, N., Abhyankar, N., Park, W.Y., Diddi, S., Ahuja, D., Mukherjee, P.K., Walia, A., 2016. Cost-benefit of improving the efficiency of room air conditioners (inverter and fixed speed) in India.

Abd-ur Rehman, H.M., Al-Sulaiman, F.A., Mehmood, A., Shakir, S., Umer, M., 2018. The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia. J. Cleaner Prod. 183, 1122–1130. http://dx.doi.org/10.1016/j.jclepro.2018.02.187.

Shah, Nihar, Amol, P., Paul, W., 2013. Cooling the Planet: Opportunities for Deployment of Superefficient Room Air Conditioners. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Shah, N.K., Khanna, N., Karali, N., Park, W., Qu, Y., Zhou, N., 2017. Opportunities for simultaneous efficiency improvement and refrigerant transition in air conditioning.

Shah, Nihar, Park, W.Y., Ding, C., 2021. Trends in best-in-class energy-efficient technologies for room air conditioners. Energy Rep. 7, 3162–3170. http://dx.doi.org/10.1016/j.egyr.2021.05.016.

Tian, C., Feng, G., Li, S., Xu, F., 2019. Scenario analysis on energy consumption and CO 2 emissions reduction potential in building heating sector at community level. Sustainability 11, 5392. http://dx.doi.org/10.3390/su11195392.

US Energy Information Administration, 2016. International energy outlook 2017-EIA.

van Ruijven, B.J., De Cian, E., Sue Wing, I., 2019. Amplification of future energy demand growth due to climate change. Nature Commun. 10, 2762. http://dx.doi.org/10.1038/s41467-019-10399-3.

Vieira, N.D.B., Nogueira, L.A.H., Haddad, J., 2018. An assessment of CO2 emissions avoided by energy-efficiency programs: A general methodology and a case study in Brazil. Energy 142, 702–715. http://dx.doi.org/10.1016/j.energy.2017.10.072.

World Air Conditioner Demand by Region, 2019. Japan refrigeration and air conditioning industry association (JRAIA). https://www.jraia.or.jp/english/World_AC_Demand.pdf.

World Development Indicators, 2020. The world bank. https://data.worldbank.org/country/pakistan.

Yu, H., Tang, B.-J., Yuan, X.-C., Wang, S., Wei, Y.-M., 2015. How do the appliance energy standards work in China? Evidence from room air conditioners. Energy Build. 86, 833–840. http://dx.doi.org/10.1016/j.enbuild.2014.09.072.