Discussion Paper

The Rising Cost of Cooling: Regional Energy Futures in a Warming Saudi Arabia



Jeyhun I. Mikayilov, Abdulelah Darandary, and Khalid Alhadrami

August 2025 I DOI: 10.30573/KS--2025-DP40

About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

This publication is also available in Arabic.

Legal Notice

© Copyright 2025 King Abdullah Petroleum Studies and Research Center ("KAPSARC"). This Document (and any information, data or materials contained therein) (the "Document") shall not be used without the proper attribution to KAPSARC. The Document shall not be reproduced, in whole or in part, without the written permission of KAPSARC. KAPSARC makes no warranty, representation or undertaking whether expressed or implied, nor does it assume any legal liability, whether direct or indirect, or responsibility for the accuracy, completeness, or usefulness of any information that is contained in the Document. Nothing in the Document constitutes or shall be implied to constitute advice, recommendation or opinion. The views and opinions expressed in this publication are those of the authors and do not necessarily reflect the official views or position of KAPSARC.

Summary

This study quantifies the impact of a warming climate on residential cooling demand in Saudi Arabia, examining four regions through 2060. Utilizing region-specific electricity demand models and IPCC temperature pathways, we find that a 1°C increase in average temperature could raise electricity consumption for cooling by 12.9% in the Western region, 10.3% in the Southern region, 8.3% in the Central region, and 4.8% in the Eastern region, based on data from 1990 to 2018. Under the high-emission SSP5 – Fossil-Fueled Development (Taking the Highway) pathway (high-emissions scenario), cooling-related electricity use in 2060 is projected to be nearly 20 TWh higher than under the SSP2 – Middle of the Road baseline. By contrast, the SSP1 – Sustainability (Taking the Green Road) scenario could reduce consumption by about 8 TWh. These findings underscore the strain that rising temperatures place on households and utilities, leading to higher bills and greater infrastructure demands.

Furthermore, using a power system optimization model to evaluate identical scenarios, we find that the SSP1 scenario yields the lowest long-term system costs, resulting in $9.41 billion in savings compared to the baseline scenario (SSP2) over the 2024-2060 period. These savings arise from reduced fuel consumption and lower investments in generation and transmission assets. Additionally, SSP1 eases infrastructure pressures associated with growing electricity demand, which could otherwise increase total system costs by as much as $22 billion over the period 2024-2060 across scenarios. These costs are ultimately borne by utility companies (which require higher capital investments), electricity consumers (who may face higher tariffs), and government budgets (which support subsidies and infrastructure).

These results underscore the economic benefits of global climate mitigation efforts for the Kingdom of Saudi Arabia (KSA). National contributions to these efforts could include policy interventions such as accelerated electricity price reforms to align with market levels, implementation of demand response mechanisms in electricity market design, and targeted efficiency investments with appropriate price signals to avoid rebound effects. Achieving net-zero emissions by 2060 while addressing adaptation challenges is critical for Saudi Arabia to effectively manage future cooling demand and mitigate economic and environmental risks.

Key Points

- All regions in Saudi Arabia are experiencing notable warming, with the Western region's summer temperature rising by 2.00°C and winter by 1.30°C between 1990 and 2020 – the highest among all regions.
- A 1°C temperature increase drives significant growth in cooling demand, raising residential electricity use by up to 12.9% in the Western region, followed by 10.3% in the Southern, 8.3% in the Central, and 4.8% in the Eastern regions, based on estimations using data from the 1990-2018 period.
- Under a Saudi-specific temperature projection corresponding to SSP5 – Fossil-Fueled Development (Taking the Highway), electricity demand in the Kingdom of Saudi Arabia in 2060 is projected to be nearly 20 TWh higher than under the SSP2 – Middle of the Road baseline. By contrast, the SSP1 – Sustainability (Taking the Green Road) scenario could reduce demand by about 8 TWh.
- System-wide cost analysis shows that SSP1 yields cumulative savings of $9.41 billion compared with SSP2, while SSP5 increases total costs by $12.57 billion. These figures, calculated over the 2024-2060 period, underscore the economic benefits of climate mitigation.
- Targeted investments in efficient cooling, renewable energy, and regional infrastructure – especially in the Western and Southern regions – combined with both price and non-price behavioral nudge mechanisms, are critical to managing warming-driven electricity demand and supporting Saudi Arabia's 2060 net-zero targets.

Keywords: Climate Change, Cooling Demand, Electricity Consumption, Saudi Arabia, Regional Energy Modeling, IPCC Scenarios, SSP Pathways, Net-Zero Emissions, Energy Efficiency, Renewable Energy

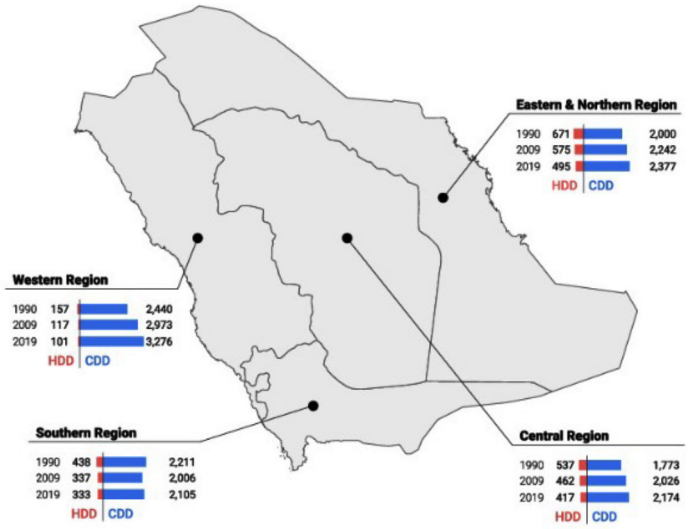
Introduction

Since the onset of the Industrial Revolution, greenhouse gas emissions have surged globally (IPCC 2021). This increase has led to significant shifts in temperature patterns worldwide, affecting socioeconomic conditions and energy systems. Saudi Arabia, situated in the Middle East, is particularly vulnerable to climate change. In 2018, the country's average temperature exceeded the 29-year historical average (Peerbocus et al. 2020). With its arid desert climate and proximity to the equator, Saudi Arabia experiences some of the highest temperatures on Earth (Lelieveld et al. 2016).

The Kingdom's energy profile is closely linked to its evolving climate conditions and socioeconomic development. Most of the population depends on cooling to maintain comfortable living conditions. Unsurprisingly, electricity demand is heavily driven by air conditioning (Howarth et al. 2020). Residential electricity demand accounts for nearly half of the Kingdom's total electricity consumption (Argaam 2025), with some regions exceeding the 50% mark. The growing number of high-temperature days poses challenges for power systems that must adapt to meet demand while aiming for long-term sustainability.

We utilize data on cooling degree days (CDD)[1] and heating degree days (HDD) from Mikayilov et al. (2020), and we extend it to the subsequent years. Figure 1 illustrates historical trends in CDD and HDD across various regions of Saudi Arabia for 1990, 2009, and 2019. It clearly demonstrates a significant increase in CDD values over the period, indicating that the climate is becoming warmer, leading to higher cooling demand. In the Western region, CDD rose notably from 2,440 in 1990 to 3,276 in 2019, marking the largest increase among the regions. Similarly, the Central region experienced a consistent increase in CDD, growing from 1,773 to 2,174 over the same period. The Eastern and Northern regions also saw an increase, with CDD rising from 2,000 to 2,377. Although the Southern region showed some fluctuations, the CDD remained relatively high overall.

Figure 1. Saudi Arabia CDD and HDD across time.



Source: Authors' calculation.

Saudi Arabia is committed to achieving net-zero carbon emissions by 2060 (Ministry of Energy 2021). Fulfilling this pledge requires a strategic approach centered on climate mitigation, with an emphasis on sustainable energy planning and low-carbon development pathways. A crucial element of this strategy is understanding how expected climate change in the country and developments in temperature scenarios will influence residential electricity demand. As temperatures rise, the demand for cooling in Saudi Arabia is expected to increase in both intensity and duration (Howarth et al. 2020). This trend presents a significant challenge for energy policymakers: balancing the rising demand for electricity with evolving load profiles driven by climate change. These changes could lead to supply challenges and potential grid instability, highlighting the importance of proactive planning. Conversely, accurately measuring and forecasting demand patterns under various temperature scenarios can guide strategic investments in system flexibility through market design, price signals that stimulate flexible demand response, smart grid infrastructure, and climate-resilient generation planning.

Recognizing the need to address energy consumption and environmental impact, Saudi Arabia has implemented various measures over the past decade to boost energy efficiency and reduce excessive electricity use. The establishment of the Saudi Energy Efficiency Center (SEEC) in 2010 aimed to promote awareness and encourage the adoption of efficient technologies, such as improved air-conditioning units, and to introduce energy efficiency labels. Through SEEC, the government has worked to foster a culture of energy conservation. Additionally, electricity price reforms in 2016 and 2018 marked significant policy shifts designed to cut subsidies that previously encouraged overconsumption (Mikayilov et al. 2020; Darandary, Mikayilov, and Soummane 2024). Looking forward, price and non-price policies should carefully consider the potential for inflation to offset reform impacts, suggesting that sustained real price increases integrated into reformed market and tariff design will be necessary to encourage load shifting and system flexibility. These reforms are part of broader structural changes under Saudi Vision 2030, which focuses on economic diversification and sustainability, and have significantly affected electricity consumption, costs, and carbon emissions, with average annual electricity consumption reductions of approximately 9% for the 2016-2019 period (Darandary Mikayilov, and Soummane 2024).

The Intergovernmental Panel on Climate Change (IPCC), established in 1988 by the United Nations Environment Program and the World Meteorological Organization, provides comprehensive assessments of climate science, impacts, and mitigation strategies. It synthesizes the latest climate research and offers periodic reports that inform policymakers about urgent environmental issues. The IPCC develops future climate scenarios that encompass a range of possible temperature increases based on varying levels of greenhouse gas emissions and socioeconomic pathways. These scenarios, known as Representative Concentration Pathways (RCPs), provide insights into how human activities might influence future temperatures and extreme weather events.

The IPCC's climate projections are particularly significant for Saudi Arabia, where high temperatures already pose environmental and social challenges. The country is highly vulnerable to the effects of global warming, which can intensify extreme temperatures, increase energy demand for cooling, and create challenges for public health, infrastructure, and economic resilience. According to the IPCC's latest report (2021), average temperatures in the Middle East are projected to rise more sharply than the global average, potentially increasing by 4-6°C by the end of the century if high-emission scenarios continue. This trend is expected to intensify heat waves and extend high-temperature periods, further increasing the already significant demand for cooling in Saudi Arabia's residential sector. The IPCC scenarios offer a valuable framework for understanding potential temperature increases in Saudi Arabia, depending on global emission trends and mitigation efforts.

Utilizing these projections, we explore how temperature increases could drive electricity demand for cooling, especially in regions where air conditioning is already prevalent. This exploration allows us to assess potential energy requirements under each scenario, providing insights into the investment needed in additional energy infrastructure, renewable resources, and energy efficiency measures to ensure a reliable supply while minimizing environmental impacts. This framework lays a foundation for planning and policy decisions that can address the energy challenges posed by climate change, supporting Saudi Arabia's broader sustainability and net-zero objectives.

Literature Overview

Several studies have explored the relationship between temperature and electricity demand in Saudi Arabia and the Gulf Cooperation Council (GCC) region. Atalla and Hunt (2016) modeled residential electricity demand as a function of its drivers, including CDD and HDD, for the Gulf Cooperation Countries (GCC).

The impact of HDD is significant only for Saudi Arabia, with an elasticity of 0.16. The CDD elasticities are 0.66, 0.58, and 0.50 for Bahrain, Oman, and Saudi Arabia, respectively, and are insignificant for Kuwait, Qatar, and the UAE. Howarth et al. (2020) modeled electricity generation as a function of temperature using regional data for Saudi Arabia. They found that for every 1°C increase in temperature, approximately 1.177 GW of additional power generation was needed.

However, at the regional level, these increases vary. For every 1°C increase in temperature, they estimate an increase in electricity generation of 334 MW (2.9% of average generation), 267 MW (2.0% of average power generation), 87 MW (2.4% of average generation), and 489 MW (4.6% of average generation) for the Central, Eastern, Southern, and Western regions, respectively. Analyzing historical temperature data from 1979 to 2018, they found a warming trend of 1.9°C over the period. The study reveals strong relationships between temperature and electricity demand, with significant regional and seasonal variations. The Western region showed the highest sensitivity to temperature changes.

Mikayilov et al. (2020) analyzed regional residential electricity demand in Saudi Arabia from 1990 to 2018, reporting long-run CDD elasticities of 0.51 for the Central region, 0.27 for the Eastern region, 0.75 for the Southern region, and 0.66 for the Western region. Only the Central region (0.16) and Eastern region (0.23) showed significant responses for HDD, while the Southern and Western regions had no significant heating demand response. Mikayilov et al. (2020) related the higher cooling impacts in regions with older housing stock (33% in the Southern region versus 22% in the Western region) and lower apartment density (30% in the Southern region versus 61% in the Western region). Heating effects were significant only in the Central and Eastern regions, potentially due to longer winters. Aldubyan and Gasim (2021) studied total residential electricity demand in Saudi Arabia (estimation period 1981-2018) and found the CDD elasticity to be 0.39. They concluded that Saudi Arabia's electricity demand significantly responds to temperature, highlighting the essential nature of cooling in the region's hot climate.

Mikayilov and Darandary (2024) modeled total electricity demand (sample period 1990-2019) for Saudi Arabian regions. They found that CDD only had a statistically significant impact in the Western region, with an elasticity of 0.57. They did not find HDD to be significant in any of the regions. They attributed the significant impact of CDD in the Western region to its status as the hottest region in Saudi Arabia and its highest share of electricity consumption in the residential sector.

Mikayilov and Al-Mestneer (2024) updated Mikayilov and Darandary's (2024) findings using revised census data and found statistically significant CDD impacts in two regions: Central (elasticity: 0.40) and Western (elasticity: 0.57). The authors explained the significant impact of CDD in the Central region, which has dry weather conditions, a hot climate, and a high share (50%) of villa-type houses. In contrast, the Western region is the hottest in the country and has a high population density. The revised analysis revealed new temperature sensitivities in the Central region while confirming previous findings for other regions.

We employ region-specific residential electricity demand models to forecast consumption patterns up to 2060, aligned with IPCC temperature scenarios for Saudi Arabia. The implications of this research extend beyond academic interest; they have practical significance for policymaking and energy strategy. The wider academic and policy community can derive valuable insights from this analysis, contributing to a growing body of literature on climate adaptation in energy systems (Pachauri and Meyer 2014). This approach ensures that Saudi Arabia can address the dual challenges of meeting growing energy security needs and advancing its net-zero agenda.

Regional Temperature Variability

Saudi Arabia spans approximately 2.15 million square kilometers, which results in significant regional weather variations due to its vast size and diverse topography. Because of its proximity to the equator, the Kingdom is known for its hot climate conditions. Table 1 summarizes the temperature data in two periods (1990-2005 and 2006-2020) for the summer and winter.

Table 1. Mean temperature for Saudi Arabian regions (1990-2020).

	Central		Eastern		Southern		Western	
Period	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
1990-2005	36.39	16.03	36.95	15.18	30.61	22.58	34.11	21.91
2006-2020	37.16	16.50	37.79	15.58	31.42	23.02	35.05	22.79
Delta temp	0.76	0.47	0.84	0.41	0.81	0.44	0.94	0.88
% Change	2.1%	2.9%	2.3%	2.7%	2.6%	2.0%	2.8%	4.0%

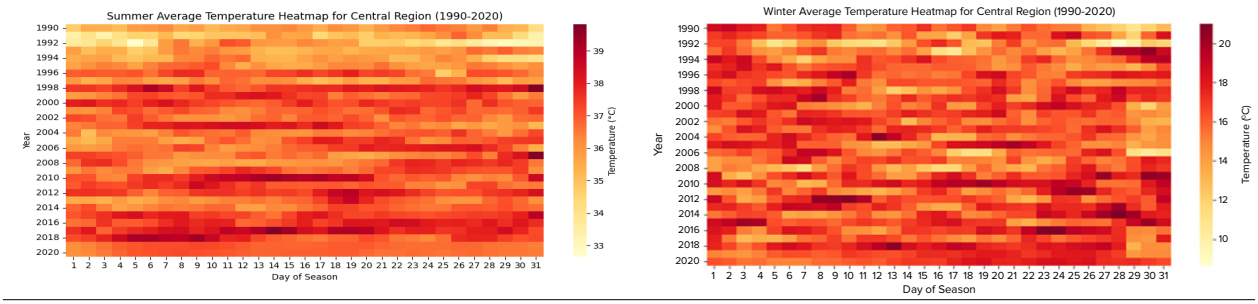
Note: The temperature data used for the weather variability are the same as those used in Mikayilov et al. (2020), with two additional updated years ending in 2020.

All regions of Saudi Arabia have experienced a similar warming trend in both summer and winter. The Central, Eastern, Southern, and Western regions recorded average summer temperature increases of 0.76°C, 0.84°C, 0.81°C, and 0.94°C, respectively, along with average winter temperature increases of 0.47°C, 0.41°C, 0.44°C, and 0.88°C. The Western region had the highest winter increase at 4.0%, indicating significant warming during the colder months. Overall, while summer periods showed slightly higher temperature increases, winter warming was particularly pronounced in the Western region, reflecting the broader impacts of climate change in Saudi Arabia.

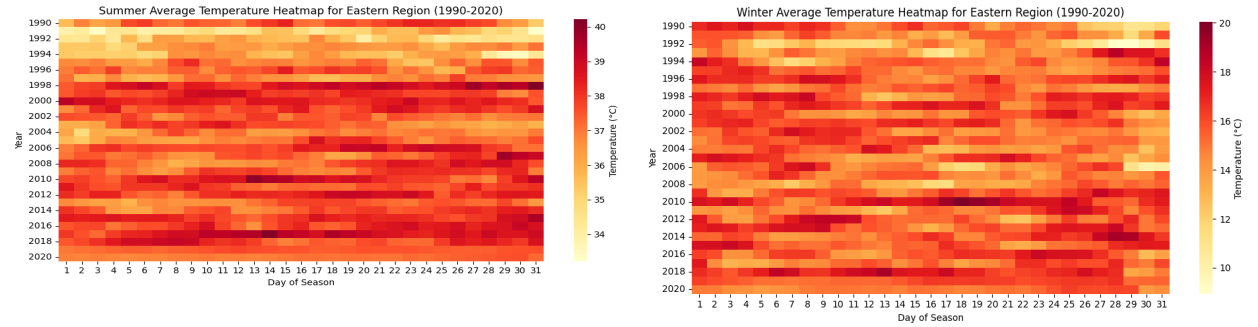
The heatmaps in Figure 2 illustrate significant warming trends over time across Saudi Arabia during both summer (June, July, August) and winter (December, January, February). On a national level, the average summer temperature has risen by 1.54°C, indicating a notable warming trend during the hottest months. Similarly, a 1.54°C increase in winter temperatures suggests consistently milder winters, highlighting year-round warming.

Figure 2. Temperature heatmaps for Saudi Arabia's regions (1990-2020).

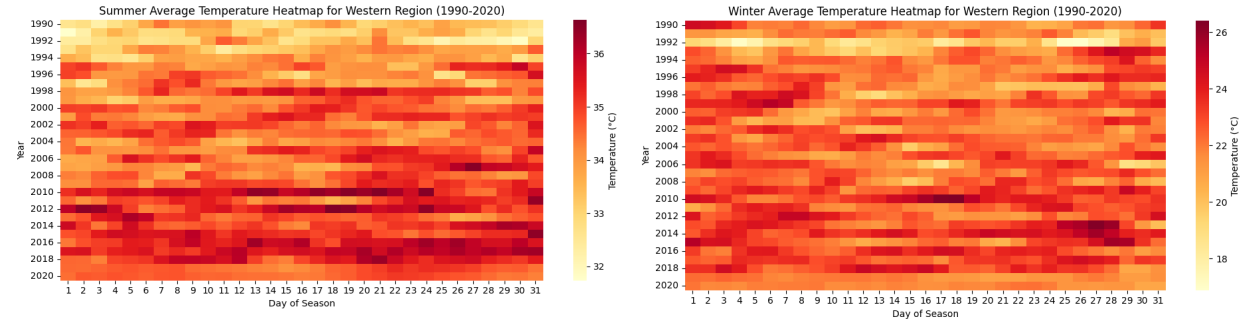
a) Central region



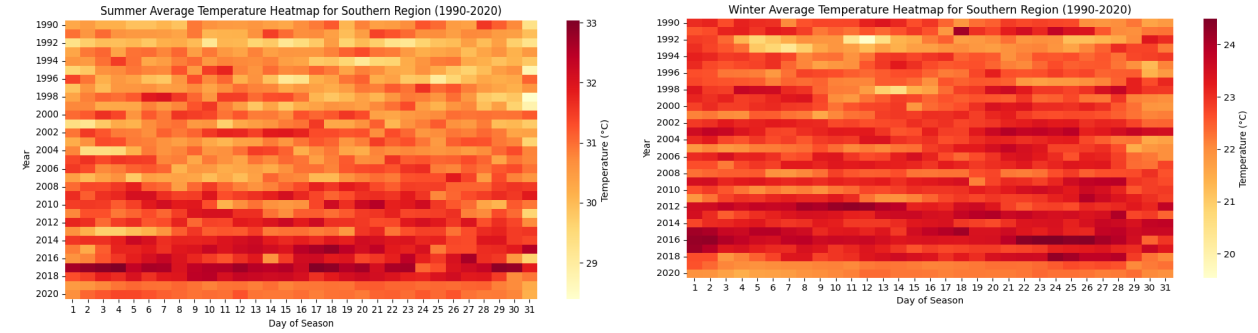
b) Eastern region



c) Western region



d) Southern region



Source: The temperature data used for the weather variability are the same as those used in Mikayilov et al. (2020), with two additional updated years ending in 2020.

In the Central region, summer temperatures rose by 1.75°C, exceeding the national average and signaling a strong warming trend. Winter warming in the Central region was even more pronounced, with a temperature increase of 2.12°C, potentially reducing extreme cold events and altering local climate patterns. In contrast, the Eastern region experienced moderate summer warming of 0.63°C, indicating less intense temperature increases than other regions. However, winter temperatures in the East rose significantly by 1.80°C, suggesting a marked shift in winter climate conditions. The Southern region saw a temperature increase of 1.38°C, reflecting moderate summer warming. This region also experienced the smallest increase during winter, at 0.56°C, indicating a slower warming trend and potentially less impact on winter conditions.

The Western region recorded the highest increase at 2.00°C, indicating a marked summer warming trend that likely leads to more extreme heat conditions and increased energy demand. Additionally, winter temperatures rose significantly by 1.30°C, demonstrating a noticeable warming trend.

Table 2 summarizes temperature changes at both national and regional levels, revealing several key insights. Summer warming is generally more intense in the Western and Central regions, while winter warming is particularly pronounced in the Central and Eastern regions. The data highlights significant regional variations in how climate change impacts different parts of Saudi Arabia, emphasizing the importance of developing region-specific adaptation strategies to effectively address each region's unique challenges and vulnerabilities.

Table 2. Summary of the temperature changes.

Region	overall change (°C)	Summer change (°C)	Winter change (°C)
KSA	1.55	1.54	1.54
Central	1.59	1.75	2.12
Eastern	1.41	0.63	1.80
Southern	1.23	1.38	0.56
Western	1.78	2.00	1.30

Temperature Scenarios for Saudi Arabia Corresponding to Global SSP Scenarios

The SSPs provide various scenarios for future temperature changes in Saudi Arabia.

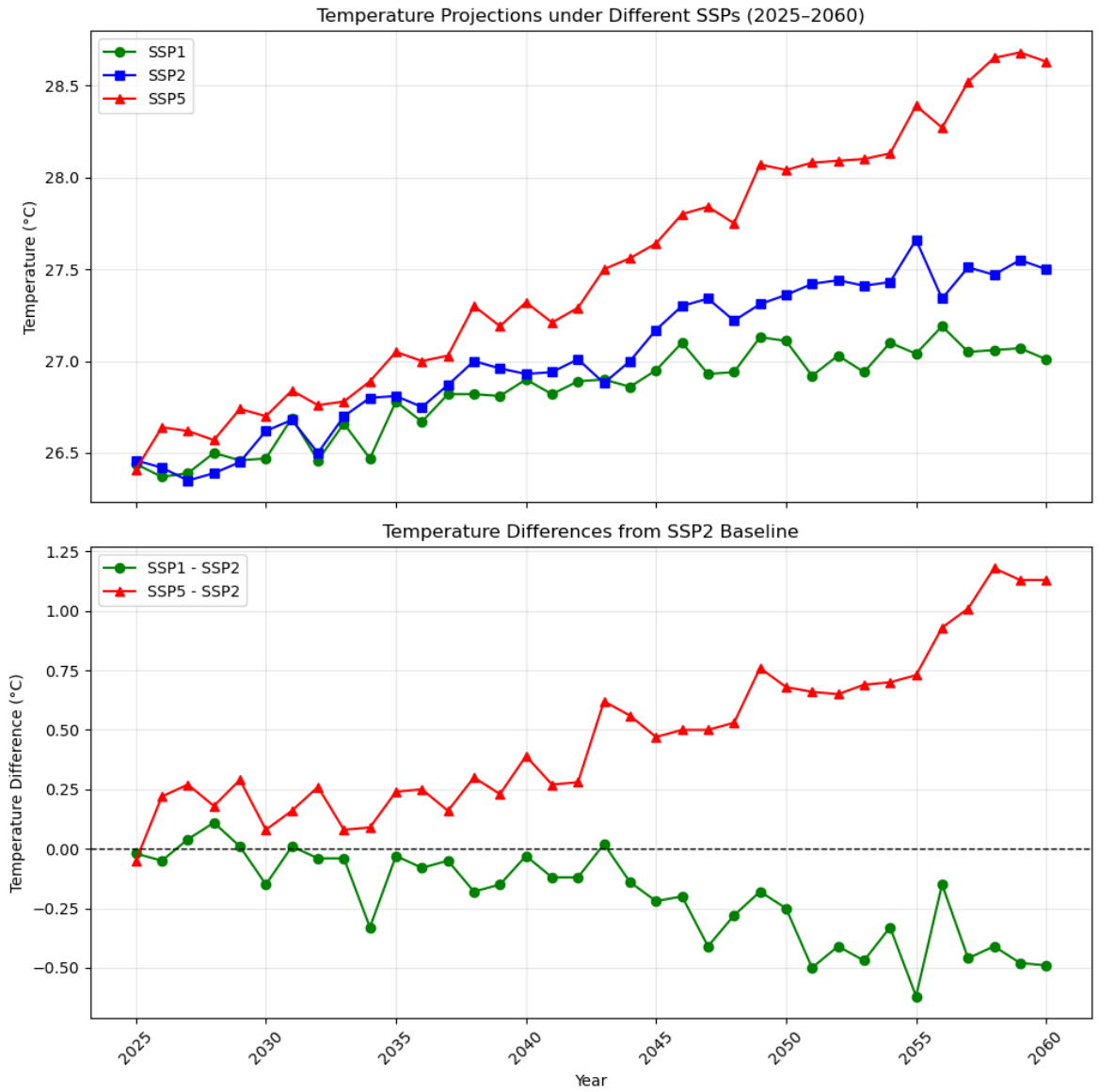
SSP1 – Sustainability (Taking the Green Road): This scenario envisions a future characterized by rapid environmental improvements, driven by significant investments in green technologies and sustainable practices. As a result, it leads to moderated temperature increases and a more resilient climate system.

SSP2 – Middle of the Road: This scenario features moderate socioeconomic and environmental changes, projecting steady growth with incremental progress in sustainability measures. Consequently, it results in intermediate temperature trends.

SSP5 – Fossil-fueled Development (Taking the Highway): In contrast, this pathway assumes continued reliance on fossil fuels and rapid economic growth, with minimal emphasis on environmental protection. This leads to more pronounced temperature increases and heightened climate impacts.

Figure 3 illustrates the temperature trends for Saudi Arabia corresponding to the Global SSP scenarios from 2025 to 2060. Table 3 provides a summary of the scenario statistics.

Figure 3. Temperature scenarios for Saudi Arabia corresponding to the Global SSP scenarios.



Source: Authors' data based on World Bank Group (2024).

Table 3. Summary statistics for SSP scenarios.

	count	mean	std	min	25%	50%	75%	max
SSP1	36	26.826	0.243	26.370	26.668	26.895	27.033	27.190
SSP2	36	27.026	0.389	26.350	26.738	27.000	27.373	27.660
SSP5	36	27.502	0.684	26.410	26.878	27.410	28.083	28.680

Empirical Estimations

Relation of Regional Cooling Degree Days to Temperature

This paper utilizes regional residential electricity models developed by Mikayilov et al. (2020) for forecasting purposes. Mikayilov et al. (2020) employed cooling degree days (CDD) as an indicator of weather conditions. To assess the impact of Shared Socioeconomic Pathways (SSP) temperature scenarios on electricity demand, we must connect average temperature to regional CDD indicators.

Accordingly, we modeled regional CDDs as a function of average annual temperature. In these modeling exercises, a maximum lag of 4 was selected based on sample size, and the optimal lag was determined using selection criteria alongside a set of diagnostic tests. The following specification was used for modeling:

$$\mathrm{CDD}_{r,t} = a_0 + \sum_{k=0}^{4} b_k \mathrm{Temp}_{r,t-k} + \epsilon_{r,t} \qquad (1)$$

Where, $\mathrm{CDD}_{r,t}$ stands for CDD for region r at time t; $\mathrm{Temp}_{r,t-k}$ is the temperature in region r, at time t-k; $\epsilon_{r,t}$ is a region-specific error term.

The World Bank Group (2024) sourced historical reference temperature data. Using the general-to-specific (GETS) modeling approach (see Hendry and Doornik 2014, among others), we modeled regional humidity-adjusted CDD numbers based on average temperature. The results are presented in Table 4.

Table 4. The impact of reference temperature on the annual regional cooling degree days.

Region	Central	Eastern	Southern	Western
Coefficient	361.500	435.210	295.379	644.880
p-values	0.000	0.000	0.001	0.000
R-square	0.740	0.735	0.872	0.706
# of observations	29	29	29	29

The coefficients in the table indicate the sensitivity of CDD to changes in average temperature for each region of Saudi Arabia. They represent how much the annual CDD will increase in response to a 1°C rise in average temperature, specifically how many degrees are needed annually to cool indoor temperatures to 21°C. Higher coefficients suggest that a region's CDD is more responsive to temperature changes, implying greater cooling demand as temperatures rise. The Western region has the highest CDD sensitivity to temperature increases, followed by the Eastern, Central, and Southern regions.

These differences highlight how regional climate characteristics influence the extent to which temperature increases drive cooling demand across Saudi Arabia. Regions with higher coefficients, such as the Western region, would experience a more significant rise in cooling requirements with even minor temperature increases, affecting electricity demand and cooling infrastructure needs in those areas.

Using the estimated models and SSP scenarios for temperature from the World Bank Group (2024), we have

projected the CDD scenarios for each region of Saudi Arabia through 2060. Specifically, we utilized the SSP1 – Sustainability (Taking the Green Road), SSP2 – Middle of the Road, and SSP5 – Fossil-Fueled Development (Taking the Highway) temperature scenarios to estimate the corresponding CDD projections.

How Temperature Impacts Electricity Demand

Using the CDD elasticities of electricity demand from Mikayilov et al. (2020) and the temperature-CDD relationship results from Table 3, we calculated the temperature semi-elasticities of electricity demand. Semi-elasticity refers to the percentage change in electricity demand resulting from a one-unit change in the temperature metric, in this case, CDD. By leveraging the CDD elasticities derived from our analysis, we quantify how sensitive electricity demand is to variations in temperature through CDD. This provides a nuanced understanding of the relationship between temperature fluctuations and electricity usage, offering insights into how climatic factors drive energy consumption patterns. The results are presented in Table 5.

Table 5. The impact of temperature on electricity consumption.

Region	Central	Eastern	Southern	Western
Semi-elasticity, %	8.3	4.8	10.3	12.9

Source: Authors' estimation results.

The provided semi-elasticities indicate the percentage change in residential electricity consumption resulting from a 1°C increase in temperature across different regions of Saudi Arabia. An 8.3% increase in the Central region suggests moderate to high sensitivity to temperature changes. This region experiences hot summers and cold winters, leading to substantial use of air-conditioning and heating systems. Dense populations and urban lifestyles in major cities like Riyadh contribute to higher energy demand. In contrast, the smallest increase among the regions is in the Eastern region (4.8%), indicating a relatively lower sensitivity to temperature changes. Proximity to the Arabian Gulf may moderate temperature extremes and reduce reliance on cooling systems. Additionally, significant industrial activity in the Eastern region may dominate overall electricity consumption, making residential temperature sensitivity less pronounced.

A 10.3% increase in the Southern region reflects a strong response to temperature changes. The diverse climates, including cooler highlands and hotter lowlands, lead to varying energy needs. The relatively high CDD elasticity observed in the Southern region may seem counterintuitive given the area's mountainous terrain and milder climate conditions. The southern highlands, including Abha and Aseer, are characterized by cooler summers and serve as popular seasonal destinations, suggesting lower cooling demands than in other regions.

Several factors may explain this high elasticity. First, the mountainous geography and milder climate may lead households to underestimate their cooling needs, resulting in delayed investment in efficient cooling equipment. When temperature increases occur, older or less efficient air-conditioning systems respond more aggressively to heat, creating higher elasticity of demand.

Second, regional differences in energy efficiency adoption patterns provide additional context. Darandary and Belaïd (2024) demonstrate that Southern regions exhibit the lowest responsiveness to energy-efficient appliance adoption compared to other areas. This finding is consistent with Mikayilov et al. (2020), who show that the Underlying Energy Demand Trend (UEDT) – a proxy for residential electricity efficiency – indicates relatively poor performance in the Southern region.

Additionally, methodological factors may contribute to the observed pattern. The apparent discrepancy between our own temperature-CDD estimates, where the Southern region shows the smallest effect (Table 4), and findings from Mikayilov et al. (2020) – where the Southern region exhibited the largest CDD impact – may reflect differences in data coverage and updated population figures revealing substantial regional changes over time.

The combination of these behavioral, technological, and methodological factors suggests that while the Southern region experiences milder temperatures overall, multiple mechanisms may contribute to the observed high elasticity of electricity demand in response to temperature changes. Rural and urban disparities might affect energy consumption patterns, with temperature increases significantly impacting cooling demand. The largest increase in the Western region (12.9%) indicates a very strong responsiveness to temperature changes. Cities like Mecca and Medina attract millions of visitors, amplifying electricity demand, especially during hotter periods. High temperatures and humidity levels increase dependence on air conditioning.

Projecting Electricity Demand

Assumptions for Demand Projections

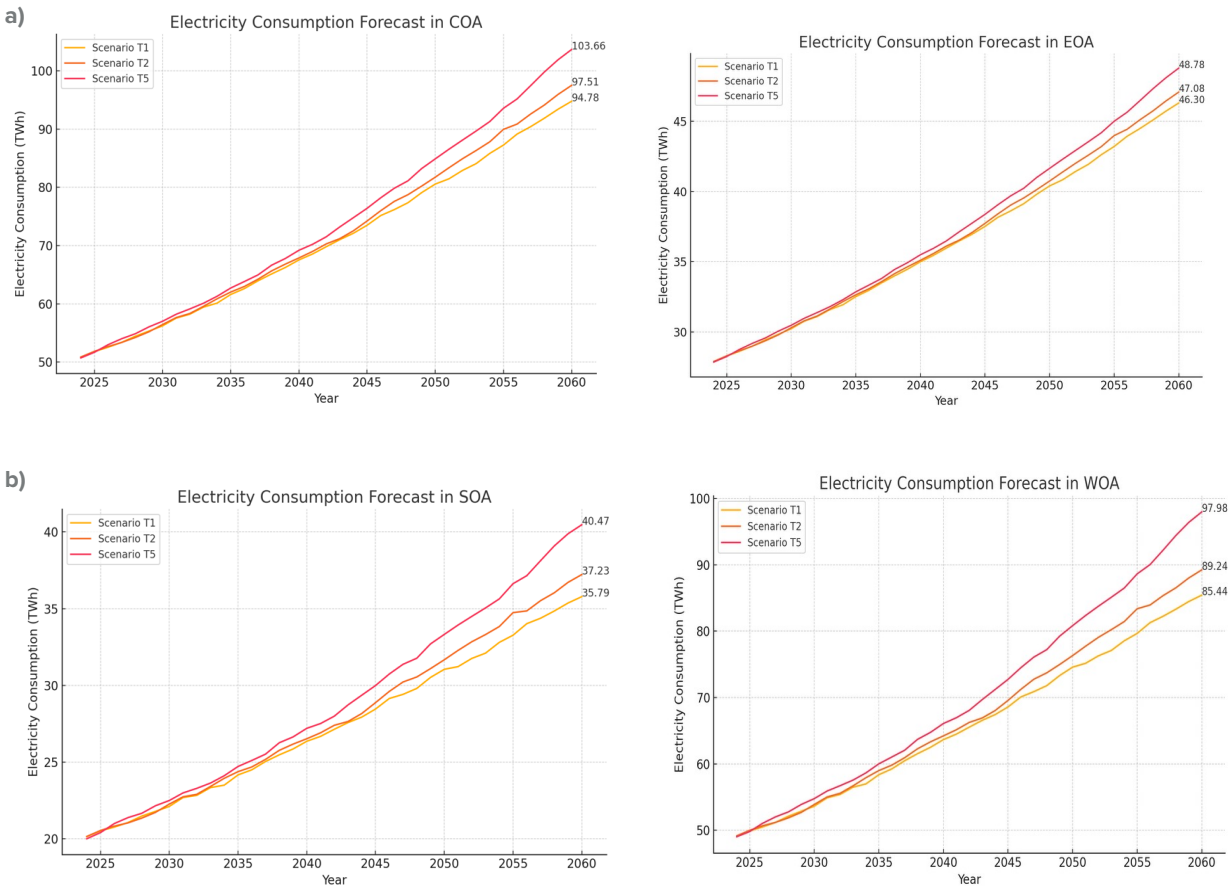
To project electricity demand through 2060, we made the following assumptions about the inputs:

- Regional CDD figures: Estimated using the SSP1, SSP2, and SSP5 temperature scenarios from the World Bank Group (2024).
- Regional electricity prices: Fixed at the 2022 nominal level. We assumed 2% annual inflation, meaning that, in real terms, prices decrease over time.
- Regional GDP numbers: Based on the last 10-year average growth.
- Regional population: Based on the last five-year average growth, using new population data from the General Authority for Statistics census (GASTAT 2023).
- HDD: Based on historical average growth.
- Regional underlying energy demand trends (UEDT): Kept constant at 2018 levels.

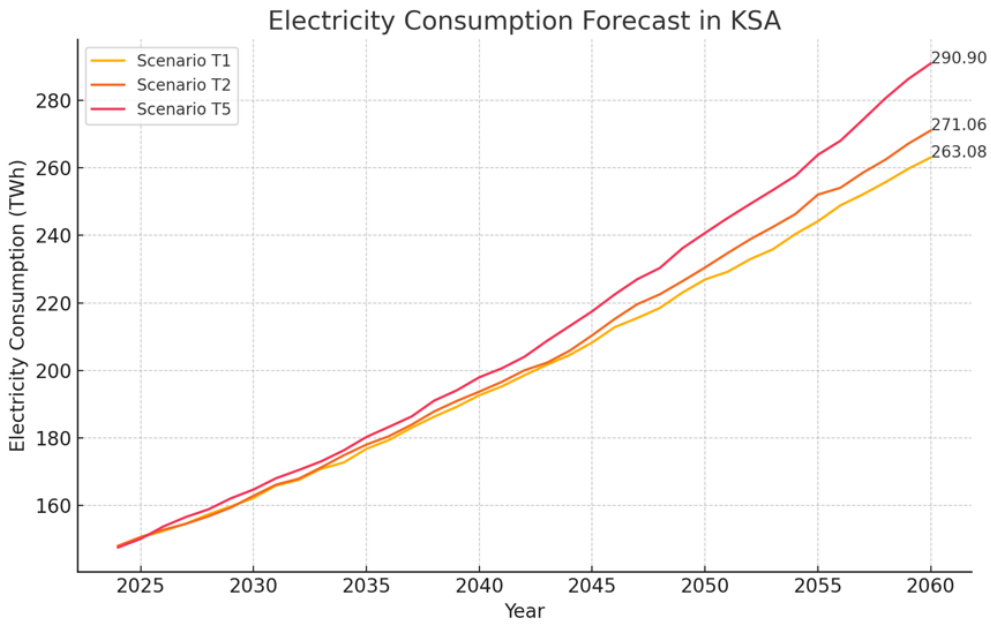
Projection Results and Discussion

Using the estimated CDD scenarios across the SPP temperature scenarios, we have projected electricity demand figures through 2060. Figures 4a-c present projections of residential electricity demand across regions for the three SSP scenarios: T1, T2, and T5, which correspond to SSP1, SSP2, and SSP5, respectively. Figure A1 in the Appendix shows demand projections for a selected years. Figure 5 compares the outputs of the SSP1 and SSP5 scenarios with those of the SSP2 scenario for the overall Kingdom using a heatmap.

Figure 4. Residential electricity consumption projections.

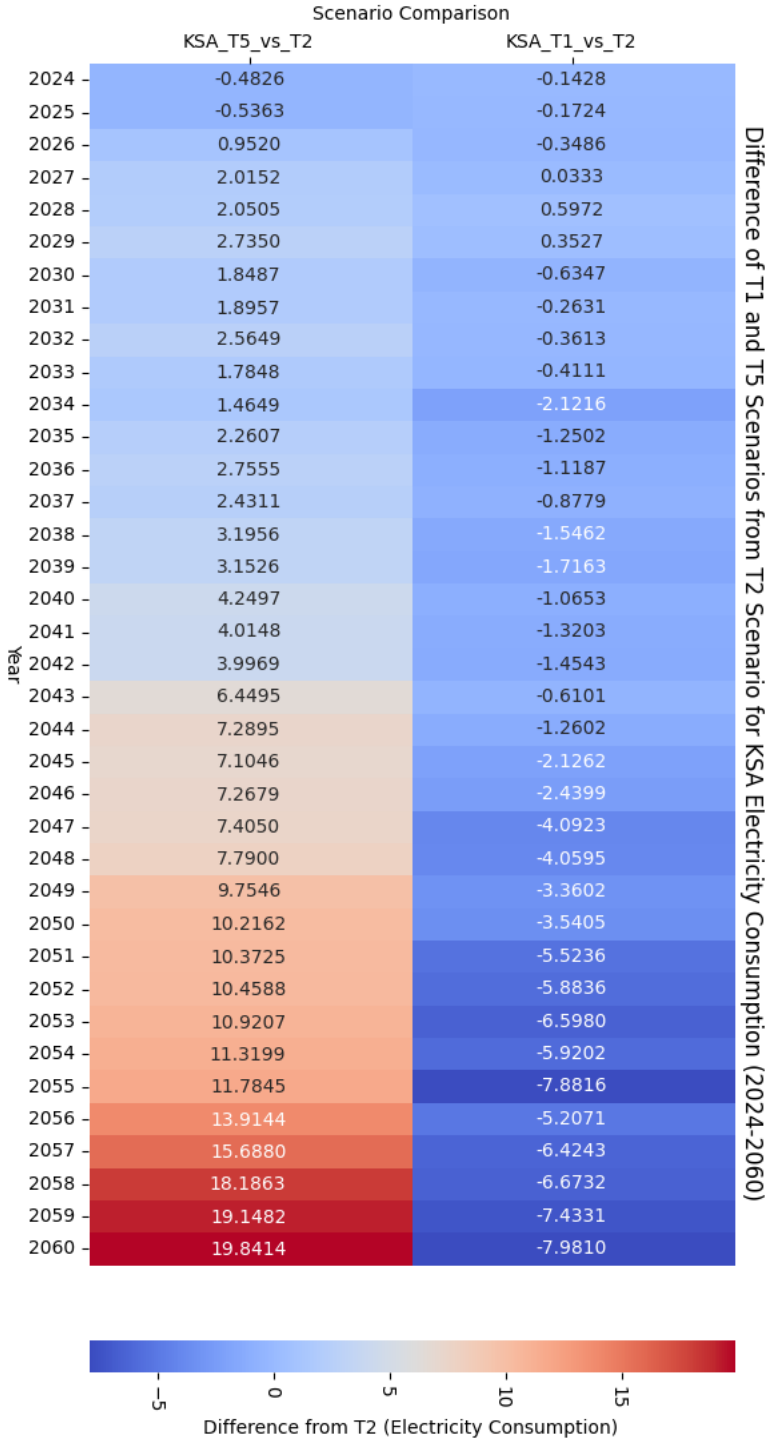


c)



Source: Authors' projections results.

Figure 5. Comparison of scenarios (T2 and T5 vs T1) in electricity consumption.



Source: Authors' design based on the projection results.

As previously mentioned, the heatmap illustrates the differences in electricity consumption between SSP1 (T1) and SSP5 (T5) relative to SSP2 (T2) for KSA.

When comparing SSP1 (T1) to SSP2 (T2), we observe negative differences (blue gradient): SSP1 consistently demonstrates lower electricity consumption than SSP2 throughout the entire period. The differences begin modestly, around -0.14 in 2024, but grow significantly over time, reaching approximately -7.98 by 2060. This widening gap indicates a substantial reduction in electricity consumption under the Sustainability (Taking the Green Road) (SSP1) scenario compared to the Middle of the Road (SSP2) scenario. The SSP1 scenario emphasizes energy efficiency, sustainable practices, and a shift toward greener technologies, resulting in a continuous decrease in electricity demand compared to SSP2, which reflects moderate technological adoption and policy actions. The notable reduction in electricity consumption aligns with aggressive sustainability measures aimed at mitigating climate change and promoting energy conservation.

In contrast, when comparing SSP5 (T5) and SSP2 (T2), we see positive differences (red gradient): SSP5 displays higher electricity consumption compared to SSP2. The differences start at a moderate level, around 0.18 in 2024, and increase sharply to about 19.84 by 2060. This trend indicates a significant rise in electricity consumption under the Fossil-Fueled Development (Taking the Highway) (SSP5) scenario compared to SSP2. SSP5 represents a pathway characterized by high economic growth driven by extensive fossil fuel use and minimal efforts in energy conservation or transition to greener technologies. The sharp increase in electricity consumption reflects a reliance on energy-intensive technologies and practices, resulting in higher overall demand.

Power System Cost Implications

As residential cooling demand rises due to climate warming, the strain extends beyond households, placing increased pressure on national infrastructure and long-term fiscal resources. To assess this broader impact, we evaluate the power system costs and generation composition associated with different climate scenarios using a power system model that incorporates electricity demand projections and Saudi Arabia's 2060 net-zero emissions commitment.

We utilize the power system optimization model developed by Alhadhrami et al. (2025) to support Saudi Arabia's net-zero target by 2060. This model minimizes total electricity system costs from 2024 to 2060, subject to constraints on energy demand, emissions, and technology deployment. The evolution of Saudi Arabia's electricity mix is derived from a Generation and Transmission Capacity Expansion Model (GTCEP) with hourly temporal resolution, implemented using PLEXOS software. It encompasses various generation and storage technologies, including solar, wind, natural gas (with and without CCS), and batteries.

Among the tested pathways, achieving net-zero with 10 $MtCO_2$ of removals via carbon dioxide removal (CDR) was identified as the most cost-effective strategy, assuming a CDR cost of $500 per ton. We adopt this scenario as our base model and apply three demand pathways (T1, T2, T5) to assess how warming-driven electricity demand affects system costs and the generation mix under a net-zero strategy.

Table 6 summarizes the average annual system costs by decade and the total costs for the 2024-2060 period. The analysis indicates that higher warming pathways significantly increase system costs. T1 has the lowest total system cost at $221.25 billion, followed by T2 at $230.66 billion, while T5 incurs the highest cost at $243.23 billion. Compared to the baseline, T1 offers savings of $9.41 billion over the entire period from 2024 to 2060. In contrast, T5 results in an additional cost of $12.57 billion due to increased electricity demand and the necessary infrastructure expansion to support it.

Table 6. Average annual system cost by scenario and time period (in billion $).

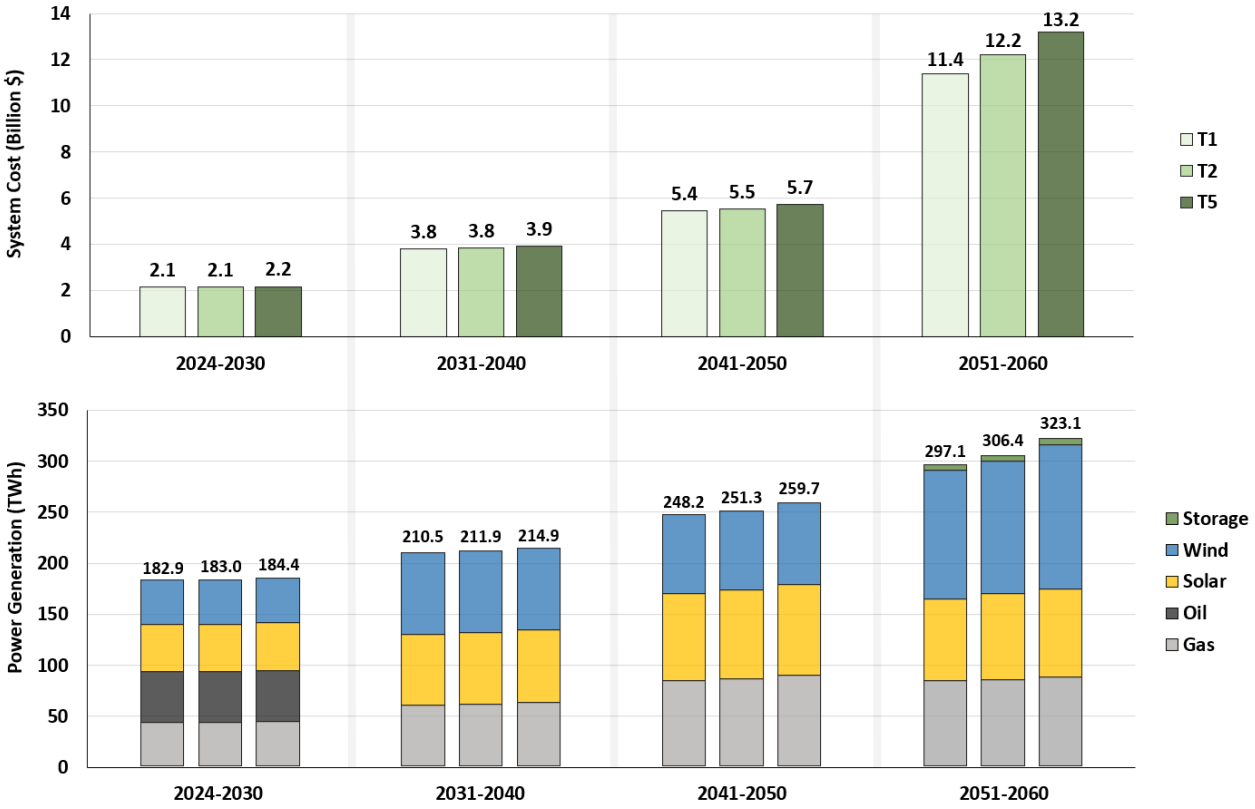
Scenarios	2024-2030	2031-2040	2041-2050	2051-2060	Full period
Average annual system (in billion $)					**Total Cost**
T1	2.14	3.78	5.44	11.40	221.25
T2	2.14	3.83	5.52	12.22	230.66
T5	2.16	3.91	5.72	13.18	243.23
Differences in average annual system cost (in billion $)					**Difference**
T5 – T2	0.01	0.08	0.21	0.96	12.57
T1 – T2	0.00	-0.04	-0.08	-0.82	-9.41

Source: Authors based on Alhadhrami et al. (2025).

The generation mix and system costs evolve significantly across scenarios in response to rising electricity demand and the constraints of a net-zero future (Figure 6). In the early period (2024-2030), oil (heavy fuel and crude) and natural gas dominate the electricity supply. While all liquid fuels are phased out by 2030, gas remains a significant contributor throughout this period. Over time, the system shifts toward greater reliance on renewables – especially wind and solar, which collectively surpass natural gas in total generation by 2051-2060 across all scenarios. However, gas-fired generation still contributes 84-87 TWh during this timeframe, reflecting its role in providing flexible capacity. Battery storage technologies begin to contribute in the final period but remain modest, accounting for about 2% of total generation.

These shifts in generation technology directly impact system costs. As shown in Table 6, costs rise consistently over time in all scenarios, driven by growing electricity demand. From 2024 to 2030, average system costs are nearly identical across all scenarios (around $2.14 to $2.16 billion per year). However, differences widen in later decades: by 2051-2060, average annual costs rise to $11.40 billion in T1, $12.22 billion in T2, and $13.18 billion in T5. Compared to the baseline (T2), T1 saves $0.82 billion per year in the final decade, while T5 incurs nearly $1 billion more per year. The middle periods show smaller but consistent trends: T5 is always more expensive, and T1 consistently offers cost savings relative to T2, particularly after 2030. These results confirm that more aggressive warming pathways lead to higher infrastructure and energy system costs.

Figure 6. Average annual system cost (billion $) vs. average annual power generation (TWh).



Note: Gas refers to natural gas. Oil includes heavy fuel and crude. Solar encompasses both photovoltaic (PV) panels and concentrated solar power (CSP) technologies. Wind refers to onshore wind turbines. Storage includes energy storage systems with durations of 2, 4, and 10 hours.
Source: Authors based on Alhadhrami et al. (2025).

This shift in the generation mix reflects not only the technical requirements for achieving net zero under higher demand but also the financial implications. The T5 scenario requires more aggressive grid expansions and investments in flexible capacity, which further inflate total system costs. In contrast, the T1 scenario allows for a smoother decarbonization trajectory, resulting in lower peak capacity requirements and reduced overall system costs.

Conclusion

This study provides critical insights into how climate change is likely to impact residential electricity demand across Saudi Arabia's regions through 2060. Our analysis reveals significant regional disparities in temperature sensitivity, with the Western region demonstrating the highest vulnerability (a 12.9% increase in electricity demand per 1°C), followed by the Southern (10.3%), Central (8.3%), and Eastern (4.8%) regions. Under the temperature scenario corresponding to the global fossil-fuel-intensive SSP5 scenario, nationwide cooling-related electricity consumption could surpass the moderate-growth SSP2 baseline by nearly 20 TWh by 2060 – equivalent to an annual average difference of 8.7 TWh between 2024 and 2060.

Conversely, under the sustainability-focused SSP1 scenario, electricity demand could decrease by approximately 8 TWh relative to SSP2 by 2060, providing annual average savings of 3.4 TWh. Regionally, the Western region faces the largest increase in electricity demand (9 TWh) under the SSP5 scenario, emphasizing its heightened vulnerability. By testing the same scenarios using a power system optimization model, we demonstrate that a sustainable pathway (T1) minimizes long-term system costs, saving $9.41 billion compared to the baseline (T2), and reduces infrastructure burdens under rising electricity demand, which increases total system costs by up to $22 billion across scenarios.

These findings highlight the importance of proactive, targeted policy interventions. It is recommended that policies prioritize investments in infrastructure and grid capacity expansions for temperature-sensitive regions, particularly the Western and Southern areas. To ensure that the benefits of stricter building efficiency standards and the adoption of advanced energy-efficient appliances are fully realized, it is essential to complement these measures with appropriate pricing signals and supportive non-price policies that help mitigate rebound effects and sustain energy savings.

Rapidly expanding renewable energy resources is crucial to sustainably meeting increased cooling demand while aligning with Saudi Arabia's 2060 net-zero goals. Future research could enrich policy development by incorporating socioeconomic factors, such as urbanization trends, income levels, housing characteristics, and the role of energy prices, examining the intersection of the water-energy nexus, and exploring impacts from extreme weather events beyond average temperature changes. Such comprehensive analyses will help Saudi Arabia navigate a path toward a secure, affordable, and sustainable energy future in the face of escalating climate risks.

Endnote

[1] CDD and HDD are used as proxies for climatic indicators in economic modeling. They quantify how much the outside air temperature exceeds a base temperature (typically 21.1°C for cooling and 18.3°C for heating) (Atalla and Hunt 2016).

References

Aldubyan, Mohammad, and Anwar Gasim. 2021. "Energy Price Reform in Saudi Arabia: Modeling the Economic and Environmental Impacts and Understanding the Demand Response." *Energy Policy* 148, Part B: 111941. https://doi.org/10.1016/j.enpol.2020.111941.

Alhadrami, Khalid, Marie Petitet, Sarah Abuouf, Abdulelah Darandary, Timothy Laing, Frank A. Felder, and Amro M. Elshurafa. 2025. "Are There Adequate Materials and Land Resources for the Saudi Power Sector to Achieve Net Zero by 2060?". Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://doi.org/10.30573/KS--2024-DP58.

Argaam. 2025. "Saudi Arabia's Electricity Consumption Rises 5.7% in 2023." April 1. https://www.argaam.com/en/article/articledetail/id/1801864.

Atalla, Tarek N., and Lester C. Hunt. 2016. "Modelling Residential Electricity Demand in the GCC Countries." *Energy Economics* 59: 149–158. https://doi.org/10.1016/j.eneco.2016.07.027.

Darandary, Abdulelah, Jeyhun I. Mikayilov, and Salaheddine Soummane. 2024. "Impacts of Electricity Price Reform on Saudi Regional Fuel Consumption and CO_2 Emissions." *Energy Economics* 131: 107400. https://doi.org/10.1016/j.eneco.2024.107400.

Darandary, Abdulelah, and Fateh Belaïd. 2024. "Decoding the Behavioral Patterns in Saudi Arabia from GASTAT's Five Year Household Energy Statistics Survey." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://www.kapsarc.org/our-offerings/publications/decoding-the-behavioral-patterns-in-saudi-arabia-from-gastat-s-five-year-household-energy-statistics-survey.

General Authority for Statistics (GASTAT). 2023. *Population Summary Report* (Saudi Census 2022). https://portal.saudicensus.sa/static-assets/media/content/20230531_GASTAT_Population_Report.pdf?crafterSite=gastat-portal.

Hendry, David F., Doornik, Jurgen A. 2014. *Empirical Model Discovery and Theory Evaluation: Automatic Selection Methods in Econometrics*. Cambridge MA: The MIT Press. https://doi.org/10.7551/mitpress/9780262028356.001.0001.

Howarth, Nicholas, Natalia Odnoletkova, Thamir Alshehri, Abdullah Almadani, Alessandro Lanza, and Tadeusz Patzek. 2020. "Staying Cool in a Warming Climate: Temperature, Electricity and Air Conditioning in Saudi Arabia." *Climate* 8 (1): 4. https://doi.org/10.3390/cli8010004.

Intergovernmental Panel on Climate Change (IPCC). 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by Valérie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L. Connors, Clotilde Péan, Sophie Berger, Nada Caud, Yuxuan Chen, Linda Goldfarb, María Isabel Gomis, Mingsheng Huang, Kristina Leitzell, Elayne Lonnoy, Jonathan B.R. Matthews, Timothy K. Maycock, Tom Waterfield, Ozlem Yelekçi, Rong Yu, and Baohua Zhou. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157896.

Lelieveld, J., Y. Proestos, P. Hadjinicolaou, M. Tanarhte, E. Tyrlis, and G. Zittis. 2016. "Strongly Increasing Heat Extremes in the Middle East and North Africa (MENA) in the 21st Century." *Climatic Change* 137 (1–2): 245–260. https://doi.org/10.1007/s10584-016-1665-6.

Mikayilov, Jeyhun I., Abdulelah Darandary, Ryan Alyamani, Fakhri J. Hasanov, and Hatem Alatawi. 2020. "Regional Heterogeneous Drivers of Electricity Demand in Saudi Arabia: Modeling Regional Residential Electricity Demand." *Energy Policy* 146: 111796. https://doi.org/10.1016/j.enpol.2020.111796.

Mikayilov, Jeyhun I., and Abdulelah Darandary. 2024. "Modelling and Projecting Regional Electricity Demand for Saudi Arabia." *OPEC Energy Review* 48 (4): 261–277. https://doi.org/10.1111/opec.12312.

Mikayilov, Jeyhun I., and Raed A. Al-Mestneer. 2024. "How the Census 2022 Results Changed the Outlook for Electricity Demand." Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://doi.org/10.13140/RG.2.2.24135.92325.

Ministry of Energy. 2021. "Saudi Arabia's Commitment to Achieving Net Zero Carbon Emissions by 2060 Announced at the Saudi Green Initiative Forum." https://www.sgi.gov.sa/saudi-global-climate-Impact/?csrt=5076408404566978375.

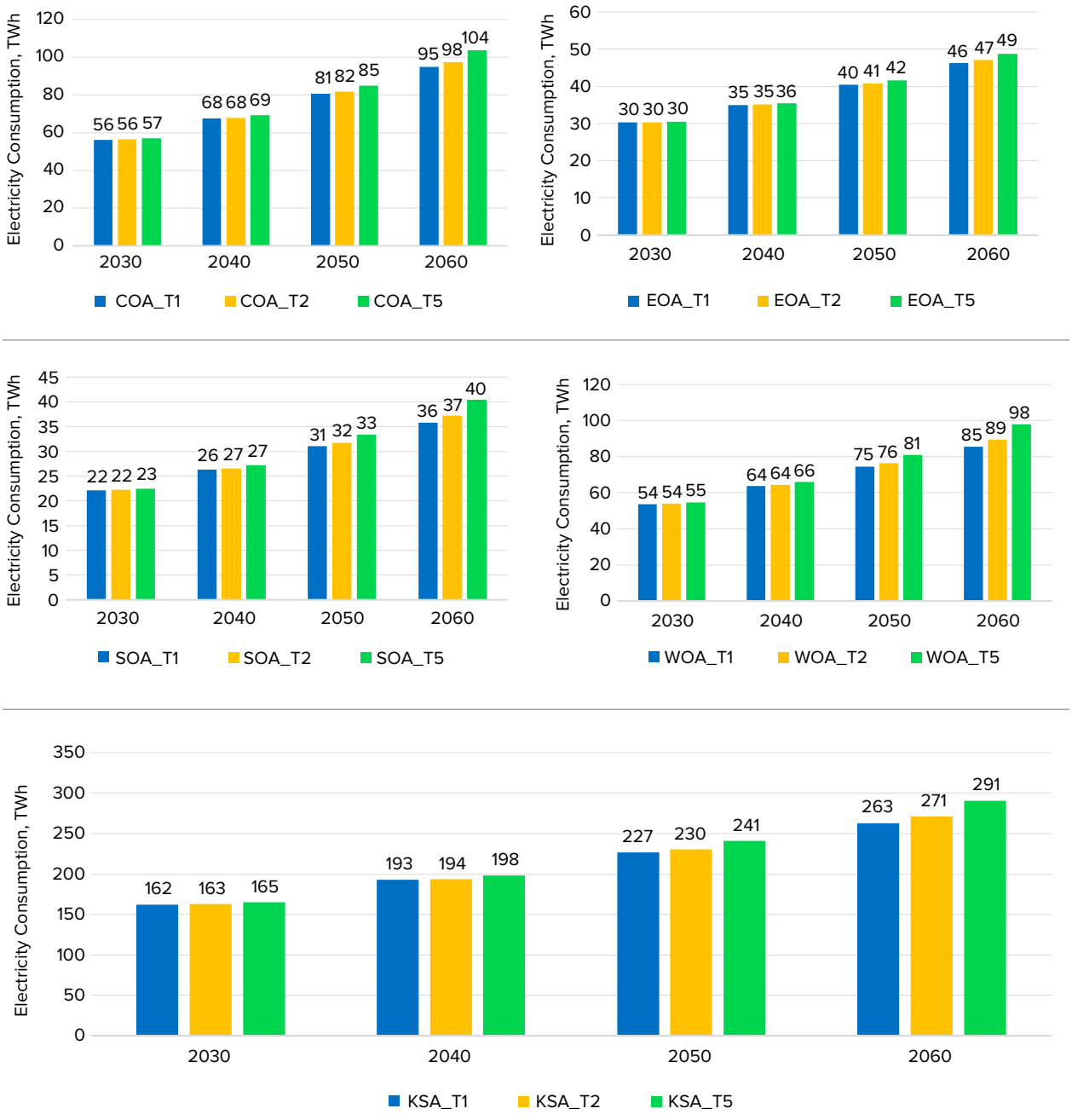
Pachauri, R. K., and L. A. Meyer, eds. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/report/ar5/syr.

Peerbocus, Nawaz, Hatem Al Atawi, Turki Al Aqeel, and Abdulrahman Al Julaifi. 2020. "Is Saudi Arabia Getting Warmer?" Riyadh: King Abdullah Petroleum Studies and Research Center (KAPSARC). https://www.kapsarc.org/our-offerings/publications/is-saudi-arabia-getting-warmer.

World Bank Group. 2024. *Climate Change Knowledge Portal: Saudi Arabia*. https://climateknowledgeportal.worldbank.org/country/saudi-arabia/climate-data-projections.

Appendix

Figure A1. Electricity consumption projections for the selected years.



Source: Authors' projection results.

About the Authors



Jeyhun I. Mikayilov

Jeyhun I. Mikayilov is a Principal Fellow at KAPSARC. He received his B.A. and M.S. from Azerbaijan State University (now Baku State University) in Mathematics. Jeyhun holds a Ph.D. in Applied Mathematics and a D.S. in Econometrics. Jeyhun's research is focused on applied time series econometrics, the economics of energy, the environment, and sustainable development. He has authored over 40 scientific articles published in peer-reviewed journals. He is an editorial board member of the *International Journal of Advanced Multidisciplinary Research and Review*, the *Journal of Management, Economics and Industrial Organization*, the *Journal of Socio-Economic Studies*, and the *Journal of Sustainable Development Issues*, as well as a member of the International Association for Energy Economics and the Italian Society for Econometrics (SIdE).



Abdulelah Darandary

Abdulelah Darandary is an economist and Research Fellow at KAPSARC with expertise in various fields, including macroeconomics, energy, international trade and investment flows, financial development, and public policy. He currently leads the project "Applying Behavioral Economics Methods to Energy Policymaking in Saudi Arabia," which has resulted in the first randomized controlled trial for electricity consumption. His work has been published in top-tier peer-reviewed journals in the field of energy economics. As a passionate advocate for evidence-based policymaking, Abdulelah is committed to using his expertise to help shape the future of energy and economic policy in Saudi Arabia and beyond, having worked on many projects for the energy ecosystem. He is also a sought-after speaker and panelist on economic and energy policy, having participated in several high-profile events and discussions.



Khalid Alhadhrami

Khalid Alhadhrami is an Analyst in the Utilities and Renewables program at KAPSARC. He is an Electrical Power and Machines Engineer with a bachelor's degree from the Department of Electrical Engineering at King Abdulaziz University. With three years of research experience, his work at KAPSARC has focused on renewables, energy modeling, and the electric power systems field.

About the Project

The goal of the “Modeling Energy Consumption and Its Impacts in Saudi Arabia” project is to conduct advisory and applied research activities focused on modeling and forecasting indicators of energy consumption and their impacts in Saudi Arabia. In line with the ongoing energy policies that the Kingdom is implementing, the project focuses on three main areas:

- Modeling and forecasting energy consumption indicators.
- Modeling and forecasting the environmental impacts of energy consumption.
- Investigating the trajectories and potential of energy efficiency.

kapsarc.org
info@kapsarc.org
/kapsarc