



RESEARCH ARTICLE

Social Perception towards Residential Solar PV Systems in Saudi Arabia: Conceptual Development of Socio-Cultural, Economic Factors, Technical Factors, and Policy and Regulatory Factors

Risha Alfaedi¹, Yazid Yaakob², Enio Kang Mohd Sufian Kang³, Suriati Paiman⁴, Saleh Ahmad Alghamdi⁵, Md Shuhazlly Mamat^{6*}

¹ Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia | Physics Department, Faculty of Science, Tabuk University, Kingdom of Saudi Arabia

² Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia | Halal Products Research Institute, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

^{3,4,6} Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

⁵ Physics Department, Faculty of Science, Tabuk University, Kingdom of Saudi Arabia

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ABSTRACT

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This conceptual paper examines the multi-dimensional factors influencing the adoption of residential solar photovoltaic (PV) systems in Saudi Arabia, focusing on economic, technical, socio-cultural, and policy-related barriers and enablers. With abundant sunlight and a strong commitment to sustainability under Vision 2030, Saudi Arabia holds significant potential for residential solar energy. However, adoption remains limited due to high installation costs, challenging desert climate conditions, limited public awareness, and an underdeveloped regulatory framework for small-scale solar systems. This study synthesizes insights from existing literature and integrates theoretical perspectives, such as Diffusion of Innovations and Socio-Technical Systems Theory, to propose a comprehensive conceptual framework for understanding the factors impacting solar PV adoption. Key findings suggest that financial incentives, advancements in dust-resistant and heat-tolerant technology, public awareness campaigns, and streamlined policies are essential to support residential PV uptake. The framework provides a foundation for future empirical research and offers actionable recommendations for policymakers, industry stakeholders, and communities to promote solar adoption. By addressing these identified challenges, Saudi Arabia can foster an enabling environment that accelerates its renewable energy transition, supporting national energy security and environmental goals aligned with Vision 2030. This conceptual approach contributes to the academic discourse on sustainable energy adoption and provides practical insights for enhancing the resilience and sustainability of Saudi Arabia's energy landscape.

*Corresponding Author:

shuhazlly@upm.edu.my

INTRODUCTION

The escalating threats posed by climate change, coupled with the rapid depletion of fossil fuels, have made renewable energy a global priority. In the Middle East, where heavy reliance on fossil fuels has traditionally shaped national economies, alternative energy sources present an unprecedented opportunity for sustainable development (Shahgholian et al., 2023). Among these, solar energy is particularly promising, given the region's abundant solar irradiance and favorable climatic conditions (Wolske et al., 2017). Countries such as Morocco, Jordan, the United Arab Emirates (UAE), and Saudi Arabia have recognized the potential of solar power, each setting ambitious renewable energy targets to reduce dependency on oil and diversify energy portfolios (Hadjipanayi et al., 2016).

Practically, Saudi Arabia, the largest Gulf Cooperation Council (GCC) member, is at the forefront of this shift (Shahgholian et al., 2023). Through initiatives aligned with its Vision 2030, the Saudi Arabia aims to transition from an oil-dependent economy to one that supports sustainable development and energy efficiency (Alqahtani and Balta-Ozkan, 2021). This vision includes plans for renewable energy, with a specific focus on residential solar photovoltaic (PV) systems to address both rising energy demands and environmental concerns (Khan et al. 2017).

The rise in energy demand in Saudi Arabia has been driven by several factors, notably population growth and economic expansion, which have fueled increased residential electricity consumption, accounting for more than 50% of the nation's total electricity usage (Alshehri et al., 2024). To meet this growing demand sustainably, solar PV systems offer a feasible solution by enabling households to generate their own power, reducing strain on the national grid and decreasing reliance on fossil fuels (Enongene et al., 2019). However, despite Saudi Arabia's vast solar potential, the adoption of residential solar PV systems faces numerous socio-economic, technical, and policy-related challenges. High initial costs, limited financing options, and an underdeveloped regulatory framework all contribute to the slow uptake of small-scale solar applications among Saudi households (Khan et al. 2017). The environmental conditions in Saudi Arabia, characterized by high temperatures and frequent dust storms, further complicate the performance and maintenance of solar PV systems, with dust accumulation potentially reducing efficiency by up to 30% (Parajuli et al., 2015).

However, public perception and social acceptance are pivotal in driving the adoption of renewable energy technologies. In Saudi Arabia, the general public's understanding of solar energy is shaped by economic considerations, environmental awareness, and cultural attitudes toward sustainability (Alrashoud and Tokimatsu, 2020). While interest in renewable energy is increasing, a lack of awareness persists about the benefits, costs, and feasibility of residential solar PV systems. Additionally, many Saudi Arabian remain unaware of the financial incentives and government programs that could make solar installations more accessible, underscoring the need for educational campaigns to inform and engage the public (Rashwan et al., 2017). Saudi Vision 2030 has created a foundation for renewable energy development, yet much of the government's focus has been on large-scale projects rather than residential installations (Alqahtani and Balta-Ozkan, 2021). For residential solar PV systems to gain traction, an expanded policy framework that includes subsidies, low-interest financing, and streamlined permitting processes is essential. Moreover, technological advancements, such as dust-resistant solar materials and automated cleaning solutions, are needed to address the operational challenges specific to Saudi Arabia's desert climate (Amran et al., 2020).

Despite Saudi Arabia's immense solar potential and commitment to sustainability under Vision 2030, residential solar PV adoption remains limited (Amran et al., 2020). High initial costs, environmental challenges, and a lack of comprehensive policy support present significant barriers for households (Chapman et al., 2016). Financial constraints, particularly the absence of subsidies and incentives, make solar PV systems financially inaccessible for many middle- and low-income families (Lee and Shepley, 2020). Furthermore, Dharshing, (2017) highlighted that the technical challenges, including dust accumulation and extreme heat, reduce PV efficiency, while limited awareness and cultural reliance on traditional fossil fuels hinder public acceptance. The regulatory landscape is underdeveloped, with complex permitting processes, a lack of net metering, and insufficient technical standards that discourage residential investment in solar energy (Lupangu and Bansal, 2017). These intertwined economic, technical, socio-cultural, and policy challenges inhibit the widespread adoption of residential solar PV systems, creating an urgent need for integrated strategies that address these barriers to enable a successful renewable energy transition in Saudi Arabia.

This study aims to explore the socio-economic, technical, and policy barriers to adopting residential solar PV systems in Saudi Arabia. By examining public perception, financial constraints, and regulatory issues, the research seeks to provide insights for policymakers and energy stakeholders by synthesizing the past empirical studies. Ultimately, the findings contribute to Saudi Arabia's energy transition goals under Vision 2030 and support global efforts to mitigate climate change by promoting sustainable energy practices at the household level.

LITERATURE REVIEW

Residential solar PV systems

Residential solar photovoltaic (PV) systems have garnered significant global interest as an effective means of generating renewable energy at the household level. These systems convert sunlight into electricity, reducing reliance on traditional energy sources and contributing to environmental sustainability (Dharshing, 2017). The potential of residential solar PV is especially relevant in high-solar-irradiance regions like Saudi Arabia, where the vast availability of sunlight offers an efficient and reliable renewable energy source (Enongene et al., 2019). However, the adoption of residential solar PV systems has encountered various barriers, including high initial costs, maintenance challenges, and socio-economic factors. Empirical studies in multiple countries have provided insights into these issues, highlighting the complex interplay between technical, financial, and social factors in residential solar adoption (Rashwan et al., 2017).

Empirically studies pointed out one of the major barriers to residential PV adoption is the high upfront cost of installation. In Saudi Arabia, for example, Rashwan et al. (2017) found that while there is substantial interest in solar energy, the financial burden remains a significant obstacle. Without adequate financial incentives or subsidies, many households face challenges in adopting solar PV systems, particularly those from low- and middle-income groups. Studies in other countries echo this issue; Gul et al. (2016) found that government incentives and financial subsidies play a crucial role in boosting adoption rates in both the United States and China. These findings suggest that financial policies, such as low-interest loans, tax credits, or grants, could be instrumental in promoting residential solar PV systems, especially in Saudi Arabia, where such initiatives could align with the Vision 2030 objectives for renewable energy (Khan et al. 2017).

Another significant factor influencing residential solar PV adoption is the technical challenge posed by environmental conditions, especially in desert climates. In Saudi Arabia, where frequent dust storms are common, dust accumulation on solar panels can significantly reduce their efficiency, affecting power output. Alhammami and An, (2021) conducted a study in the United Arab Emirates, which faces similar desert conditions, and reported efficiency losses of up to 20% due to dust accumulation on PV panels. Their findings suggest that dust-resistant coatings or automated cleaning systems could enhance PV system performance in regions like Saudi Arabia. Similarly, a study by Fakher Alfahed et al. (2019) in Iraq found that efficiency losses from dust could be mitigated with regular maintenance, underscoring the need for technical solutions tailored to desert climates. Public perception and social acceptance also play an essential role in the adoption of residential solar PV systems. Studies indicate that social factors, such as awareness of environmental benefits and community acceptance, strongly influence adoption rates. For instance, a survey conducted by Alqahtani and Balta-Ozkan, (2021) in Saudi Arabia revealed that while many residents recognize the long-term benefits of solar PV, misconceptions about maintenance costs and durability persist, hindering adoption. This aligns with findings from a study in Australia by Chapman et al. (2016), where consumer education and awareness programs increased acceptance and adoption rates of residential PV systems. These studies highlight the importance of targeted awareness campaigns to address misconceptions and promote the benefits of solar energy.

Furthermore, policy frameworks and regulatory support are essential to overcoming adoption barriers. Alrashoud and Tokimatsu, (2020) highlight the role of supportive policy in countries with high PV adoption, noting that streamlined permitting processes, clear regulations, and supportive frameworks can accelerate adoption. The researchers argue that while Saudi Arabia has made strides with large-scale solar projects, there is still a need for policies focused on residential solar PV to make it more accessible and affordable for individual households (Chapman et al., 2016). Such regulatory measures could not only facilitate higher adoption rates but also contribute to achieving the Kingdom's Vision 2030 goals.

In sum, the literature on residential solar PV systems suggests that while they hold great potential for sustainable energy generation, various financial, technical, and social factors influence their adoption. Empirical studies underscore the importance of government incentives, technical adaptations for desert conditions, public awareness campaigns, and supportive policies. Addressing these barriers in Saudi Arabia could lead to increased adoption of residential solar PV systems,

helping to advance the country's renewable energy objectives and environmental sustainability goals.

Social perception of residential solar PV systems in Saudi Arabia

Social perception plays a critical role in the adoption of residential solar photovoltaic (PV) systems, as public acceptance and awareness influence both individual and collective decisions to invest in renewable energy (Alrashoud and Tokimatsu, 2019). In Saudi Arabia, a country undergoing a significant transformation under the Vision 2030 framework, the shift towards renewable energy has introduced solar PV as a sustainable alternative to traditional fossil fuels (Amran et al., 2020). However, while the government has made considerable strides in promoting solar energy, studies indicate that social acceptance of residential solar PV systems remains a challenge, driven by cultural, economic, and informational factors (Alrashoud and Tokimatsu, 2020). Public awareness of solar energy benefits is a primary determinant of social perception, yet studies show that awareness levels remain relatively low. According to Bouaguel and Alsulimani, (2022), while there is a growing recognition of solar PV as a potential energy solution, many Saudi citizens lack a comprehensive understanding of its benefits and the technical aspects of the technology. This study surveyed Saudi residents to assess their perception of residential PV systems and found that concerns over high installation and maintenance costs, coupled with doubts about system reliability, negatively impacted interest in solar energy (Ali et al., 2024). Additionally, misconceptions persist regarding the maintenance needs of solar panels and the durability of PV systems in the harsh Saudi climate, where sand and dust storms are prevalent. This finding suggests a need for targeted public education campaigns to address common misconceptions and emphasize the cost savings, energy independence, and environmental benefits associated with solar PV systems (AlOtaibi et al., 2020).

Social norms and cultural attitudes also influence how residential solar PV systems are perceived in Saudi Arabia. In a society where the traditional energy infrastructure has been dominated by oil, adapting to solar energy represents a cultural shift. Research by Ali et al. (2024) suggests that while younger generations in Saudi Arabia are increasingly environmentally conscious, older generations may be more hesitant to adopt new technologies, especially those that depart from familiar, oil-based systems. This generational divide points to a broader cultural challenge in transitioning to renewable energy, underscoring the importance of framing solar energy adoption within the values of environmental stewardship and economic resilience. Salam and Khan (2018) found that households with younger members were more inclined to invest in solar PV systems, driven by environmental awareness and alignment with global sustainability trends.

Economic considerations also weigh heavily on social perception. The high initial costs of installing residential solar PV systems remain a significant barrier to widespread acceptance, particularly among middle- and low-income households. Ali et al. (2024) found that while financial savings in energy costs are an appealing long-term benefit, many households in Saudi Arabia perceive the initial investment as prohibitive. The researchers argue that financial incentives and subsidies are essential to shifting public perception by reducing upfront costs, making solar energy more accessible to a broader demographic (Makinde, 2014). This aligns with findings in other high-sunlight countries, where government subsidies have proven effective in making solar PV systems more appealing and attainable for households across income brackets.

Lastly, studies indicate that environmental concerns are increasingly influencing social perception in Saudi Arabia. According to a study by Alrashoud and Tokimatsu (2019), heightened awareness of climate change and pollution among Saudi citizens, particularly in urban areas, is fostering a positive attitude toward renewable energy solutions. The researchers noted a shift in public sentiment, with more residents acknowledging the environmental impact of fossil fuels and expressing interest in solar energy as a cleaner alternative (Alsulami et al., 2024). This growing environmental awareness provides a critical opportunity to promote residential solar PV systems as a viable and sustainable energy solution aligned with Saudi Vision 2030 goals.

In conclusion, social perception of residential solar PV systems in Saudi Arabia is shaped by awareness, cultural attitudes, economic factors, and environmental concerns. Empirical studies suggest that while there is a budding interest in solar energy, misconceptions about costs and durability, cultural resistance, and economic barriers limit broader adoption. Public awareness

campaigns, financial incentives, and framing solar adoption within national sustainability objectives could help shift social perception, fostering a more receptive environment for solar PV systems in Saudi Arabia.

METHOD

A conceptual paper aims to develop, explore, or refine a theoretical framework or model to advance understanding of a specific research area. In the case of residential solar photovoltaic (PV) systems in Saudi Arabia, this conceptual paper will focus on synthesizing existing literature, identifying key barriers and enablers, and proposing a conceptual framework that links social, economic, technical, and policy-related factors influencing PV adoption. This section outlines the methodology used to achieve these objectives.

Research design and approach

This conceptual paper adopts a qualitative, descriptive approach to explore the factors affecting residential solar PV adoption in Saudi Arabia. The primary objective is not to collect or analyze empirical data but rather to synthesize and integrate existing theories, models, and empirical findings from related research fields. This approach will allow for the development of a comprehensive conceptual framework that provides insights into the factors influencing residential solar PV adoption. The paper will focus on literature-based insights, theoretical constructs, and analytical reasoning to propose a model that can guide future empirical studies.

Literature review and synthesis

The foundation of this conceptual paper lies in a systematic literature review that synthesizes relevant studies on residential solar PV adoption, renewable energy policies, socio-cultural influences, and technological challenges specific to the Saudi context. The literature review will be conducted using established databases such as Google Scholar, ScienceDirect, JSTOR, and IEEE Xplore to access academic journals, government publications, industry reports, and white papers. Keywords for the search will include "residential solar PV adoption," "Saudi Arabia solar energy," "renewable energy barriers," "solar energy policy," and "socio-technical systems."

The review will follow a structured process to identify gaps, categorize factors, and assess theoretical perspectives. Relevant studies will be selected based on their focus on key dimensions such as Socio-cultural factors (e.g., public perception, environmental awareness), Economic factors (e.g., cost, financial incentives), Technical factors (e.g., environmental challenges, maintenance needs), and Policy and regulatory factors (e.g., subsidies, permitting process). Once key studies are identified, a thematic analysis will be conducted to highlight recurring themes, conflicting perspectives, and research gaps. This synthesis will form the basis for constructing a conceptual framework that integrates these factors.

RESULTS

As this is a conceptual paper, the "results" section presents the outcomes of the literature synthesis, the proposed conceptual framework, and the potential relationships among factors influencing the adoption of residential solar PV systems in Saudi Arabia. The results do not consist of empirical data but rather insights and a structured model that can guide future research and policy development. display higher levels of environmental consciousness and interest in sustainable energy solutions, compared to older generations more accustomed to fossil fuel-based energy (Salam and Khan, 2024). This generational divide underscores the importance of aligning solar adoption with values of environmental stewardship and national pride tied to Vision 2030.

Community norms further shape adoption rates. In close-knit communities, decision-making is influenced by social approval and peer behavior, meaning that if solar PV systems become normalized, adoption rates are likely to increase. This finding aligns with Diffusion of Innovations Theory, which posits that social acceptance grows as adoption spreads within social networks. Overall, socio-cultural factors are central to shaping Saudi Arabia's renewable energy future, indicating that awareness campaigns, cultural alignment, and community-based initiatives could foster a more supportive environment for residential solar PV adoption.

Economic factors in residential solar PV adoption in Saudi Arabia

Economic factors, particularly high upfront costs, limited financial incentives, and return on investment concerns, are significant barriers to residential solar PV adoption in Saudi Arabia (Schelly, 2014). Although the country has considerable solar potential, the financial burden of installing solar systems remains a major constraint for most households, especially among middle- and low-income groups (Lee and Shepley, 2020). The initial cost of purchasing and installing PV panels, along with maintenance expenses, deters many potential adopters despite the long-term savings associated with solar energy.

Empirical studies emphasize the critical role of financial support mechanisms in promoting solar PV adoption. For instance, Alrashoud and Tokimatsu, (2019) found that households in Saudi Arabia are highly sensitive to financial incentives, such as subsidies, low-interest loans, or tax rebates, which can significantly reduce the financial barriers to adoption. In other high-irradiance countries, government subsidies and incentives have been instrumental in increasing adoption rates, suggesting that similar measures could be effective in Saudi Arabia (Ali et al., 2014). Additionally, perceived return on investment (ROI) is a determining factor in adoption decisions. Although solar PV systems can lower electricity bills over time, the lack of net metering policies where excess generated energy is credited back to the user reduces the attractiveness of solar as a long-term investment (Chapman et al., 2016). Households often question whether they will achieve a sufficient ROI within a reasonable period. Addressing this issue could include implementing net metering policies or creating buyback programs for excess solar energy (Alrashoud and Tokimatsu, 2019).

Furthermore, the economic stability of the country and its dependence on oil revenues impact the level of investment in renewable energy (Alsulami et al., 2024). While Saudi Vision 2030 aims to diversify the economy and promote sustainability, government support for residential PV systems is still developing. Expanding financial incentives and establishing clear policies to offset upfront costs could make solar PV systems more economically accessible, aligning household financial motivations with national energy goals (Imam and Al-Turki, 2019).

Technical factors in residential solar PV adoption in Saudi Arabia

Technical factors are a crucial consideration in the adoption of residential solar PV systems in Saudi Arabia, particularly given the country's desert climate and environmental conditions (Ali et al., 2014). High temperatures, frequent dust accumulation, and maintenance requirements pose significant challenges for PV system efficiency and longevity, impacting the reliability and attractiveness of solar technology for residential use (Salam and Khan, 2024). One of the most notable technical challenges is dust accumulation on solar panels, which can significantly reduce energy output. In desert regions like Saudi Arabia, sandstorms and dust buildup frequently block sunlight, reducing PV efficiency by up to 20% (Barbiero and Grillenzoni, 2019). Regular cleaning is essential to maintain efficiency, but it adds to the overall maintenance costs and can be burdensome for homeowners (Alsulami et al., 2024). This need has spurred interest in innovations such as automated cleaning systems and dust-resistant coatings, although these solutions often come at an additional cost, potentially increasing the financial burden on adopters (Chapman et al., 2016).

High ambient temperatures also affect PV system performance. Solar PV panels operate less efficiently in extreme heat, a factor that limits their output in the peak summer months. Research shows that heat can reduce PV conversion efficiency, with degradation accelerated over time, potentially impacting the system's long-term ROI (Schelly, 2014). To address this, advancements in heat-tolerant PV technology are essential, though these are still under development and may not be widely accessible or affordable in Saudi Arabia (Alshehri et al., 2024). Infrastructure limitations also pose technical challenges. Integrating residential solar PV with the national grid requires reliable and compatible infrastructure, including effective energy storage solutions for excess energy produced during peak sunlight hours (Bouaguel and Alsulimani, 2022). Currently, limited grid support and lack of net metering policies mean that homeowners may not benefit fully from their solar installations (Chapman et al., 2016).

In summary, technical barriers related to dust accumulation, high temperatures, and grid compatibility affect residential solar PV adoption in Saudi Arabia. Addressing these issues with

innovations in PV technology and supportive infrastructure improvements will be essential to enhance the viability and appeal of solar energy for residential use.

Policy and regulatory factors in residential solar PV adoption in Saudi Arabia

Policy and regulatory factors play a pivotal role in shaping the adoption of residential solar PV systems in Saudi Arabia, where a supportive regulatory environment is essential to accelerate the transition to renewable energy (Mosly and Makki, 2018). Despite Saudi Vision 2030's ambitious goals to diversify the energy mix, specific policies and regulations tailored for residential solar PV adoption are still developing, presenting both challenges and opportunities (Alsulami et al., 2024). One of the primary regulatory barriers is the lack of a streamlined permitting and approval process for residential solar installations (Alshehri et al., 2024). Currently, households interested in installing PV systems must navigate complex regulatory procedures, which can deter adoption. Simplifying these procedures by establishing a clear, consistent permitting framework would reduce administrative barriers, making it easier for households to invest in solar energy (Alwulayi and Debbage, 2024).

Financial incentives are another critical policy gap. While Vision 2030 emphasizes renewable energy at a national level, there is limited financial support specifically for residential adopters (Mosly and Makki, 2018). In other countries, incentives such as tax credits, rebates, and low-interest loans have proven effective in lowering the financial burden of residential solar adoption. Implementing similar subsidies and financial incentives in Saudi Arabia would make solar PV systems more accessible and attractive to a broader demographic. Net metering and grid-tied policies are also lacking. In countries with net metering, households can sell excess generated energy back to the grid, creating an additional financial incentive for adopting solar PV (Alam et al., 2021). Without net metering or buyback programs, Saudi residents miss out on a significant economic benefit, which could otherwise enhance the financial viability of solar investments. Establishing net metering regulations would allow households to offset their energy costs more effectively, increasing the appeal of solar PV systems (Alsulami et al., 2024). Additionally, policies supporting technical standards and safety protocols for residential solar PV installations are essential. Regulatory standards that ensure system reliability, efficiency, and safety would boost consumer confidence and promote quality installations. Establishing these standards would also facilitate the integration of residential PV systems with the national grid, enhancing energy security and stability (Chapman et al., 2016).

In conclusion, policy and regulatory enhancements such as streamlined permitting, financial incentives, net metering, and technical standards are crucial for promoting residential solar PV adoption in Saudi Arabia. These changes would not only align with Vision 2030's sustainability goals but also enable households to contribute meaningfully to the country's renewable energy transition.

Proposed conceptual framework

Based on the findings from the literature, a conceptual framework is proposed to model the interaction among economic, technical, socio-cultural, and policy-related factors that influence solar PV adoption in residential sectors in Saudi Arabia (Imam and Al-Turki, 2019). First, financial incentives (e.g., subsidies, grants, and low-interest loans) are proposed to reduce the upfront cost barrier, particularly for middle- and low-income households (Lee and Shepley, 2020). This dimension may help test hypotheses regarding the relationship between financial incentives and adoption rates. Second, the framework emphasizes the impact of environmental challenges (e.g., dust and heat) on PV efficiency (Alam et al., 2021). It suggests that adoption may be higher in regions with advanced dust-resistant technology and adequate maintenance infrastructure. Future studies can empirically examine the effectiveness of these technologies in desert climates (Schulte et al., 2022). Third, this part of the framework focuses on public awareness and cultural attitudes toward renewable energy. It proposes that increased awareness through educational campaigns could improve public perception and interest in PV systems, especially if tied to Saudi Vision 2030's sustainability goals (Amran et al., 2020). Fourth, policy dimension integrates policy support mechanisms (e.g., streamlined permits, net metering, and regulatory guidelines) as essential to reducing barriers and simplifying the adoption process (Mosly and Makki, 2018). The framework suggests a positive relationship between regulatory support and PV adoption rates.

Interrelationships and hypotheses

The conceptual framework identifies potential relationships among these factors:

H1: Financial incentives positively impact residential solar PV adoption rates by making installations more affordable for households across socio-economic strata.

H2: Technical advancements, specifically in dust-resistant and heat-tolerant solar PV systems, improve system efficiency and adoption rates, especially in desert regions.

H3: Increased public awareness and alignment with cultural values (e.g., sustainability in Vision 2030) positively influences social perception and interest in adopting solar PV systems.

H4: Policy and regulatory support, including streamlined permitting and clear installation guidelines, has a positive effect on adoption rates by reducing administrative barriers.

DISCUSSION

The proposed conceptual framework for understanding the barriers and enablers of residential solar PV adoption in Saudi Arabia offers valuable insights for both theoretical and practical applications. This section discusses how the findings can contribute to academic discourse while providing actionable recommendations for policymakers, industry stakeholders, and communities to drive solar PV adoption.

Theoretical implementation

The results of this conceptual study advance the understanding of residential solar PV adoption by integrating four primary factors—economic, technical, socio-cultural, and policy related into a cohesive framework. This approach contributes to existing theories in the following ways. First, the conceptual framework reinforces diffusion of innovations theory (DOI) (Wolske et al., 2017), which posits that the adoption of new technologies depends on perceived benefits, social norms, and ease of access. By aligning with DOI, the framework suggests that factors such as public awareness, financial incentives, and regulatory support influence the perceived advantages of adopting solar PV systems in Saudi Arabia (Bouaguel and Alsulimani, 2022). For instance, households are more likely to adopt solar PV if they perceive it as economically beneficial and socially accepted, a finding supported by prior studies on renewable energy adoption globally.

Second, this framework also enhances socio-technical systems theory by highlighting the interaction between technical infrastructure (dust-resistant and heat-tolerant PV technology) and social dynamics (public perception, cultural acceptance) (Makinde, 2014). socio-technical systems theory acknowledges that adoption rates depend on a balance between technological compatibility with environmental conditions and the readiness of social systems to embrace these solutions (Haque et al., 2021). The framework thus proposes that technical solutions alone are insufficient without social and cultural buy-in, aligning with literature on the adoption of complex technologies in challenging environments.

Third, the framework's socio-cultural dimension aligns with theory of planned behavior (TPB), which emphasizes that behavioral intentions (such as adopting solar PV) are influenced by attitudes, social norms, and perceived control (Tanveer et al., 2021). In this case, social perceptions and attitudes toward energy independence, environmental sustainability, and economic benefits are significant predictors of PV adoption. The framework suggests that initiatives that foster positive attitudes toward renewable energy and enhance perceived behavioral control, such as financial incentives and supportive policies, could lead to higher adoption rates (Zulu et al., 2022). The integration of these theories creates a robust model that accounts for both the rational and cultural drivers of solar PV adoption in Saudi Arabia, providing a foundation for future empirical research that can validate and expand upon these theoretical insights.

Practical implementation

From a practical perspective, the findings offer actionable insights for policymakers, industry stakeholders, and communities interested in advancing solar PV adoption in Saudi Arabia. The framework's factors highlight critical areas where intervention can help overcome adoption barriers

and support Saudi Arabia's Vision 2030 goals. Key practical applications include. First, the framework underscores the importance of financial incentives, such as subsidies, grants, or low-interest loans, in making solar PV more accessible. Policymakers could consider adopting a tiered subsidy program that prioritizes middle- and low-income households, addressing affordability concerns and promoting equity in access to renewable energy. Additionally, simplifying the permitting process and establishing clear regulatory guidelines for residential solar installations could reduce administrative barriers and improve adoption rates.

Second, practical insights from the framework suggest the need for innovations that specifically address the technical challenges posed by Saudi Arabia's desert climate. Industry stakeholders could focus on developing dust-resistant and heat-tolerant PV technologies to optimize efficiency and longevity. Additionally, implementing automated cleaning systems or community-based cleaning services could help maintain system performance while reducing maintenance burdens on individual households.

Third, addressing the socio-cultural barriers to PV adoption may require public awareness campaigns that emphasize the economic and environmental benefits of solar energy (Makinde, 2014). Government and industry stakeholders can collaborate on outreach programs that educate the public on cost savings, environmental impact, and system reliability. Integrating solar energy awareness into educational curricula could also foster positive attitudes among younger generations, who are likely to be future adopters of sustainable technologies.

Fourth, framing solar PV adoption as part of Saudi Vision 2030's sustainability agenda can enhance public support. This alignment can resonate with cultural values of national pride and environmental stewardship, fostering a sense of collective responsibility toward renewable energy adoption. Additionally, promoting solar energy as a contribution to the Kingdom's global leadership in sustainability can create a positive image that encourages adoption.

RESEARCH LIMITATIONS AND FUTURE RESEARCH SUGGESTIONS

As a conceptual paper, this study relies primarily on existing literature and theoretical insights to propose a framework for understanding residential solar PV adoption in Saudi Arabia. This approach has inherent limitations.

Firstly, the lack of empirical validation poses a challenge, as the proposed framework and its relationships among economic, technical, socio-cultural, and policy factors are based on literature synthesis rather than direct data. Without primary data, it is difficult to quantify the actual impact of each factor or validate these relationships. Additionally, the framework's context-specific applicability may not fully capture regional differences within Saudi Arabia, such as variations between urban and rural areas or across socio-economic groups. The unique environmental, cultural, and regulatory landscape of Saudi Arabia may also limit the findings' applicability to other countries with different energy needs or socio-political structures. The dynamic nature of the renewable energy landscape presents another limitation. As policies, financial incentives, and technological advancements evolve, some aspects of this framework may become outdated, necessitating adjustments to reflect new developments. Furthermore, this study's theoretical scope, relying on established theories (e.g., Diffusion of Innovations, Theory of Planned Behavior, Socio-Technical Systems), may overlook emerging frameworks or potential moderating variables, such as education levels or local environmental awareness, that could further impact adoption outcomes.

To address these limitations, future research could explore several areas. Empirical testing of the framework through surveys, interviews, or case studies would validate the relationships among factors and provide statistical support for or refinement of the model. Longitudinal studies could track how changes in policies, incentives, and public awareness affect adoption over time, offering insights into the responsiveness of households to new initiatives. Comparative studies across urban, suburban, and rural areas would capture regional variations in adoption, contributing to region-specific policy recommendations.

Further research should conduct an in-depth analysis of socio-cultural barriers through qualitative methods to understand better how social and age groups view solar PV adoption. Exploration of moderating and mediating variables like environmental awareness and education levels could help

reveal how these factors influence the effectiveness of financial incentives and adoption outcomes. Additionally, examining technological advancements such as automated cleaning systems, dust-resistant coatings, and smart grid integration could assess their potential to reduce maintenance burdens and improve efficiency, making solar PV more attractive. Lastly, policy impact assessment studies evaluating interventions like subsidies, net metering, or streamlined permitting could identify which policies are most effective, providing data-driven insights for policymakers aiming to support residential solar PV adoption in Saudi Arabia.

CONCLUSION

This conceptual paper presents a framework for understanding the factors influencing residential solar PV adoption in Saudi Arabia, focusing on economic, technical, socio-cultural, and policy-related dimensions. Saudi Arabia's commitment to sustainability under Vision 2030 provides a unique opportunity to promote renewable energy, yet adoption of residential solar PV systems faces several barriers. High upfront costs, challenging desert environmental conditions, limited public awareness, and a need for supportive policies remain primary obstacles to widespread adoption. By synthesizing insights from the literature and established theories, such as Diffusion of Innovations and Socio-Technical Systems Theory, this study offers a structured approach to understanding these barriers and enablers in a unified framework.

The findings underscore the importance of financial incentives, technological adaptations, public education, and regulatory support to create an enabling environment for solar PV adoption. Financial support through subsidies or low-interest loans can reduce affordability constraints, while advancements in dust-resistant technology could improve system efficiency under desert conditions. Public awareness campaigns emphasizing the benefits of solar energy, particularly its alignment with Saudi Vision 2030, could further enhance social acceptance and foster a positive attitude toward renewable energy. Streamlined policies, such as simplified permitting processes and grid-tied incentives, could also reduce administrative barriers and encourage adoption. This framework not only provides a basis for future empirical research but also offers actionable recommendations for policymakers and industry stakeholders. By addressing the identified challenges, Saudi Arabia can accelerate its renewable energy transition, reducing reliance on fossil fuels and enhancing energy security. As the country progresses toward its Vision 2030 goals, fostering a supportive environment for residential solar PV systems will be critical in realizing its sustainable energy ambitions, contributing to a cleaner and more resilient energy future for Saudi Arabia.

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