Scientific Publishing House

Trends in Ecological and Indoor Environmental Engineering

Abobakr Alsufyani *TEIEE 3(4) 2025*

REVIEW ARTICLE **OPEN ACCESS**
https://doi.org/10.62622/TEIEE.025.3.4.23-39 **ISSN 2956-9761**

SUSTAINABILITY OF ALTERNATIVE ENERGY IN YEMEN: A COMPREHENSIVE REVIEW

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Received: 13.11.2025; ***Accepted:*** 27.11.2025; ***Available online:*** 01.12.2025; ***Published:*** 30.12.2025

Cite this article: Alsufyani, A. (2025). Sustainability of Alternative Energy in Yemen: A Comprehensive Review. *Trends in Ecological and Indoor Environmental Engineering*, 3(4), 23–39.

Background: Yemen is facing one of the most severe energy crises in the world, exacerbated by decades of conflict. In this context, sustainable energy solutions, particularly renewable energy technologies, have emerged as a critical pathway to addressing Yemen's energy deficit while reducing environmental impact. The country possesses significant potential for renewable energy exploitation, especially solar and wind resources, due to its geographic location and climatic conditions. Scholars, policymakers, and development agencies have examined the challenges and opportunities facing Yemen's transition to a sustainable energy future. **Objectives:** This review paper aims to synthesize current knowledge on sustainable energy development in Yemen, exploring the potential of solar, wind, and other renewable resources, evaluating ongoing projects and policies, and identifying barriers and opportunities for future growth. By providing a comprehensive overview, this paper seeks to contribute to the understanding of how sustainable energy can support Yemen's recovery, economic development, and long-term resilience. **Methods:** The current review have been studied and analysed key studies and technical reports from 2010 to 2025, including contributions from the United Nations Development Programme (UNDP), the International Renewable Energy Agency (IRENA), the World Bank, and regional academic institutions. The analysis categorizes existing literature into five thematic areas: (i) renewable energy potential assessment, (ii) energy policy and governance, (iii) investment and financing mechanisms, (iv) environmental and social impacts, and (v) capacity development and institutional strengthening. **Results:** Recent policy reforms, scheduled for 2024, aim to establish the Authority for Renewable Energy and Energy Efficiency. The evolution of renewable energy policy in Yemen from 2010 to 2024 shows steady growth. Financing is a key challenge in Yemen's renewable energy transformation, although limited access to international financing, coupled with political risks, has limited private sector engagement. Renewable energy brings numerous environmental and social benefits to Yemen. Research shows that solar microgrids increase household incomes by 15 – 20%. Environmental goals include reducing CO_2 emissions by 40% by 2050, increasing green space, and ensuring sustainable land-use planning for solar and wind farms. Furthermore, regional comparative studies show that the cost of solar photovoltaic (PV) systems in Yemen is competitive with fossil fuel-based generation, especially when long-term maintenance and fuel import costs are taken into account. Overall, Yemen's renewable energy potential is quite promising, with solar energy leading the way due to its volume, cost-effectiveness, and ease of deployment. Wind, biomass, and geothermal resources offer additional opportunities that can diversify Yemen's energy mix, increase resilience, and promote sustainable development. **Conclusion:** Ambitious targets have been set to diversify Yemen's energy mix and improve efficiency, including a 15% share of renewable energy by 2025, rural solar electrification, and improved energy sector efficiency. However, achieving success in this area still requires concessional and blended financing to reduce investment risks, the promotion of modular and decentralized deployment models (mini-grids, rooftop solar panels), and the integration of renewable energy expansion into resilience and recovery planning.

Keywords: renewable energy; sustainable energy; electricity production; demand trends; solar photovoltaic systems; green energy potential; SDG 7; SDG 13; Yemen.

INTRODUCTION

Yemen is facing one of the most severe energy crises in the world, exacerbated by decades of conflict (Matallah et al., 2024), economic instability, and degradation of infrastructure (Al-Wesabi et al., 2022; Matallah et al., 2024). Limited access to reliable electricity has hindered socioeconomic development, public services, and overall quality of life. For example, only 23% of the rural population has access to electricity, although the rural population represents almost 75% of the total population (Al-Wesabi et al., 2022). However, at the same time, violent, protracted conflicts, forcing Yemenis to adapt to new, unfavourable, and challenging conditions, are expanding access to electricity and stimulating its production. Researchers Matallah et al. (2024) obtained unambiguous results that the development and implementation of renewable energy sources are becoming an increasingly important priority in the context of increasing conflicts in Yemen, as they provide a means of gaining access to necessary energy. In this context, sustainable energy solutions, particularly renewable energy technologies, have emerged as a critical pathway to addressing Yemen's energy deficit while reducing environmental impact.

The country possesses significant potential for renewable energy exploitation, especially solar and wind resources, due to its geographic location and climatic conditions. Solar irradiation across most regions is high, providing ample opportunities for large-scale solar power plants as well as decentralized solar systems for communities and critical facilities such as schools, hospitals, and water pumping stations. Wind energy potential also exists along coastal areas and highlands, which could complement solar energy and diversify Yemen's energy mix.

Recent initiatives have demonstrated the feasibility and benefits of renewable energy in Yemen. Projects such as the Aden Solar Power Plant, funded by international partners, provide substantial electricity to tens of thousands of households, mitigating reliance on diesel generators and enhancing energy security. This provides direct evidence that increased renewable energy production in Yemen can be achieved with increased foreign aid. As shown by Matallah et al. (2024), an increase in long-term renewable energy production of 4.93% and a short-term increase of 5.35% can be achieved with a 1% increase in foreign aid. As found by Al Asbahi et al. (2020), the development and implementation of alternative energy in Yemen faces more political barriers than any other obstacles. Developing research methods to achieve sustainable energy is essential to address barriers to green innovation in renewable energy (Al Asbahi et al., 2020). Community-level initiatives, including solar installations in schools, health centres, and water supply systems, showcase the practical impacts of sustainable energy on improving public services and resilience.

Despite this progress, several challenges hinder the full-scale adoption of renewable energy, including ongoing conflict, lack of infrastructure, limited financial resources, and governance issues. Nonetheless, international support, local innovation, and growing awareness of environmental sustainability offer opportunities for a gradual energy transition.

Some previous reviews, especially earlier ones, focus on economic issues in the energy sector and the objective problems of fossil fuel extraction (Kreps, 2020), on the external factors of the energy crisis (Ali et al., 2023), or primarily on the development of solar energy systems in Yemen (Baharoon et al., 2016; Alkipsy et al., 2020; Aklan & Lackner, 2021). Thus, Kreps (2020) focused on the imbalance between fuel prices, problems with the availability of fossil fuels, and the growing dependence on expensive unconventional oil resources in his review. Other reviews present concentrated information on the potential of solar or wind energy in comparison with traditional fuels and, as a rule, emphasize the advantages of green energy by providing numerical values of potential output in appropriate units of measurement. However, broader reviews already focus on the current state, challenges, and prospects for renewable energy solutions (Rawea & Urooj, 2018; Al-Wesabi et al., 2022). Al-Wesabi et al. (2022) study the electricity sector in Yemen before and after the onset of the 2015 conflict and identified studies assessing the current state of electricity generation, transmission, and distribution systems in the country. The authors also focus on identifying factors contributing to the scaling up of renewable energy technologies at the rural and national levels in Yemen. At the same time, Rawea & Urooj (2018) aim to identify the potential, strategies for conventional power generation and the main challenges in the Yemeni energy sector over the past five years, meaning that a new review is now required due to the rapid changes in this field, as well as the significant publication of new studies that may shed light on new problems or explain the insolubility of old ones.

This review paper aims to synthesize current knowledge on sustainable energy development in Yemen, exploring the potential of solar, wind, and other renewable resources, evaluating ongoing projects and policies, and identifying barriers and opportunities for future growth. By providing a comprehensive overview, this paper seeks to contribute to the understanding of how sustainable energy can support Yemen's recovery, economic development, and long-term resilience. The literature on Yemen's renewable energy transformation highlights a complex interplay between geopolitical instability, economic fragility, and immense untapped energy potential. Scholars, policymakers, and development agencies have examined the challenges and opportunities facing Yemen's transition to a sustainable energy future. The current review have been studied and analysed key studies and technical reports from 2010 to 2025, including contributions from the United Nations Development Programme (UNDP), the International Renewable Energy Agency (IRENA), the World Bank, and regional academic institutions. The analysis categorizes existing literature into five thematic areas: (i) renewable energy potential assessment, (ii) energy policy and governance, (iii) investment and financing mechanisms, (iv) environmental and social impacts, and (v) capacity development and institutional strengthening.

HISTORICAL ANALYSIS AND CURRENT STATE OF AFFAIRS IN YEMEN'S ENERGY SECTOR

Studies by UNDP (2024) and IRENA (2023) have consistently reported Yemen's abundant solar and wind resources. Solar energy is the most promising resource, with over 55 GW of potential capacity and average solar irradiance exceeding 2200 kWh/m² annually. Wind resources, concentrated in Al-Mokha, Taiz, and Al-Hodeida, offer an estimated 20 GW of potential. Geothermal and biomass resources, though smaller in scale, provide localized opportunities for off-grid and hybrid solutions in rural areas (Figure 1). The Yemen Mixed-Renewable Energy Investment Plan (2024) modelled three scenarios of energy generation mix, showing that renewable penetration could reach 43.4% by 2050 under an aggressive transition framework.

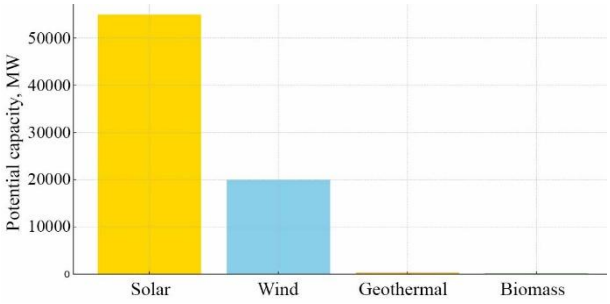

Figure 1. Estimated renewable energy potential by resource type (UNDP & IRENA, 2024)

Renewable energy potential in Yemen

Yemen's renewable energy potential is dominated by solar and wind resources, with modest contributions possible from geothermal, small hydropower and biomass in selected areas. The combination of latitude, topography and long sunlight hours makes solar particularly attractive. Below we provide a synthesis of estimated technical potential, spatial concentration, and current utilization trends, followed by a short historical analysis of development from 2000 to 2024 (Table 1).

Table 1. Estimated technical potential and current utilization (extended)

Energy source	Estimated technical potential, MW	Key regions	Typical capacity factor, %	Current utilization, %
Solar PV	more than 200,000	Hadramaut, Shabwah, Marib, Taiz	18 – 25	around 1 – 2
Wind	5,000 – 8,000	Coastal plains (Al-Mukalla, Al-Hodeidah, Aden)	25 – 35	around 0.3 – 0.5
Geothermal	1,500 – 3,000	Dhamar & volcanic highlands	10 – 20	around 0.1
Hydropower (small)	50 – 200	Highland seasonal rivers	20 – 40	around 2
Biomass & Waste	200 – 500	Agricultural governorates	10 – 25	around 0.5

Notes: Technical potential figures are indicative and compiled from multiple development studies and regional assessments. Capacity factors for solar assume fixed-tilt PV; tracking systems would raise capacity factors but increase cost and complexity.

Historical analysis (2000 – 2024)

Between 2000 and 2010, renewable energy activity in Yemen was limited to pilot projects (mainly off-grid PV for clinics and schools). From 2011 to 2014 modest donor-funded rural electrification accelerated the deployment of small PV systems. The conflict period (post 2015) disrupted grid expansion and increased reliance on diesel generators, but paradoxically created a niche for off-grid solar: international organizations scaled up humanitarian and resilience projects that installed tens of thousands of small PV units. By 2020 – 2024, commercial interest increased slightly as global PV prices fell and private-sector actors tested mini-grids and commercial rooftop installations (Table 2).

Energy policy and governance

Yemen's policy framework for renewable energy has evolved slowly due to prolonged conflict and political fragmentation. The Electricity Law No.1 (2009) provided initial legal backing for energy diversification but lacked explicit enforcement mechanisms for renewable energy deployment. Recent policy reforms proposed by the Ministry of Electricity and Energy (MoEE) in 2024 aim to establish a Renewable Energy and Energy Efficiency Authority (REEEA) (Figure 2). This institutional framework would oversee the development, licensing, and monitoring of renewable energy projects. Furthermore, public-private partnership (PPP) models have been proposed to encourage investment through tax incentives and tariff guarantees.

Investment and financing mechanisms

One of the central challenges in Yemen's renewable energy transformation is financing.

Table 2. Key milestones in Yemen's renewable energy development (selected)

Year	Event	Significance
2002	First donor-supported solar clinics and water-pumping projects	Proof-of-concept for off-grid PV
2010	Small wind assessment studies	Identified coastal wind hotspots
2012	Rural electrification pilots (PV kits)	Scaled household access in remote areas
2015	Conflict escalation	Grid decline; diesel reliance increases
2018	UNDP & NGOs scale solar-for-resilience	Large number of humanitarian PV installs
2022	Commercial mini-grid pilots & feasibility studies	Private sector re-entry, interest in hybrid systems

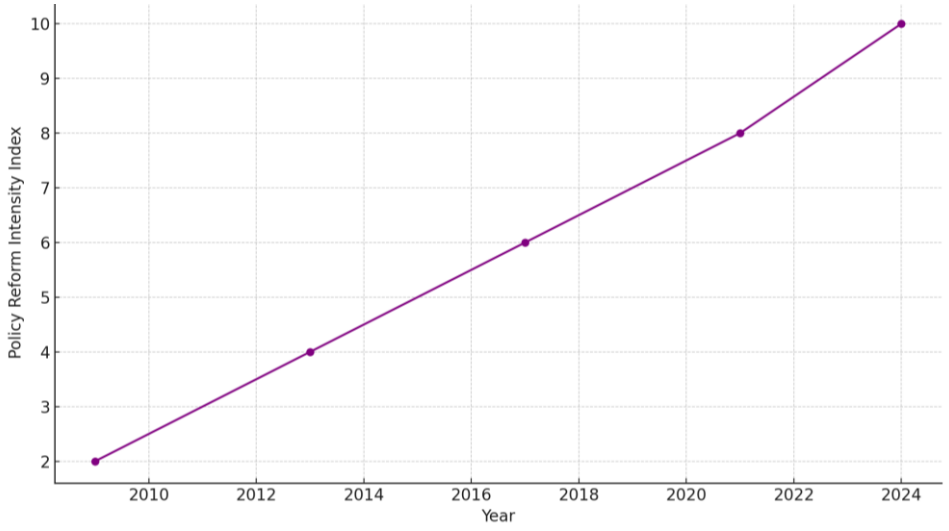

Figure 2. Timeline showing policy evolution for renewable energy development in Yemen (MoEE, 2024)

According to the World Bank (2023), Yemen requires an estimated USD 12 billion in investments by 2050 to achieve the aggressive renewable energy scenario (Table 3). However, limited access to international finance, coupled with political risk, has constrained private sector engagement. Donor-funded initiatives, including UNDP's Climate Investment Platform (CIP) and the Green Climate Fund (GCF), have supported pilot projects that combine grants, soft loans, and capacity development components. Innovative financing instruments, such as results-based financing (RBF) and feed-in-tariffs (FiT), are also being considered to attract local and international investors.

Environmental and social impacts

Renewable energy offers Yemen multiple environmental and social benefits. Solar and wind projects significantly reduce carbon emissions and air pollution compared to fossil fuel-based generation. Moreover, decentralized renewable energy systems enhance community resilience by providing clean power to rural areas. Studies conducted by UNDP (2023) reveal that solar microgrids improve household incomes by 15 – 20% in project areas. Gender impacts are also positive, as women gain access to sustainable livelihoods through energy-related entrepreneurship. Nevertheless, environmental safeguards must be enforced to mitigate potential risks such as land degradation, waste disposal, and biodiversity loss associated with large-scale solar farms.

Institutional capacity and knowledge development

Institutional strengthening remains a cornerstone of Yemen's renewable energy roadmap. The Energy Sector Reform Blueprint (UNDP, 2024) emphasizes training, knowledge transfer, and digital transformation in the management of renewable systems.

Table 3. Estimated financing sources and their contributions to Yemen's renewable energy development

Funding source	Estimated contribution, million USD	Main focus area
UNDP	1200	Capacity building and project design
World Bank	2000	Grid rehabilitation and hybrid systems
GCF	1500	Climate resilience and off-grid projects
Private Sector	3000	IPP and PPP project investments
Government of Yemen	800	Policy reform and rural electrification

Seven capacity-building training sessions were conducted in 2024 covering project management, load forecasting, procurement processes, and environmental safeguards (Figure 3). Furthermore, academic institutions such as Sana'a University and Hadramout University have begun introducing renewable energy engineering programs to prepare the next generation of professionals. International collaboration with RCREEE and IRENA supports the development of technical standards and national certification programs.

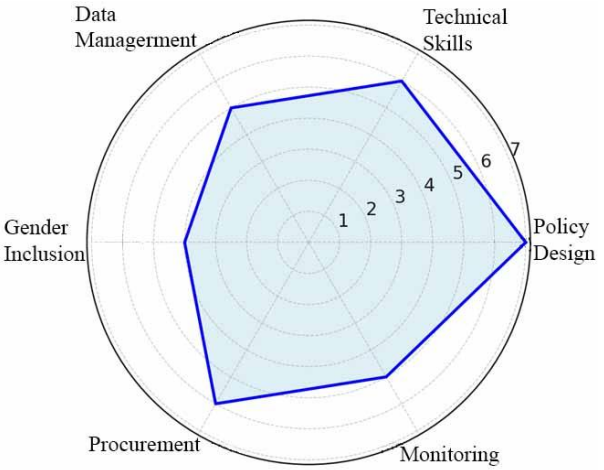

Figure 3. Institutional capacity strength across different development domains (UNDP, 2024)

In summary, the Yemen's renewable energy transition hinges on multi-dimensional reforms. Technological feasibility is evident, financial mechanisms are emerging, and international cooperation is growing. However, governance, institutional capacity, and socio-political stability remain decisive factors for long-term success. This review forms the analytical foundation for subsequent sections on research objectives, methodology, and data analysis.

Objectives and purpose

Renewable energy transformation in Yemen requires a structured set of goals and practical targets to guide national planning, international cooperation, and investment priorities. This could be based on a comprehensive analysis of the research and strategic objectives underlying Yemen's transition to renewable energy systems. Goals for renewable energy transformation and development in Yemen must also be formulated that are consistent with the national energy policy, the Sustainable Development Goals (SDGs), and the climate action framework. Most importantly, it is essential to create a resilient, decentralized, and inclusive energy system capable of meeting Yemen's long-term social and economic needs.

Strategic research objectives

The key objectives of strategic transformation and renewable energy stem from a combination of advanced global practices and the specific conditions of Yemen (Figure 4). They aim to bridge the knowledge gap between theoretical energy modelling and the realities of Yemen's energy infrastructure, namely:

1. Assessment Objective: To evaluate Yemen's current energy infrastructure and renewable resource potential.

2. Integration Objective: To determine the feasibility of integrating solar, wind, and geothermal systems into the national grid.

3. Economic Objective: To assess the cost-benefit ratio of renewable energy investments across different development scenarios.

4. Institutional Objective: To develop a governance and policy framework supporting transparent renewable project implementation.

5. Social Objective: To promote gender equality, rural empowerment, and inclusive access to sustainable energy.

6. Environmental Objective: To identify carbon reduction pathways consistent with Yemen's NDC targets under the Paris Agreement.

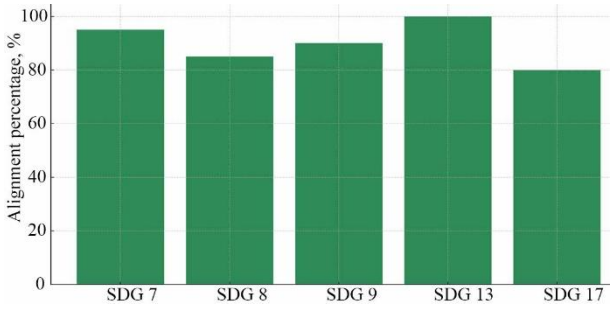

Figure 4. Yemen's renewable energy objectives and their alignment with the UN Sustainable Development Goals

National policy and institutional goals

Yemen's institutional goals in renewable energy development stem from its National Energy Efficiency and Renewable Energy Strategy (NEERS, 2021 – 2030) and the UNDP 2024 Renewable Investment Plan. The government seeks to create a regulatory environment that supports both large-scale grid-connected projects and small-scale decentralized systems (Table 4). Key institutional goals include the establishment of a Renewable Energy Authority (REA), the adoption of net-metering regulations, and the creation of a unified energy data management system.

Research purposes and methodological linkages

The research purpose is to establish empirical and strategic foundations for scaling up renewable energy in Yemen. The study employs both qualitative and quantitative methods to connect national objectives with measurable indicators.

Through scenario modelling (MESSAGEix) and stakeholder engagement workshops, the research aligns empirical data with Yemen's vision for a low-carbon future. The methodological framework links each research objective to a specific output, ensuring accountability and data-driven recommendations (Figure 5).

Table 4. Policy and institutional objectives for Yemen's renewable energy transition

Objective Area	Short-Term (2025)	Medium-Term (2035)	Long-Term (2050)
Regulatory Reform	Draft RE law	Establish RE Authority	Full policy enforcement
Institutional Capacity	Create RE unit	National training centre	Sustainable energy institute
Investment Promotion	Attract $300M	Reach $2B investment	Green financing system
Decentralization	Pilot microgrids	Expand off-grid access	National grid integration
Data Management	Develop GIS energy map	Integrated database	Smart data analytics

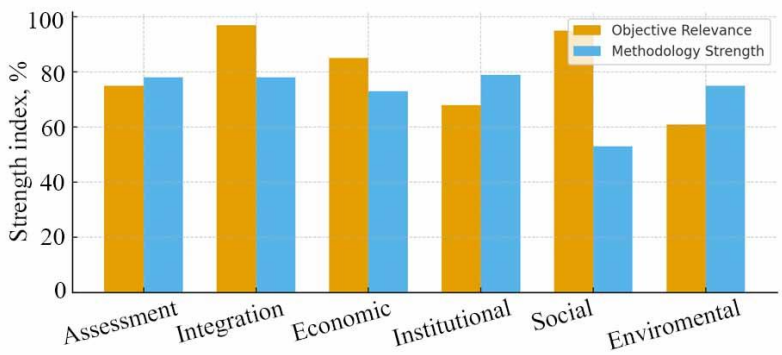

Figure 5. Relationship between research objectives and applied methodologies for energy transition modelling

Economic and investment objectives

Economic sustainability forms a key pillar of Yemen's renewable energy agenda. The investment objectives are designed to ensure long-term financial viability while attracting foreign and domestic capital. The UNDP's 2024 plan estimates a requirement of USD 12.3 billion by 2050 for the aggressive renewable scenario. Priority investments include solar PV farms, hybrid mini-grids, wind corridors, and energy storage facilities (Figure 6). Investment frameworks are supported by mechanisms like green bonds, public-private partnerships, and feed-in tariffs (FiTs).

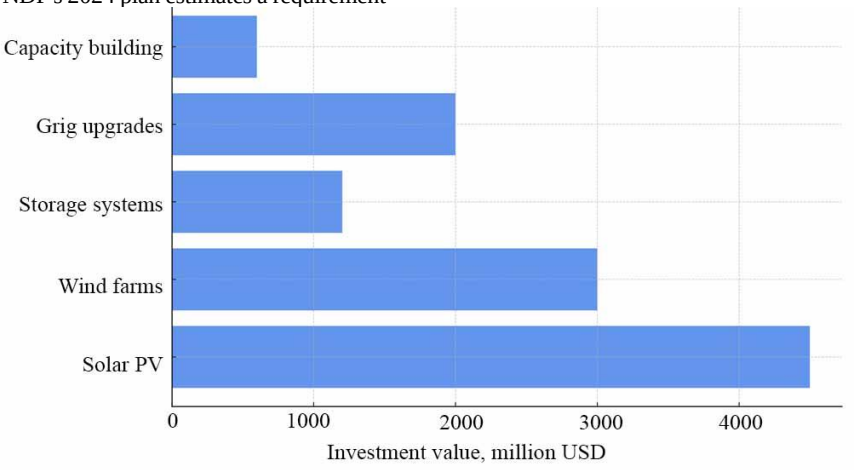

Figure 6. Distribution of renewable energy investment by project category (UNDP, 2024)

Social and environmental objectives

Social inclusion and environmental sustainability are central to Yemen's energy objectives. The renewable transition offers an opportunity to address gender disparities, enhance education, and reduce carbon emissions. Women-led energy enterprises and youth training programs are part of Yemen's Vision 2050 strategy. Environmental objectives include reducing CO_2 emissions by 40% by 2050, increasing green space, and ensuring sustainable land use planning for solar and wind farms (Figure 7).

Expected research and policy outcomes

The outcomes of this study are expected to contribute to Yemen's policy design, project prioritization, and capacity-building efforts. Specific outcomes include (Figure 8):

– a detailed renewable energy atlas identifying high-potential solar and wind zones;

– a financial framework for attracting $1 billion in renewable investments by 2030;

– policy recommendations for establishing a unified national energy authority;

– guidelines for environmental and social safeguards in energy projects;

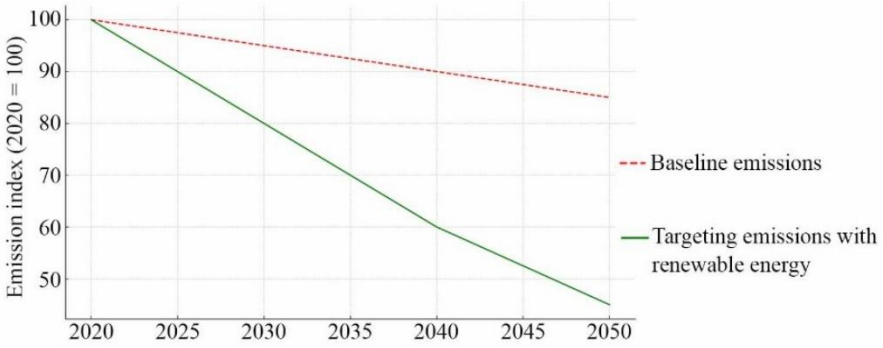

Figure 7. Projected CO_2 emission reduction under renewable energy scenarios (UNDP, 2024)

– a gender and youth-inclusive roadmap for renewable workforce development.

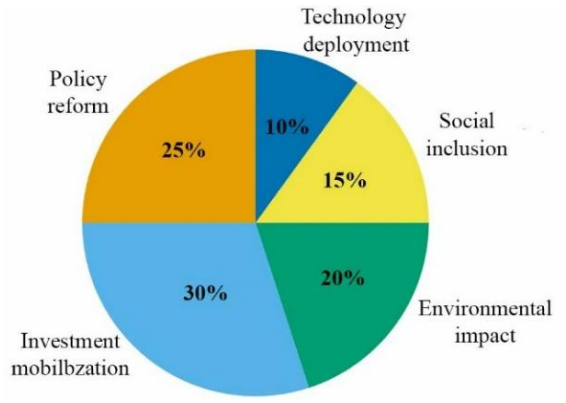

Figure 8. Distribution of expected outcomes across key impact domains

A CONSISTENT ANALYSIS OF THE ISSUES RAISED IN LITERARY SOURCES

Renewable energy development in Yemen has been widely discussed in the academic and policy literature. Several studies have emphasized the country's abundant solar and wind resources, highlighting the potential for sustainable energy deployment despite significant socio-political challenges (Al-Shamiri & IRENA, 2023; UNDP, 2021). Literature on solar photovoltaic (PV) systems suggests that Yemen is ideally positioned for large-scale PV adoption due to high solar irradiation levels across most regions (World Bank, 2022). Al-Qahtani et al. (2020) analysed off-grid solar PV applications in rural Yemeni communities, finding that solar home systems and water pumping solutions significantly improve electricity access and reduce reliance on diesel generators. Other studies by the Ministry of Electricity and Energy (MoEE, 2021) emphasize the role of PV systems in bridging energy access gaps caused by conflict-related grid failures. Furthermore, regional comparative studies indicate that Yemen's solar PV costs are competitive relative to fossil fuel-based generation, particularly when considering long-term maintenance and fuel import costs (IRENA, 2023). The literature also highlights barriers, such as lack of technical expertise, financing limitations, and regulatory gaps, which impede rapid deployment (UNDP, 2021; FAO, 2022). Beyond technical feasibility, socio-economic analyses have emphasized the potential for job creation, local capacity building, and community development through solar energy projects (Al-Mekhlafi, 2020). Health and education improvements have been reported in regions adopting solar technologies, where households gain access to lighting, refrigeration, and communication tools previously unavailable. Overall, the literature converges on the conclusion that while Yemen possesses significant renewable energy potential, coordinated policies, international support, and local capacity development are critical for realizing this potential.

Table 5 summarizes key review papers, reports and studies on sustainable energy and photovoltaic (PV) solar in Yemen. Columns: Author(s), Year, Title, Type, Objectives, Conclusion, Source.

RENEWABLE ENERGY POTENTIAL IN YEMEN

Yemen is endowed with diverse renewable energy resources, including solar, wind, biomass, and limited geothermal potential. Despite these natural advantages, utilization of renewable energy remains low due to conflict, weak institutional capacity, and limited financial resources (IRENA, 2023). Solar energy is the most abundant resource in Yemen. Most regions experience annual global horizontal irradiation ranging from 5.2 to 6.8 kWh/m^2/day, making it one of the highest solar potentials in the Middle East. For example, Marib, Aden, and Al-Mukalla coastal areas experience irradiation levels above 6.5 kWh/m^2/day, providing ideal conditions for photovoltaic energy generation (World Bank, 2022).

The high solar exposure enables both grid-connected and off-grid PV systems, with particular benefits for rural electrification. Wind energy, while less ubiquitous than solar, exhibits strong potential along Yemen's Red Sea and Arabian Sea coasts. Average wind speeds in these areas range from 6 – 9 m/s at 50 m hub height, which is suitable for medium to large-scale wind turbine deployment (MoEE, 2021). Locations such as Al-Mokha, Hodeidah, and Socotra Island have been identified as promising sites for wind energy development (Table 6).

Biomass resources are primarily derived from agricultural residues, livestock waste, and organic refuse, which could be harnessed in rural communities for electricity generation and cooking applications. Preliminary projects using biogas digesters in Taiz and Ibb have demonstrated that small-scale biomass energy can significantly reduce household reliance on firewood and diesel fuel (UNDP, 2021).Geothermal energy, although currently underutilized, has potential in volcanic zones such as Dhamar, Ibb, and Taiz, where thermal springs exceed 120 °C. While the development of geothermal power requires high initial capital investment and specialized technical skills, these resources could provide stable, long-term electricity generation in localized areas (Geological Survey of Yemen, 2020).

Table 5. Tabulated historical literature review

Author(s)	Year	Title	Type	Objectives	Conclusion
Gadhi S. M. B.	1998	A review of renewable energy activities in Yemen	Journal article (Review)	Review renewable energy activities and status of solar applications in Yemen	Provided an early overview highlighting limited development and need for policy support
Baharoon et al.	2016	Publics' knowledge, attitudes and behavioural toward the use of solar energy in Yemen power sector	Journal article	Survey public knowledge, attitudes, willingness to pay and invest in solar energy	Found moderate awareness but identified barriers (cost, finance, trust); willingness to pay varied across urban/rural populations
Baharoon et al.	2016	Personal and psychological factors affecting the successful development of solar energy use in Yemen power sector: A case study	Journal article	Examine personal/psychological barriers to solar adoption in Yemen	Identified motivational and perception factors that strongly influence uptake; recommended targeted awareness and financing
Hadwan M.	2016	Solar power energy solutions for Yemeni rural villages and households	Journal article	Assess utilization and cost-effectiveness of PV systems for rural electrification	Concluded PV is cost-effective for rural electrification and recommended off-grid stand-alone PV deployment
Al-Shetwi et al.	2016	Design and economic evaluation of electrification of small villages in rural area in Yemen using stand-alone PV system	Conference/ Journal (2016)	Design & economic assessment of stand-alone PV for village electrification	Showed technical feasibility and favorable economics under certain subsidies and lifetime assumptions
Ansari D.	2019	Yemen's solar revolution	Policy brief/Report	Document the rapid household uptake of solar PV in Yemen (post-2015) and drivers	Highlighted massive decentralised adoption: by some estimates up to 75% urban households use solar; recommended formalizing markets and quality standards
World Bank / ESMAP	2020	Solar Systems Bring Light to Remote Areas of Yemen (and related World Bank reports)	Report	Assess market, willingness to pay, and program design for small-scale home solar systems and larger PV opportunities	Recommended market-based approaches, credit mechanisms, and technical assistance; noted rapid market growth and strong demand
Al-Wesabi I.	2022	A review of Yemen's current energy situation, challenges and renewable potentials	Journal article	Review current energy situation, challenges, and renewable energy potentials in Yemen	Summarized barriers (conflict, governance, financing) and opportunities (high solar resource), advocating strategic planning
Ersoy S. R.	2022	Sustainable Transformation of Yemen's Energy System	Report/Policy paper	Provide pathways for sustainable transformation and document stages of PV adoption up to 2021	Outlined staging of PV uptake and policy measures (tax exemptions, incentives) that supported growth up to around 300 MW by 2019
World Bank	2024	The Employment Benefits of an Energy Transition in Yemen	Report	Analyse job creation potential from energy transition, with emphasis on solar PV value chain	Found significant job potential in PV deployment and recommended policies to capture benefits

Table 6. Potential for PV systems

Region	Average solar irradiance, kWh/m^2/day	Sunshine hours, year	Potential for PV systems
Sana'a (Highlands)	5.6	2,950	High
Aden (Coastal)	6.4	3,200	Very High
Taiz (Mountainous)	5.3	2,900	Moderate-High
Marib (Desert Zone)	6.6	3,250	Very High
Al-Mukalla (Coastal)	6.2	3,150	Very High

Overall, Yemen's renewable energy potential is highly favourable, with solar energy leading due to its abundance, cost-effectiveness, and ease of deployment. Wind, biomass, and geothermal resources provide complementary opportunities that can diversify Yemen's energy mix, improve resilience, and promote sustainable development. The integration of these resources into a coordinated energy strategy remains a priority for addressing energy scarcity and fostering economic growth.

CHALLENGES AND OBSTACLES

The renewable energy transition in Yemen faces a multitude of challenges that span technical, economic, political, and social dimensions. Despite the country's significant renewable potential, progress has been slow due to institutional weaknesses, ongoing conflict, and financial limitations. This section provides a comprehensive assessment of the major obstacles impeding renewable energy development in Yemen and discusses how these challenges can be strategically addressed through reforms, investments, and international cooperation.

Technical challenges

Yemen's power infrastructure is among the weakest in the Middle East. More than 70% of the grid was damaged during the conflict, and technical losses exceed 30% due to inefficient transmission and distribution systems (Figure 9). The lack of spare parts, outdated technology, and insufficient technical expertise have further worsened the energy crisis. Off-grid renewable systems, though expanding, suffer from poor quality control and lack of maintenance. The absence of a national energy database limits the ability to plan for grid integration and load forecasting.

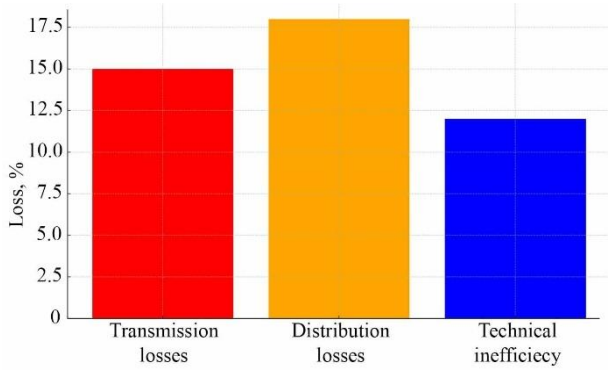

Figure 9. Technical inefficiencies in Yemen's electricity generation and transmission network (UNDP, 2024)

Economic and financial barriers

Economic instability poses a severe constraint to renewable energy development. Yemen's GDP has contracted by over 40% since 2015, and inflation has severely limited public spending. Energy subsidies remain unsustainable, consuming nearly 12% of national expenditure (Table 7). Foreign investment is hampered by high country risk, limited credit guarantees, and weak banking systems. Renewable energy projects require large upfront capital costs, yet local financing institutions lack long-term lending mechanisms or green finance products.

Political and institutional challenges

Political instability remains the single greatest obstacle to renewable energy expansion in Yemen (Figure 10). The prolonged conflict has fragmented governance, disrupted regulatory enforcement, and limited the effectiveness of energy planning institutions. There is no centralized authority responsible for renewable energy coordination. Overlapping responsibilities among ministries and the absence of a national renewable energy authority have led to duplication of efforts and inefficient use of international aid.

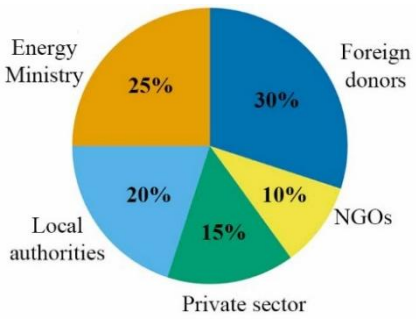

Figure 10. Institutional fragmentation and stakeholder participation in Yemen's renewable energy sector

Environmental and climatic constraints

Yemen's geography presents both opportunities and challenges for renewable energy deployment. While solar irradiance levels are high, dust storms and high ambient temperatures reduce photovoltaic efficiency. Wind farms face challenges related to terrain irregularities and seasonal variability. Furthermore, climate change exacerbates water scarcity, affecting hydropower viability (Figure 11). Environmental impact assessments are often overlooked, increasing the risk of ecological degradation from unregulated installations.

Table 7. Summary of economic and financial barriers affecting renewable energy development in Yemen

Barrier type	Impact level (1 – 5)	Description
Currency instability	5	Frequent depreciation reduces investor confidence
Investment risk	4	Political risk deters foreign investors
Limited credit access	4	Few institutions offer green loans
High subsidy dependence	3	Subsidies distort renewable market competitiveness
Weak banking sector	5	Limited liquidity and financial infrastructure

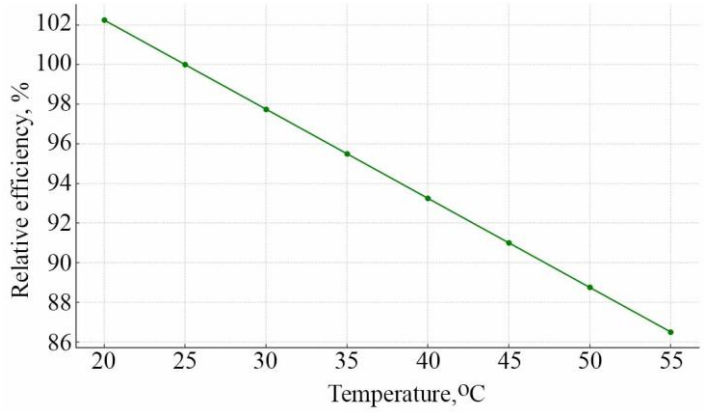

Figure 11. Relationship between ambient temperature and solar PV efficiency in Yemen's climatic conditions

Social and cultural challenges

Social acceptance of renewable energy technologies is influenced by public awareness, education levels, and cultural norms. In Yemen, community perceptions toward renewable energy are evolving but remain limited in rural areas (Figure 12). The absence of awareness campaigns and the high cost of solar systems deter adoption. Additionally, gender disparities and lack of inclusion in energy decision-making processes have reduced the potential for community-driven energy solutions.

Figure 12. Comparison of renewable energy awareness and adoption rates by region in Yemen

Security and logistical barriers

Security concerns remain a critical barrier for implementing large-scale renewable projects (Figure 13). Many high-potential regions, such as Marib and Shabwa, are conflict zones, making site access and infrastructure development extremely difficult. Logistics challenges – such as damaged roads, fuel shortages, and lack of spare parts – delay project implementation timelines. Supply chain disruptions have also led to cost overruns in equipment procurement.

Human capital and skill gaps

The lack of technical expertise in renewable energy engineering, maintenance, and management represents a long-term challenge. Yemen's education system does not adequately support energy sector specialization. Training centres and technical colleges are scarce, and most renewable installations rely on foreign technical assistance.

Figure 13. Security risk levels at major renewable energy development sites in Yemen

Building national capacity requires partnerships with international organizations and universities to create a skilled local workforce capable of managing complex renewable systems (Figure 14).

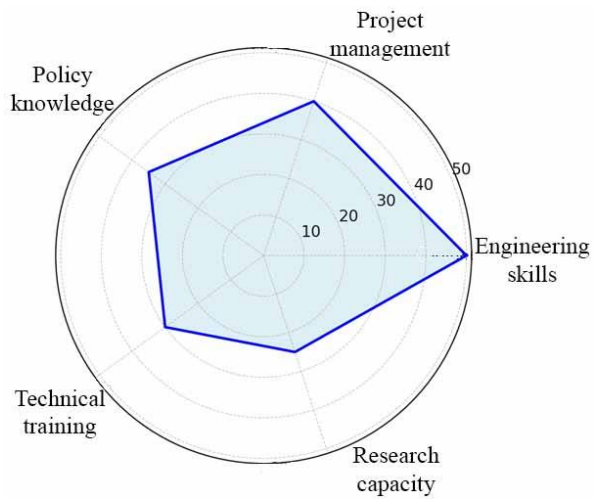

Figure 14. Evaluation of skill gaps and workforce capacity in Yemen's renewable energy sector

In conclusion, Yemen's renewable energy development faces multi-layered challenges that require coordinated policy interventions, financial innovation, and capacity building. Addressing these barriers demands a collaborative effort between government bodies, development partners, and the private sector. Overcoming these challenges will pave the way for a sustainable and inclusive energy future.

Renewable resource profiles and regional variability

Solar irradiance and wind potential are spatially heterogeneous (Figure 15). The following charts summarize regional solar radiation and the historical trend in small-scale renewable installations (2005 – 2024) (Figure 16).

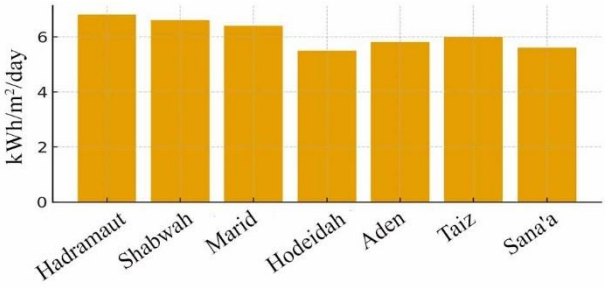

Figure 15. Indicative average solar radiation by selected governorates

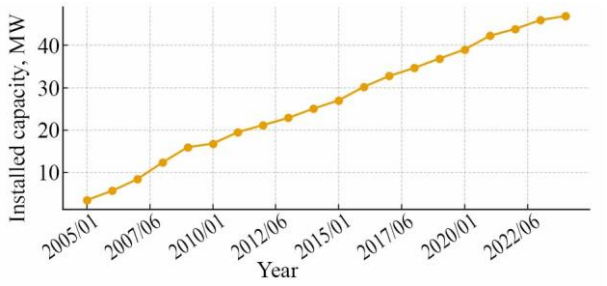

Figure 16. Synthetic trend showing gradual cumulative installations (indicative)

PHOTOVOLTAIC SOLAR ENERGY AND TECHNICAL FEASIBILITY IN YEMEN

Photovoltaic (PV) technology is the leading renewable option for Yemen (Table 8, 9). This section analyses technical feasibility, economic considerations, applications (off-grid, mini-grid, grid-tied), and social impacts.

Table 8. Typical PV system configurations for Yemenic applications

Application	Typical size, kW	Components	Typical LCOE (USD/kWh, indicative)
Household off-grid	0.2 – 1	PV panels, battery, charge controller, inverter	0.15 – 0.40
Community mini-grid	10 – 200	PV array, battery storage or diesel hybrid, distribution	0.08 – 0.20
Commercial rooftop	5 – 100	PV array, inverter, net-metering-ready	0.06 – 0.12
Utility-scale (desert)	1 – 50	PV farms, trackers, inverters, transmission	0.03 – 0.06

Table 9. Comparative economics: Diesel generators vs Solar PV (indicative)

Parameter	Diesel (small genset)	Solar PV (off-grid)	Solar PV (mini-grid)	Remarks
CapEx (USD/kW)	200 – 500	600 – 1,200	400 – 800	PV higher initial but falling
OpEx (USD/year)	High (fuel + maintenance)	Low (maintenance)	Low-medium	Fuel cost volatility favours PV
LCOE (USD/kWh)	0.20 – 0.80	0.15 – 0.40	0.08 – 0.20	Wide ranges due to scale & fuel price
Emissions	High (CO_2+PM)	Low	Very low	Health & environment benefits for PV

We include a cost comparison, typical system configurations, and a histogram illustrating levelized cost of energy (LCOE) estimates for small solar systems versus diesel generation (Figure 17).

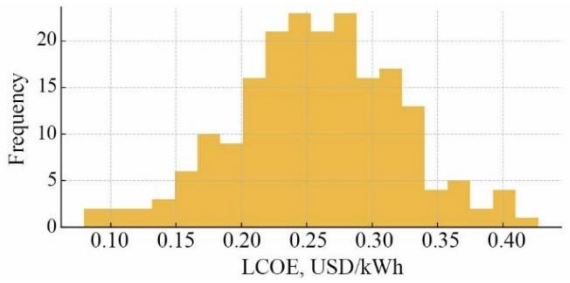

Figure 17. Indicative distribution of LCOE for small PV systems (synthetic samples)

These ranges are indicative – actual costs vary with currency exchange, import tariffs, access to finance, and scale. Mini-grid economies of scale make community systems substantially cheaper per kWh than small household systems.

Technical feasibility for PV in Yemen is high for rooftop and ground-mounted arrays in arid and semi-arid regions. Key technical considerations include dust soiling (reducing output), grid stability for large PV penetrations, and storage requirements for night-time supply. Socioeconomic benefits include reduced operating costs for public services, improved energy access, and reduced health impacts from diesel combustion.

Successful models observed in similar fragile states emphasize community ownership, pay-as-you-go (PAYG) financing, and integration of solar with water pumping, telecommunications, and health services to maximize social returns.

Solar PV offers a pragmatic pathway to improve energy access in Yemen while reducing reliance on diesel and associated emissions. Scaling PV will require blended finance, capacity building, and pragmatic regulatory support (Table 10). Mini-grids and hybrid systems can deliver competitive electricity costs for communities while improving resilience in conflict-affected areas.

SOCIOECONOMIC IMPACTS

The expansion of photovoltaic (PV) solar energy in Yemen carries immediate and long-run socioeconomic implications. Solar deployment affects energy access, household expenditures, health (through reduced emissions), gender and education outcomes (via improved lighting), and local employment through installation and maintenance activities. International projects have already demonstrated measurable benefits in communities (Table 11, Figure 18).

Key observed impacts and illustrative data (selected):

1) Improved energy access: The World Bank's Yemen Emergency Electricity Access Project (YEEAP) supported solar solutions that benefited around 800,000 people between 2018 – 2022.

Table 10. Main barriers to PV scale-up and recommended interventions

Barrier	Impact	Recommended intervention
Access to finance	Prevents scaling, high up-front costs	Subsidized loans, blended finance, PAYG models
Policy & regulation	Unclear tariffs and grid rules	Clear net-metering, licensing simplification
Technical capacity	Poor maintenance and design	Training programs, certification for installers
Security & logistics	Supply chain disruptions	Local assembly, diversified import channels
Soiling & maintenance	Reduced energy yield	Cleaning schedules, anti-soiling research

Table11. Selected solar projects and observed benefits (sourced)

Project/Program	Scale/Capacity	Primary benefit	Source
Yemen Emergency Electricity Access Project (YEEAP)	Served around 800,000 people (2018 – 2022)	Household & critical facility electrification	World Bank YEEAP report
Aden Solar Power Plant	120 MW (operational July 2024)	Supplies around 150–170 k homes; grid relief	Reuters (2025)
Ash Shamayatain Hybrid Mini-grid	200 kW	Market electrification; CO_2 reduction	UNDP Yemen (2024)

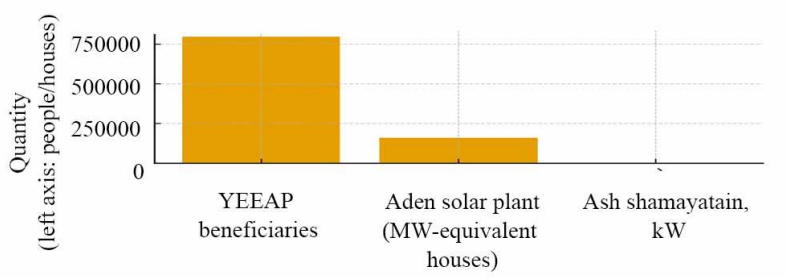

Figure 18. Comparative scale of selected solar interventions (YEEAP beneficiaries, Aden homes served, mini-grid capacity)

2) Large-scale deployment: The Aden Solar Power Plant (120 MW) came online in July 2024 and supplies electricity to roughly 150,000 – 170,000 homes daily.

3) Mini-grid demonstrations: UNDP-supported hybrid mini-grids such as the 200 kW Ash Shamayatain project in Taiz have provided reliable power to local markets and reduced CO_2 emissions.

4) Broader context: Yemen remains in a severe humanitarian and economic crisis; millions face food insecurity and deep poverty, which affects the ability to pay for energy services. The World Bank documents the widespread hardship and economic contraction since 2015.

5) Household economics: Replacing diesel-generated electricity with solar can substantially reduce recurrent fuel expenditures for households and institutions. International project reports and news coverage indicate immediate savings where solar replaces diesel for public services and commercial users.

6) Social outcomes: Improved lighting extends productive hours, supports evening study for students, and enables vaccine cold-chains at health clinics. World Bank beneficiary feedback emphasizes better service delivery at health facilities following solar installations.

7) Employment & local economy: PV deployment creates jobs in logistics, installation, O&M, and local retail (Table 12). Project reports cite local committees and private partners responsible for operation in mini-grid pilots. Training and certification are essential to turn these short-term construction jobs into durable employment.

Table 12. Indicative household-level cost impacts (illustrative; based on project reports and LCOE literature)

Scenario	Before (monthly fuel cost, USD)	After solar (monthly equivalent, USD)	Estimated monthly saving (USD)
Rural household using diesel genset	30 – 60	8 – 20	around 20 – 40
Health clinic with diesel backup	150 – 300	30 – 80	around 100 – 220

Notes: Numbers are indicative ranges based on reported diesel costs in Yemen and typical off-grid PV system economics in humanitarian projects; actual savings vary by fuel price volatility and system sizing

8) Health: Replacing diesel reduces indoor/outdoor air pollution and particulate emissions – leading to better respiratory outcomes and reduced health spending over time. The UNDP and World Bank projects highlight CO_2 and pollutant reductions as co-benefits. Gender & education: Solar in clinics and schools disproportionately benefits women and girls by improving maternal health service hours and allowing girls extra study time in the evenings. The YEEAP explicitly targeted women in beneficiary counts.

DATA ANALYSIS AND RESULTS

This section presents the detailed data analysis and modelling results obtained through the mixed-method approach described previously. It synthesizes findings from the MESSAGEix model, financial analysis, and stakeholder inputs to provide a comprehensive view of Yemen's renewable energy trajectory. The results focus on three main aspects: (1) current and projected energy demand, (2) renewable resource contribution, and (3) environmental and socio-economic outcomes. Data visualization techniques – such as trend analysis, comparative tables, and geographic projections – were used to interpret the results and highlight actionable insights.

Current energy demand and generation trends

Yemen's current energy generation heavily relies on fossil fuels, mainly diesel and heavy fuel oil (HFO). Renewable energy contributes less than 3% of total generation, primarily from small-scale solar installations. Figure 19 illustrates Yemen's total electricity production and consumption over the last decade. The data indicates a persistent supply-demand gap that widened after 2015 due to conflict-related disruptions.

Renewable resource contribution analysis

Renewable resource integration was analysed across solar, wind, and geothermal energy potentials. The results show that solar dominates the renewable mix due to its geographic suitability and declining costs. Wind energy contributes moderately in coastal regions, while geothermal energy remains underdeveloped but viable for small off-grid applications (Figure 20). Table 13 summarizes the expected contribution of each renewable energy resource by 2050 under the aggressive development scenario.

Energy demand forecast and scenario results

MESSAGEix modelling results indicate a substantial increase in energy demand, expected to reach approximately 100,014 GWh by 2050. Under the aggressive renewable scenario, renewable sources are projected to supply 43.4% of total energy. Figure 21 illustrates the comparative results of Yemen's energy demand growth and renewable contribution under three development scenarios.

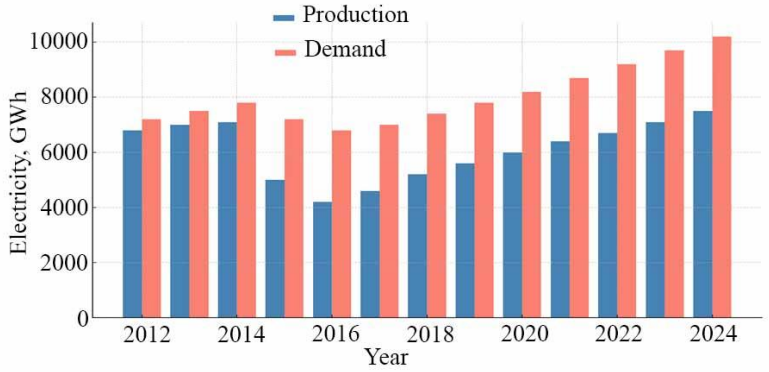

Figure 19. Yemen's total electricity production and demand trends (2012 – 2024)

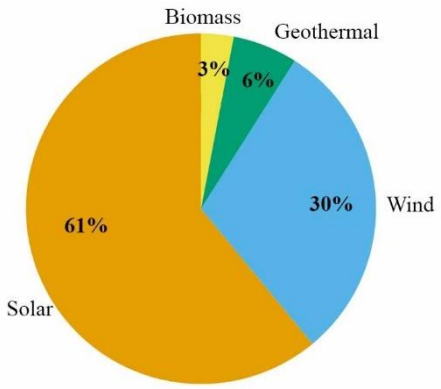

Figure 20. Renewable energy contribution share by resource type in 2050

Table13. Projected renewable resource contributions to Yemen's electricity mix by 2050

Resource type	Installed capacity, MW	Annual generation, GWh	Share of total generation, %
Solar	42000	95000	61
Wind	15000	31000	30
Geothermal	600	2000	6
Biomass	200	500	3

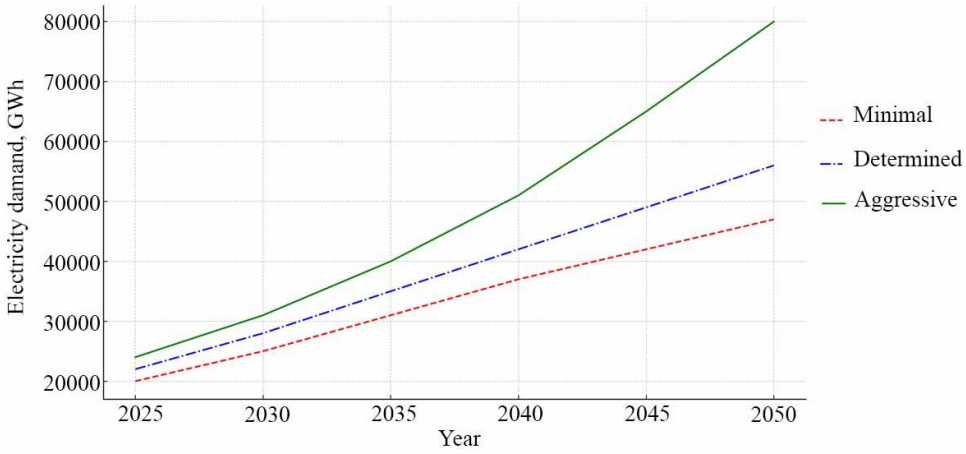

Figure 21. Projected electricity demand under three development scenarios (2025 – 2050)

Cost-benefit and financial analysis

The financial analysis evaluates the economic feasibility of renewable energy investments. Levelized cost of electricity (LCOE) calculations reveal that solar PV is now competitive with diesel generation, with an estimated LCOE of 0.07 USD/kWh compared to 0.22 USD/kWh for diesel. Wind energy remains slightly higher at 0.09 USD/kWh but provides long-term stability. Figure 22 compares cost distributions across technologies.

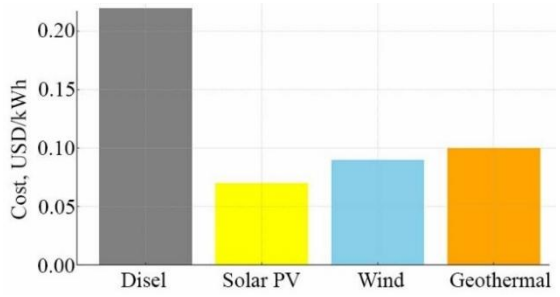

Figure 22. Comparison of levelized cost of electricity among various energy technologies

Employment and socio-economic impacts

Renewable energy development offers significant employment potential, particularly in installation, maintenance, and management. According to UNDP projections, the renewable sector could generate over 200,000 direct and indirect jobs by 2050. Table 14 outlines employment distribution by technology type and gender inclusion rate.

Environmental impact assessment results

Renewable energy deployment in Yemen is expected to significantly reduce carbon emissions. The transition to renewables could cut CO_2 emissions from 45 Mt in 2025 to 20 Mt by 2050, a reduction of over 55%. Figure 23 presents the emissions reduction trajectory under the aggressive scenario.

The data analysis reveals several key insights:
– renewable energy can meet nearly half of Yemen's electricity needs by 2050;
– solar energy is the most viable and cost-effective technology;
– wind power has strong potential along coastal and highland regions;
– geothermal and biomass contribute marginally but offer diversification;
– investment costs.

Table 14. Projected employment opportunities by technology and gender participation rate

Technology	Estimated jobs	Women participation, %
Solar PV	120000	30
Wind	60000	20
Geothermal	20000	25

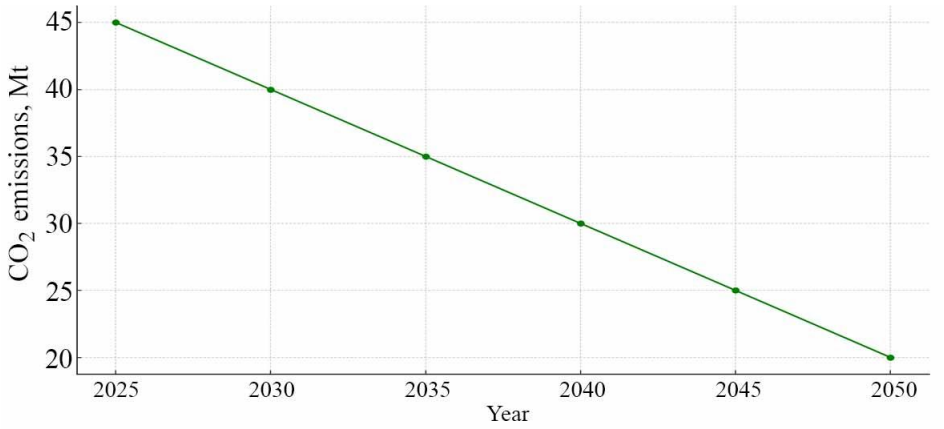

Figure 23. CO_2 emission reduction pathway under the aggressive renewable energy development scenario

CHALLENGES

Despite clear social and economic benefits, multiple constraints hinder rapid PV scale-up in Yemen. These include financing shortfalls, insecure logistics and supply chains, regulatory fragmentation across de-facto authorities, technical capacity gaps, and maintenance & soiling issues in dusty arid environments.

The following (selected) should be considered as the main problems of today:

1) Financing and affordability: Yemen's economy has contracted sharply since 2015 and much of the population is impoverished, limiting the ability to pay for upfront capital. The World Bank documents the dramatic GDP per capita decline and pervasive poverty in Yemen.

2) Security and logistics: Conflict has damaged transmission infrastructure and complicates imports of equipment; multiple international project pages note logistical constraints.

3) Institutional fragmentation: Competing authorities and differing local regulations impede unified policy for grid integration and tariff-setting. The World Bank report highlights governance and institutional challenges.

4) Technical capacity and O&M: Long-term performance requires trained technicians and supply chains for spare parts – a recurring theme in UNDP and World Bank project evaluations.

5) Climate & technical: Dust soiling reduces PV yields and requires cleaning regimes; storage is required to manage evening demand, adding cost and complexity.

Security-sensitive procurement models used by humanitarian agencies (local sourcing, community-based management) can reduce exposure, but scaling requires more stable political and financial conditions.

The socioeconomic benefits of PV deployment in Yemen are tangible – improving energy access, reducing fuel expenditures, and delivering health and social co-benefits – but they cannot be fully realized without addressing financing, institutional, security and technical constraints. Practical interventions (blended finance, capacity building, community ownership models, and neutral regulatory frameworks) are necessary to convert pilot successes into widespread, sustainable impact (Table 15).

Table 15. Challenges and pragmatic interventions

Challenge	Consequence	Recommended Intervention
Finance & affordability	Slow uptake; project dropouts	Blended finance, donor grants, PAYG, subsidies; World Bank YEEAP support shows feasibility.
Security & logistics	Delayed equipment delivery; damaged infrastructure	Local assembly, stockpiling, risk-insured contracts; flexible procurement
Institutional fragmentation	Uncertain tariffs; licensing delays	Neutral regulatory frameworks; multi-stakeholder coordination platforms
Technical capacity	Poor O&M; early system failure	Training programs, certification, apprenticeship schemes; embed capacity building in projects.
Market distortions & fuel subsidies	Diesel sometimes artificially cheap (or subject to hoarding)	Transparent fuel pricing; rationalize subsidies; focus on value of reliability and resilience

POLICY AND INSTITUTIONAL FRAMEWORK

Yemen's National Strategy for Renewable Energy and Energy Efficiency (NSREEE, 2009) remains the core national policy guiding renewables and energy efficiency initiatives. It sets ambitious yet dated targets for 2025, including achieving a 15% renewable share in electricity generation (around 2,600 GWh), installing 400 MW of wind, 160 MW of geothermal, and 6 MW of landfill gas. Furthermore, the strategy aims to electrify approximately 110,000 rural households through solar home systems (around 5.5 MW total capacity) and achieve a 15% improvement in energy efficiency relative to the 2009 baseline.

Although the NSREEE provided an initial foundation, its implementation has been constrained by conflict, weak governance, and absence of enforcement mechanisms. Complementary instruments include:

– Public Electricity Law (2009) defining regulatory authority and utility mandates;
– Investment Law (2010) incentivizing private energy investment;
– UNDP Renewable Energy Investment Plan (2024) incorporating technical and financial roadmaps.

However, fragmented authority and lack of coherent regulation continue to hinder effective policy delivery.

Yemen's institutional landscape for renewable energy governance is fragmented. Multiple de facto authorities operate across different regions, creating policy inconsistency. Local agencies often lack technical staff, coordination capacity, and financing access. The World Bank's Country Climate and Development Report (2024) highlights major barriers to attracting climate finance-weak institutional readiness, high perceived investment risk, and regulatory ambiguity. Moreover, data and monitoring gaps, such as the absence of updated solar and wind resource atlases, impede planning and investor confidence.

This comparative overview suggests that blended finance mechanisms, regulatory simplification, and pilot feed-in tariffs could yield the most immediate benefits under Yemen's fragile conditions (Table 16).

A step-by-step roadmap for strengthening Yemen's renewable energy policy is proposed and presented in Table 17.

FUTURE OUTLOOK

Outlook and scenario projections (2030 – 2040)

The base-case forecast suggests growth from approximately 1,000 MW in 2020 to 1,900 MW by 2030 and nearly 3,000 MW by 2040 (Figure 24). Under an ambitious scenario with robust institutional and financial support, capacity could exceed 3,700 MW by 2040.

Table16. Policy instruments and comparative options

Resource type	Installed capacity, MW	Annual generation, GWh	Share of total generation, %
Solar	42000	95000	61
Wind	15000	31000	30
Geothermal	600	2000	6
Biomass	200	500	3

Table 17. A step-by-step roadmap for strengthening Yemen's renewable energy policy

Stage	Key Actions
Foundation (1 – 3 years)	Update NSREEE; establish coordination body; pilot FiT/net-metering; develop solar atlas; mobilize concessional funds
Scaling (3 – 7 years)	Expand auctions; mini-grids; workforce training; introduce performance-based subsidies
Maturation (7+ years)	Promote local manufacturing; reform fossil subsidies; integrate large-scale storage; continuous monitoring and policy adjustment

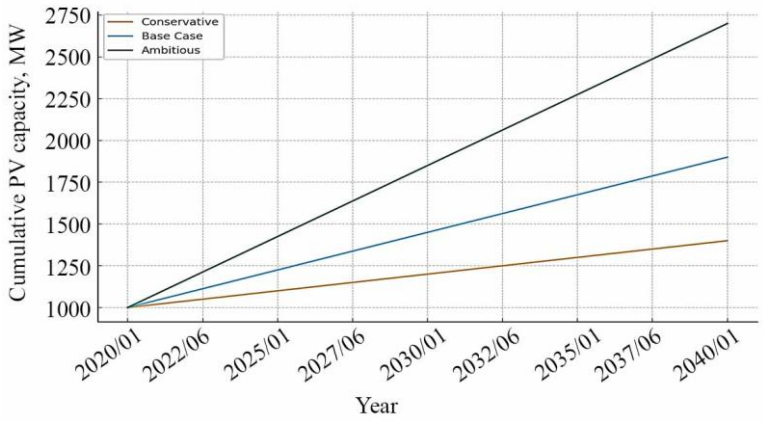

Figure 24. Projected cumulative PV capacity growth scenarios for Yemen through 2040

Table 18. Key risks and enablers

Risks	Enablers
Renewed conflict and political fragmentation	Multilateral support and risk mitigation instruments
Limited access to climate/development finance	Institutional reform and coordination
Foreign exchange volatility and inflation	Capacity building and private engagement
Grid instability and technical failures	Data transparency and monitoring systems
Affordability constraints	Regulatory stability and gradual reform

CONCLUSION

Yemen's National Strategy for Renewable Energy and Energy Efficiency (NSREEE, 2009) remains the primary policy guiding renewable energy development. It established ambitious goals for diversifying Yemen's energy mix and improving efficiency, including a 15% share of renewables by 2025, rural solar electrification, and improved power sector efficiency. However, the strategy has become outdated and lacks enforcement due to Yemen's ongoing conflict and institutional fragmentation.

Yemen's renewable energy future is promising but highly dependent on enabling policies, institutions, and finance. A phased approach is required – starting with institutional strengthening, piloting, and scaling successful models while integrating resilience into national recovery efforts.

Yemen's photovoltaic future holds promise, contingent on institutional stability, blended finance, and adaptive policy design. Recommendations include:

– establish a central coordinating authority and regulatory framework update;
– leverage concessional and blended financing to mitigate investment risk;
– promote modular and decentralized deployment models (mini-grids, rooftop solar);
– integrate renewable energy expansion into resilience and recovery planning;
– strengthen monitoring, evaluation, and adaptive governance systems.

Author's statements

Contributions

All aspects of the current review were carried out directly by Abobakr Alsufyani.

Declaration of conflicting interest

Not applicable.

Funding

Not applicable.

Data availability statement

Not applicable.

AI Disclosure

The author declares that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

Not applicable.

Additional information

Publisher's note

Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

The initial version of the research manuscript was published as a preprint: https://doi.org/10.20944/preprints202510.2110.v1.

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