FUTURE OPPORTUNITIES AND CHALLENGES FOR SUSTAINABLE ENERGY TRANSITION IN QATAR: A COMPREHENSIVE CASE STUDY OF POLICY, DRIVERS AND TECHNOLOGICAL ACHIEVEMENTS

OPORTUNITĂȚI ȘI PROVOCĂRI VIITOARE PENTRU TRANZIȚIA ENERGETICĂ DURABILĂ ÎN QATAR: UN STUDIU DE CAZ CUMPĂRĂTOR AL POLITICILOR, FACTORILOR MOTORI ȘI REALIZĂRILOR TEHNOLOGICE

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Abstract. *Sustainable energy transitions in hydrocarbon-dependent economies, such as Qatar, are fraught with technical feasibility, economic viability, and policy coherence challenges. Despite these hurdles, Qatar has emerged as a leader in sustainable energy investments and renewable infrastructure development since the 2010s. This paper analyzes Qatar's energy diversification efforts from 2014 to 2024 and how they reshape its economic landscape and socio-economic dynamics. Through a comprehensive review of approximately 57 scientific sources, data sets, and case studies, this study identifies and analyzes the unique drivers, challenges, and opportunities associated with Qatar's energy transition. The paper delves into Qatar's government's strategic initiatives to enhance public awareness, foster innovation, and stimulate research and development in the energy sector. Moreover, this review introduces a novel perspective on Qatar's readiness for the sustainable energy transition, emphasizing the interplay between limited energy diversification, global energy market fluctuations, and policy implementation and monitoring effectiveness. The findings suggest that while Qatar is strategically positioned to advance its sustainable energy goals, it must navigate significant obstacles, including the volatility of international markets and the complexity of enforcing and adapting policies in a rapidly evolving energy landscape.*

Keywords: Renewable Energy, Solar, Wind, Fossil Fuels, Power, Electricity, Challenges.

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Rezumat. *Tranzițiile energetice durabile în economiile dependente de hidrocarburi, cum ar fi Qatarul, sunt pline de provocări legate de fezabilitatea tehnică, viabilitatea economică și coerența politicilor. În ciuda acestor obstacole, Qatar a devenit lider în investițiile în energie durabilă și dezvoltarea infrastructurii regenerabile încă din anii 2010. Această lucrare analizează eforturile Qatarului de diversificare energetică din 2014 până în 2024 și modul în care acestea remodelează peisajul său economic și dinamica socio-economică. Printr-o analiză cuprinzătoare a aproximativ 57 de surse științifice, seturi de date și studii de caz, acest studiu identifică și analizează factorii determinanți, provocările și oportunitățile unice asociate cu tranziția energetică a Qatarului. Lucrarea analizează inițiativele strategice ale guvernului Qatarului pentru a spori gradul de conștientizare a publicului, a promova inovația și a stimula cercetarea și dezvoltarea în sectorul energetic. Mai mult, această analiză introduce o perspectivă nouă asupra gradului de pregătire al Qatarului pentru tranziția energetică durabilă, subliniind interacțiunea dintre diversificarea energetică limitată, fluctuațiile pieței energetice globale și implementarea politicilor și eficacitatea monitorizării. Constatările sugerează că, deși Qatar este poziționat strategic pentru a-și atinge obiectivele energetice durabile, trebuie să depășească obstacole semnificative, inclusiv volatilitatea piețelor internaționale și complexitatea aplicării și adaptării politicilor într-un peisaj energetic în rapidă evoluție.*

Cuvinte cheie: Energie regenerabilă, Solară, Vânt, Combustibili fosili, Energie electrică, Electricitate, Provocări.

1. Introduction

Most Gulf Cooperating Council (GCC) countries are known to be highly hydrocarbon-dependent and at the forefront of oil and gas (O&G) production that fuels the World's energy demand and requirement. Notably, paradigms have changed significantly since the last decade, as the energy sector is undergoing a rapid and substantial transition towards greener, low-carbon, and sustainable energy mix profiles [1]. The implications for GCC economies highly dependent on petroleum and hydrocarbon-derived energy mixes have become clear: energy security and economic growth are subject to volatility shortly as the World adjusts to low-carbon or carbon-neutral energy. Incentivization for this purpose has proven effective for the GCC [2].

As a significant player in the global energy market, Qatar's move towards renewable energy indicates a broader regional trend in the Middle East and North Africa (MENA) region [4]. This shift presents an opportunity for Qatar to set an example for other countries in the region,

showcasing how resource-rich GCC nations can successfully diversify their energy portfolios while contributing to global sustainability efforts. The challenge associated with this transition is perhaps best realized by considering the estimated costs of the energy transitions, for which the costs are relatively large for Qatar, the UAE and Saudi Arabia, similar to one another [5]. Qatar has been known to become less liable for foreign debt obligations owing to its successful sustainable energy transition initiatives (see Figure 1).

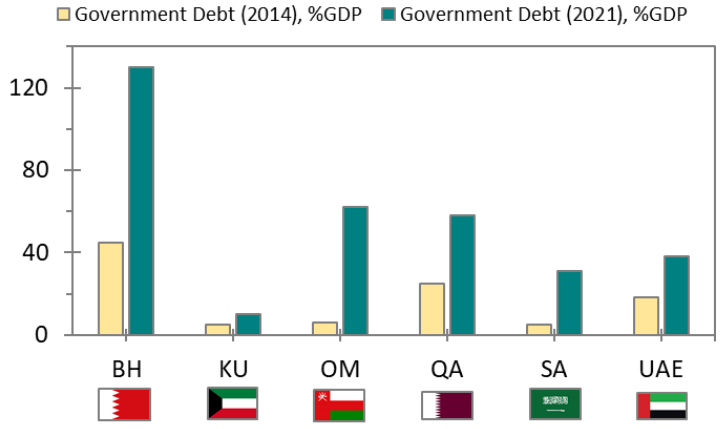

Figure 1. Qatar reported a substantial reduction in Government Debt Liabilities owing to the increasing energy transition towards renewables. Data from BNP Paribas [3]

Furthermore, this review article provides a comprehensive and exhaustive case study-based review of how the Qatari energy transition policy frameworks, such as the Qatar National Vision 2030 and Qatar National Development Strategy, emphasize sustainability and environmental preservation as key national priorities [6, 7]. The work ascertains how various Qatari project cases contribute to technological innovation in harsh climates, Qatar's economic diversification and socio-economic implications. These include (but are not limited to) the Al Kharsaah Solar Project and Blue Hydrogen projects [8]. Qatar's challenges, opportunities and achievements driven by policy, technological innovation and investment (or lack thereof) in sustainable energy transition have been further analyzed. In this regard, it is imperative to analyze how Qatar differs from its peers and whether it has successfully mitigated its energy transition challenges more substantially than its peers. This article delves into the comprehensive scientific analysis of Qatar's energy transition. It underscores the country's

strategic initiatives in diversifying its energy mix, highlighting its endeavours to reduce carbon emissions and bolster the adoption of renewable energy technologies.

2. Methodology

This review has employed the case study and conventional review-based methodology, commonly ascribed for reviews on sustainability energy policy research [9], such as this review article. This review article has considered case studies, academic articles, industrial and official whitepapers, and reports acquired from peer-reviewed and authentic databases. Literature considered in this review spans from the previous decade to date (2014 - 2024). The databases in question are Google Scholar, Scopus, Springer Link, and Emerald Insights. Additionally, official repositories, including the International Monetary Fund (IMF), the World Bank, and the Qatari government's archives, provide critical policy documents and economic indicators relevant to Qatar's energy transition. Furthermore, Boolean search strategies were systematically employed to refine literature searches, ensuring high retrieval precision. Search terms such as "Qatar AND Sustainability OR Energy Transition AND Policy AND Socio-economic Impact" enabled targeted extraction of studies that analyze policy effectiveness, technological advancements, and economic implications. Despite these methodological strengths, limitations exist in accessing real-time data on ongoing projects, necessitating future research that integrates primary data collection and stakeholder interviews to bridge existing knowledge gaps. [10, 11]. The Boolean strategy employed in this regard for the literature review search is as under:

"Qatar" AND "Sustainability" OR "Energy Transition" AND "Policy" AND "Socio-economic" OR "Economic" AND "Impact" And, "Qatar" AND "Sustainability" OR "Energy Transition" AND "Project" OR "Example" AND "Socio-economic" OR "Economic" AND "Impact".

The Boolean search strategy plays a crucial role in refining literature searches by ensuring precision and relevance in retrieving scholarly sources on Qatar's sustainable energy transition. This study employs a structured Boolean approach to systematically filter academic articles, policy reports, and industry whitepapers from databases such as Google Scholar, Scopus, and Springer Link. By utilizing specific search operators—such as "Qatar" AND "Sustainability" OR "Energy Transition" AND "Policy" AND "Socio-economic Impact"—the study enhances the accuracy of literature selection,

reducing the inclusion of non-relevant or outdated materials. This method enables the identification of key themes, including policy frameworks, renewable energy projects, and economic diversification efforts. Additionally, the strategy ensures that literature from both global and local perspectives, such as Qatar's National Vision 2030 and reports from the International Renewable Energy Agency (IRENA), are comprehensively reviewed [1, 3, 12].

3. Literature Review

Qatar's energy transition has evolved significantly over the past decade, influenced by shifts in government policies, global sustainability commitments, and advancements in renewable energy technologies [5]. Between 2014 and 2024, Qatar has progressively integrated sustainability into its national development agenda, particularly through initiatives such as the Qatar National Vision 2030 and the Qatar National Development Strategy (NDS) 2018–2022. Early efforts (2014–2018) primarily focused on policy formulation and feasibility studies for renewable energy projects, while the latter years (2019–2024) witnessed accelerated investments in solar, wind, and hydrogen technologies, most notably the Al Kharsaah Solar Power Project and Qatar's Blue Hydrogen Initiative. Furthermore, global energy market dynamics, including oil price fluctuations and international climate agreements like the Paris Accord (COP21), have shaped Qatar's renewable energy commitments. Despite these advancements, the country still faces challenges in fully integrating renewables into its energy mix, necessitating ongoing policy adjustments and infrastructure investments [1]. A detailed analysis of energy production metrics, policy shifts, and investment trends over this period provides crucial insights into Qatar's progress and the obstacles that remain in achieving a low-carbon, sustainable energy future.

3.1. Drivers of Energy Transition in Qatar:

3.1.1. Economic Dimensions

This transition is not only a result of the changing geography of energy but it is a shift in the right direction due to the changing nature of the global energy system. This shift from focusing on fossil fuel commodities to

renewable energy and sustainability is quite a dramatic change in direction for the country. Qatar has largely depended on the oil and gas industry and this has proven with the associated risks of oil price volatility and the fact that hydrocarbon resources are finite. Nevertheless, Qatar is at the forefront of a rather challenging process of transforming the energy landscape onto a more sustainable one [3]. Additionally, while recognizing these risks, the country actively pursues economic diversification as a key driver for its energy transition. Diversifying the energy mix helps reduce the dependency on oil and gas revenues, thus making the economy more resilient to global market changes [13]. The shift towards renewable energy is seen as an environmental or social responsibility and a strategic economic move to ensure long-term sustainability and stability.

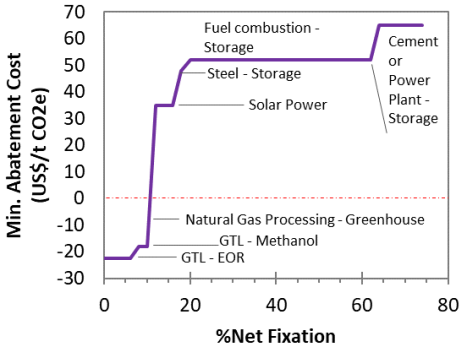

Figure 2. Cost Abatement Curve for Qatar [14]

Theoretical Models such as the TIMES model have allowed policymakers and energy transition cost estimators to realize the optimization of a low-hydrocarbon and renewable energy mix. The use of this model has reportedly allowed Qatar to develop effective policies for ensuring sustainability across its entire economic ecosystem, from fuel extraction and refining or renewable power generation—including energy imports and exports—through to transmission, distribution, and end-use in all sectors of the energy economy (buildings, transport, power generation, and industry [5]. Costs across these economic and non-economic activities have contributed much to the average GCC burden on renewable resources, especially Qatar's. In this regard, the cost factor is a substantial economic driver for Qatar, which is also evident from the cost abatement curve (see **Error! Reference source not found.**), where Qatar can remove 80% of the costs associated with CO_2e per US $/tonne of fuel, by switching to solar power.

Table 1. **Summary of Opportunity and Challenges Evident for Qatar in its Sustainable Energy Transition**

		Opportunity	Challenge	References (Name, Year, Type)		
1	Techno-economic	• Good solar potential • Relatively viable wind potential • Cost abatement is substantial (80%) if Qatar transitions 10% of its energy production to solar. • Desalination leads to higher desertification. • Non-hydrocarbon GDP per capita increased at a higher rate than other GCC members (+5%) last decade. • Hydrogen production has more economic potential than that of Australia and other countries. • Low adaptability of renewables to the national grid. • Significant projects at a large scale with higher energy and cost-efficiency than conventional power plants, e.g. Al-Kharsaah, yielding $14.03/MWh cost instead of the expected $24.6 – $39.2/MWh. • Hydrogen production is marred by distribution problems and the ammonia transport option is highly viable. • Wind farms at Haloul could outperform gas-operated turbines by +366 kWh/kW/yr. At a total cost of USD 289,000	• Reducing the economy's 'heavy' reliance on conventional hydrocarbon mix (primarily gas) • Slowed energy diversification will incur higher costs in the long-term • Poor performances in terms of renewable energy mix and consumption per capita • High water consumption • Hydrocarbon asset desertification leads to substantial economic loss • Solar power projects are vulnerable to technical failures in harsh climates and incur high R&D costs to stay resilient. • The renewable energy mix is too dependent on solar (lower energy security and resilience). • Wind power is less viable than solar.	Alashqar et al.	2022	Article
				Hasid et al.	2023	Case Review
				Perez-Astudillo et al.	2022	Article
				Munawwar & Ghedira	2014	Article
				Al-Mohannadi & Al-Mohannadi	2022	Case Review

Table 1 (continued)

		Opportunity	Challenge	References (Name, Year, Type)		
2	Socio-economic	• Social discontent with higher prices of hydrocarbon fuels • Qatari consumers are relatively more aware and likely to adopt cheaper, renewable alternatives, unlike their GCC peers • Employment opportunities are expected to continue to rise in Qatar owing to the non-hydrocarbon/renewable sectors • High investments in infrastructure, e.g., student housing, introducing carbon audits for lowering CO_2e, and GHGe inventorisation	• Vulnerability for continued investment owing to human rights indices and stakeholder trust regarding labor welfare. • Lack of an agile, skilled workforce in the short or medium term to cope with energy transition at a rapid pace • Increasing focus on education, awareness and engagement is needed.	Richer	2015	Article
				Sever & Tok	2022	Article
				Al-Musalmani & Maalouf	2022	Article
3	Politics and Policy	• O&G dependence influences policymaking, though investor pressure has improved renewable energy incentivization • Adequate and robust policy framework defined by the QNV 2030, the NDS 2018-2022, QEECS 2021 and other regulations • Increasing PPP (3H) • The policy promotes technological innovation and sustainability improvements across Qatari O&G industries (e.g., zero-flaring) • Gradual increase in renewable energy investments and compliance with carbon-neutral targets • Compliance with binding agreements such as COP21 and Paris.	• The policy is not adequately enforced and only provisions are effective to date. • The policy can potentially offset losses due to hydrocarbon asset desertification as investment and capital influx increases in the renewable sector. • Tight monetary policy, e.g., fixed investments	Wright	2021	Case Review
				Kaminekar & Stewart	2015	Report

3.1.2. Politico-Economic Dimensions

A policy-driven transition towards sustainability and the friction caused by Qatar's oil and gas (O&G) giants and operators is a case that is common with GCC countries [5]. Energy geopolitics are pivotal in driving the price of energy commodities, be they renewable or non-renewable. Additionally, this politico-economic dimension frequently drives technological innovation and the extent to which sustainability innovation a country conducts vis-à-vis international/multilateral support or restrictions [15]. Qatar's strategic geographic location also offers unique opportunities for the export of renewable energy and collaboration with neighboring countries. The country could potentially become a hub for renewable energy in the MENA region, exporting excess solar energy or green hydrogen to neighbouring countries, thus contributing to the broader regional energy transition [13]. Much like its GCC neighbors, the energy transition in Qatar has followed similar parallels in terms of increasing renewable energy investments and compliance with carbon-neutral targets. The political drive in this regard follows a competing nature and Qatar is well-oriented towards research and innovation in the renewable energy sector. A political push-driven diversification in this regard is well observed for the UAE and Qatar, of which the latter is more leading in the recent decade than other GCC members [4, 12, 16]. This owes to previous poor performances in renewable energy mix and consumption per capita.

3.1.3. Social Dimensions

The IMF mentions that for GCC countries like Qatar, mounting pressures exist from domestic and global consumer social discontent for higher energy prices for traditional fuels [1]. Meltzer et al. further note that in certain instances, social drivers in Qatar would not restrict sustainability initiatives such as carbon storage [12]. Qatar performs relatively poorly regarding the proportion of water consumed against the renewable resources available. This hints at a lack of general public health awareness and socio-political motivations in 2014, though this has significantly changed in the current decade, as manifest in Qatar National Vision 2030 [17]. Consumers are more willing to adopt and utilize cheaper, renewable alternatives, also abounded by substantial environmental sustainability [3]. Social preferences for Qatari citizens have been increasingly shifting towards diversified energy mixes, i.e., increasing end-user preference for sustainable and greener fuels.

3.2. Regional Focus and Global Relevance

International 'push' towards sustainable energy has become ever prominent in the last 20 years, to which Qatar's response on the world stage has been agile and dynamic. Qatar's energy transition policies are well-aligned with its international commitments, including the Paris Agreement, the Conference of the Parties (COP) 21 agreement and the United Nations' 17 Sustainable Development Goals (SDGs). The country actively participates in international forums and collaborates with global organizations such as the International Renewable Energy Agency (IRENA) to learn from best practices and contribute to the global dialogue on sustainable energy [18]. Public-Private Partnerships are a key component of Qatar's policy framework, enabling collaboration that has featured multilateral/international cooperation and investments in the past five years [13].

The increase in non-hydrocarbon GDP per capita for the entire GCC amounts to a mere +5% from the 2010s to 2020s. Oman and Qatar have shown an incredible increase in non-hydrocarbon revenues (+18% and 17% respectively). Despite high diversification, the non-hydrocarbon GDP in Bahrain and the UAE has indicated insignificant change. In Saudi Arabia, non-hydrocarbon GDP has only increased slowly by 10% in the same period [3]. The sustainable energy transition in the GCC region has led to the threat of the so-called 'hydrocarbon asset desertification' where its peers can take advantage slow adoption of renewable energy alternatives such as solar and wind power. This can in effect lead to a protracted impact in terms of the cost estimate for the energy transition and lower efficiency for Qatar [15]. Assets are liable to be deserted leading to a significant loss for Qatar, as with other GCC countries. Thus, potential hindrances exist in fulfilling said environmental commitments and climate change awareness goals.

3.3. Integrating Local and International Policies

The policy framework governing Qatar's energy transition is comprehensive and multifaceted, encompassing various strategies, laws, and initiatives [19]. These policies are designed to facilitate the transition from a hydrocarbon-based economy to a more diversified, sustainable, and resilient energy system. For instance, the Qatar National Vision (QNV) 2030, the Qatar Energy Efficiency and Conservation Strategy (QEECS) 2021 and Qatar National Development Strategy (NDS) 2018-2022 [1, 5-7]. Such policy

frameworks on a local scale articulate clear goals for economic, social, human, and environmental development, with sustainability as the core pillar.

The Qatar National Vision 2030 is central to driving the country's energy transition by aligning its energy policies with such vision [18]. The Third National Development Strategy 2018-2022 provides a more detailed framework for implementing the country's development goals [6]. It includes specific targets for renewable energy capacity, energy efficiency improvements, and carbon emissions reduction. Qatar is relatively under-performing in terms of ramping up renewable energy resource production for export compared to other gas-exporting countries such as China, Saudi Arabia and Algeria. Policies such as the Qatar NDS 2018-2022 aim to help Qatar increase renewable hydrogen production as alternative energy fuel [20]. The performance of such a policy is expected to surpass the effectiveness of that of Australia. This strategy underscores the importance of transitioning to a knowledge-based economy, with an emphasis on research and innovation in the field of sustainable energy.

Recognizing the significance of energy efficiency in the transition process, Qatar has also established the QEECS 2021 aiming to reduce energy consumption across residential, commercial, and industrial sectors [5]. The present literature review finds that a robust legislative and regulatory framework is needed for Qatar's sustainable energy transition that mitigates its predicted economic losses and challenges with the shift. Wright (2021) mentions that global energy transformation have been deeply influenced by international market dynamics in that the World in the present stage is still highly dependent on fossil fuels [13]. This implies that the adaptability of most of the World's economies to increasing renewable energy mixes is often not as simple and not without repercussions, e.g., in Australia, where renewable hydrogen has poor economic potential owing to public preferences [20]. Binding disclosures on targets set by the Paris Agreement (COP21) in 2015 have allowed countries like Qatar to ramp up public mobilization and awareness for adapting to such renewables [21, 22]. It has substantially improved focus on implementing energy-saving measures, promoting energy-efficient technologies, and raising public awareness about energy conservation.

3.4. Technological Innovation and Advancement in Harsh Climates

Considering the ongoing shift towards mixed energy and low-hydrocarbon portfolio, Qatar sets an example for other GCC countries in embracing innovative technologies for renewable energy and sustainable

practices. The significance of sustainable innovation has become popular in the recent decade for the GCC as countries attempt to improve energy security, economic resilience and social sustainability [3, 4, 7]. Qatar reportedly has the highest solar irradiation levels in the world, making it an ideal location for solar energy development. The country receives abundant sunshine throughout the year, averaging 9-10 hours per day [23]. This translates into a significant potential for both photovoltaic (PV) and concentrated solar power (CSP) technologies [24]. The government has recognized this potential and actively invests in large-scale solar projects. Further discussion on a case-by-case basis for the various technological innovations is provided below as follows:

3.4.1. Case Study – Energy Transition Projects in Qatar

Several successful initiatives and ground-breaking projects mark Qatar's journey towards a sustainable energy future. These case studies demonstrate the country's commitment to renewable energy and serve as a model for other nations pursuing similar paths. One notable example is the Al Kharsaah Solar PV Plant, which, upon completion, is expected to be one of the largest solar power plants in the region [11]. Other cases, such as the Blue Hydrogen projects, Pilot Wind Power Plants and others, will be comprehensively discussed herein.

3.4.1(a). Al Kharsaah Solar Power Project

Al Kharsaah Solar PV Plant is the largest solar power project in the Middle East (ca. 1,000 ha), once fully operational. The project is located 80 km west of Doha, the capital. It is designed to supply a substantial portion of Qatar's electricity needs (up to 400 MW-peak per two phases) and 10% of its peak electricity. The Al-Kharsaah project is expected to reduce CO_2e by 26 metric tonnes [25]. The project is a testament to Qatar's ability to implement mega renewable energy projects and sets a benchmark for future regional solar energy developments. As per the QNV 2030 and the Qatari government's considerations, Al Kharsaah will contribute 50% of the total planned electricity generation from solar for Qatar by 2030 [26]. Technoeconomic analysis reveals that the US $14.03/MWh rather than the conventional $24.6 – $39.2/MWh for most 'efficient' combined cycle gas turbines that utilize fossil fuels such as heavy oil and gas [27]. This implies that the Al Karsaah Solar Power Project is relatively more efficient and set to contribute significantly to cheaper renewable energy for Qatar. Though, the cost of the PV-levelised cost of electricity (LCOE) is the lowest for Al-Dhafra solar plant in the UAE

The Qatar Solar Energy Program is another key initiative to develop local expertise and technological capacity in solar energy. This program encompasses various projects, including research and development in solar technologies, the manufacturing of solar panels within Qatar, and the development of solar-powered desalination plants [28]. This comprehensive approach demonstrates Qatar's commitment to adopting renewable energy and becoming a leader in solar technology. Qatar has made significant strides in adopting and advancing photovoltaic (PV) technology. The nation is exploring innovative PV cell designs that are more efficient and better suited to its harsh desert climate. Efforts are underway to enhance solar panels' durability and heat resistance, ensuring they maintain high performance despite extreme temperatures and dusty conditions. Concentrated Solar Power (CSP) is another area where technological advancements are being pursued [10], focusing on improving the efficiency of solar thermal energy conversion and storage.

3.4.1(b). Qatar Blue Hydrogen Project(s)

Apart from solar and wind, Qatar is exploring the potential of green hydrogen as a future energy source. Green hydrogen, produced through electrolysis using renewable energy sources, represents a clean and sustainable energy carrier that can be used in various applications, including transportation, industry, and power generation. Qatar's abundant solar energy resources make it an ideal candidate for green hydrogen production, which could become a significant component of its energy transition strategy [13]. Qatar Energy entered a recent agreement with Korea to develop and expand their respective hydrogen industries. Qatar boasts a larger capacity of CO_2 emissions sequestered/stored than Saudi Arabia and the UAE, by +78% and +92%, respectively [29]. Green and/or blue hydrogen, produced by using renewable energy to power water electrolysis, is emerging as a key area of focus in Qatar's energy strategy. The development of efficient and cost-effective solid oxide electrolysis fuel cells (SOEFCs) is a priority, as it holds the potential to revolutionize the energy sector, offering a clean alternative for transportation, industry, and power generation. Qatar extensively relies upon shipping and incurs higher costs for hydrogen transportation as a result [29].

Particular focus has been put on liquid hydrogen transportation (energy intensive, costly and complex), which further adds to CO_2e burden owing to the compression performed by diesel-run pumps [18]. In this regard, blue hydrogen is derived from fossil fuels from conventional petrochemical and petroleum refining processes [20]. Alternatively, hydrogen allows for carbon capture, utilization, and storage (CCUS). As opposed to Qatar, the UAE has considered

liquid organic hydrogen carriers, allowing it to attain a more advantageous position than Qatar [5, 29]. Arguably, Qatar has more rapport relations with clients such as Australia, which can allow it to outperform and position itself as a leading hydrogen producer in the GCC [20]. To this end, Qatari companies have found alternative transportable forms for hydrogen fuels as liquid ammonia, methanol, or liquid organic carriers, such as the particular method developed by Qatar Fertiliser Company (QAFCO).

3.4.1(c). Wind power

While solar energy is Qatar's most prominent renewable resource, the potential for wind energy is also being explored. Certain areas of Qatar, particularly along the coastline, experience consistent wind patterns (ca. 5.1 m/s from 1976 - 2000) conducive to wind power generation [30]. Although wind energy development in Qatar is still nascent compared to solar, the exploration and assessment of wind resources are gaining momentum. Investments in wind energy research and feasibility studies are underway, aiming to determine the most suitable locations for wind farms and the potential scale of energy production [31]. Technoeconomics reveals that wind farms at Haloul could outperform gas-operated turbines by +366 kWh/kW/yr. At a cost of USD 289,000 (-15.5% more than gas-operated turbines) [32]. Although solar power dominates Qatar's renewable energy landscape, wind energy also presents significant opportunities that could be availed. Realizing this potential, Qatar has, to some extent, invested in wind farms such as the 7MW project proposed in Haloul, northern Qatar [31]. The project is anticipated to be the largest by size (135m height); in parallel to Al Khasraah. Research is focused on developing turbines that can withstand high temperatures and sand abrasion, thus enhancing their operational life and efficiency.

3.4.1(d). Other Renewable Energy Projects and Technologies

Qatar has made significant strides in green building and sustainable urban development. For example, the Msheireb Downtown Doha project is a pioneering initiative that integrates sustainable design, renewable energy, and smart technology to create an eco-friendly urban space [33]. This project sets a precedent for future urban development projects in Qatar and the region. Qatar is integrating renewable energy into its water management strategies. Projects like solar-powered desalination plants are being developed to provide sustainable solutions to Qatar’s water needs. These initiatives not only conserve energy but also reduce the environmental impact of water

desalination [34]. Given Qatar's geographical setting, desalination is essential for water supply. Integrating renewable energy into desalination processes is an area of innovation that Qatar is actively pursuing. Solar and wind-powered desalination plants are being researched and developed, offering a sustainable solution to meet the country's water needs without the heavy carbon footprint of traditional desalination methods [5].

3.4.2. Implications

Renewable energy integration becomes more complex and costly with the induction of larger projects that would lower the adaptability of such projects into the national grid; Qatar is investing in grid infrastructure development and smart grid technologies. This includes modernizing the existing grid infrastructure to handle the variable nature of renewable energy and implementing systems for energy storage and demand-side management [35]. Qatar has also sought to enhance sustainability within its traditional oil and gas sector. This includes implementing cleaner production technologies and reducing flaring (zero-flaring). For instance, in the first UNFCCC Clean Development Mechanism (CDM) project, Qatar made the Al-Shaheen Oil Field Gas Recovery and Utilisation Project reduce its flaring to 90%. Further reducing GHGe by capturing flared gas and allocating it into clean electricity. The ‘zero flaring’ should be a standard applied to all industrial production in Qatar [13]. There are some commitments from Qatar Energy to reduce methane emissions, which are liable to increase as a consequence of an increase in scale relative to CCUS induction on sites.

Qatar invests in state-of-the-art technologies to harness its significant solar and wind resources, aiming to become a regional hub for renewable energy technology and innovation. The present review thus finds that technological advancements in renewable energy have been pivotal in enabling Qatar's energy transition yet have further exposed it to considerable risks and costs [5]. The balance between cost and efficiency of renewable technologies, particularly in solar and wind energy, required further attention. The implications of said technologies on economic diversification for Qatar are discussed below.

3.5. Energy Diversification in Hydrocarbon-dependent Economies:

As evident from the various case projects above, Qatar's renewable energy potential is a cornerstone in its journey toward an energy transition. The country's geographic and climatic conditions are uniquely favorable for

developing solar and wind energy, offering a significant opportunity to diversify its energy mix and reduce reliance on fossil fuels [36]. Renewable energy sources offer Qatar greater energy security and independence. By diversifying its energy mix, the country reduces its vulnerability to external energy market fluctuations and geopolitical tensions. This self-reliance in energy production is a strategic goal, ensuring a stable and predictable energy supply for the nation's economic and social development. Arguably, projects like Al Kharsaah indicate that Qatar's focus had historically been more oriented towards solar projects due to their feasibility and potential [31]. However, wind power is still viable as an economic diversification alternative. Qatar has shown ambitions to shift towards more diversified renewable energy technologies such as wind power [30]. Economic diversification in this regard, is much driven by the need for energy security and resilience as well as the implications of international (hydrocarbon) market dynamics.

Charfeddine and Barkat analyzed the impact of oil and gas prices on Qatar's energy (and thus, energy) diversification via renewable energy production and distribution [37]. Their results indicate that real oil prices and O&G revenues substantially impact Qatar's non-oil GDP and push economic diversification in the country. As the international O&G market behaves with considerable volatility, Qatari policymakers have realized that shifting towards a knowledge-oriented economy and a sustainable/circular economy is ever more relevant [38]. Compared with MENA/GCC peers, academics and experts have been sceptic regarding Qatar's focus on expanding domestic gas manufacturing rather than ramping up solar, wind and other hydrogen production at a similarly rapid pace [39]. However, regulatory reforms, as evident from the QNV 2030 and the Qatar NDS 2018-2022, all indicate that Qatar is relatively well-positioned to compete with its GCC neighbors. Qatar's focus is predominantly related to downstream gas, including blue hydrogen and ammonia production as an economic diversification priority, followed by solar, wind and desalination technologies.

3.5.1. Socio-economic Implications for Qatar's Energy Diversification

The renewable energy sector offers new employment opportunities, contributing to job diversification and developing new skill sets among the workforce [6]. The World Bank reported that Qatar's real GDP growth slowed to 2.8% in 2023 owing to its predominant O&G market volatility and the weakening of its construction sector. Despite tightening its monetary policy

(fixed investments), Qatar expects rampant growth in the renewable energy and fuels sectors, estimated to rise by 3.6%. This has been a significant force behind improving Qatar's quality of life and standards, with many of the non-hydrocarbon revenues directly funding Qatar's hosting of 14 major sporting events, including the FIFA World Cup 2022 [40].

Employment opportunities are expected to continue to rise in Qatar owing to the non-hydrocarbon/renewable sectors. Skeptics indicate that Qatar needs to continue improving work participation, pay, accessibility to infrastructure and compensation for its females, migrants and expatriates. [41]. In this regard, Qatar has introduced significant labor reforms such as the *Kafala* reforms, though enforcement risk and abuses are still evident [42]. The transition to renewable energy also promises substantial social benefits, including improved public health and job creation [7]. By reducing reliance on fossil fuels, Qatar aims to decrease air pollution and associated health risks, thereby enhancing the overall well-being of its population.

3.6 Opportunities and Challenges

3.6.1 Education/Capacity Building and Upskilling of the Workforce in Qatar

The socio-economic benefits of Qatar's energy transition are reflected in its increasing expenditure on the development of educational and research capacities [5]. Investment in research and development, particularly in universities and research institutions, fosters innovation in renewable energy technologies, such as solar, desalination, wind power, and green construction [4, 8]. This focus on education and research not only supports the energy transition but also contributes to the development of a knowledge-based economy in Qatar. The government supports educational programs and training initiatives to develop a skilled workforce capable of driving the energy transition forward [43] alongside international collaborations conducting research oriented towards the challenges and opportunities of the region's energy transition [44].

The transition to a new energy paradigm requires a workforce with skills in renewable energy technologies, which is currently limited. To address this, Qatar is investing in education and training programs to develop local expertise in renewable energy [44]. The Qatar Foundation (QF) in this regard, has been a key driving force behind the capacity building, upskilling and knowledge creation in Qatar vis-à-vis the research and innovation (R&I)

being performed in Qatar [45]. Example programs include infrastructure building for student housing, introducing carbon audits for lowering CO_2e, and GHGe inventorisation. The Education City flagship project is perhaps the best manifestation of Qatar's energy transition, reshaping its education, infrastructural and research landscape [5]. The Education City hosts the research-based Hamad Bin Khalifa University (HBKU), schools for specialized education, libraries and policy research institutes [45]. Collaborations with universities and international institutions are being strengthened to provide specialized training and education.

3.6.2 Research, Development and Innovation (RD&I) in Renewable Energy and Sustainable Energy Production in Qatar

The Qatar Science and Technology Park features numerous tech start-ups and cultural institutions to promote sustainable technological and cultural innovation [45]. Public-private multinational partnerships that have been conducted to date with the Qatar Environment and Energy Research Institute (QEERI) are focused on improving the adaptability and economic viability of commercial solar and wind power to the national grids ('integration') [31, 35]. RD&I has also focused on Qatar's most significant issue, higher water consumption against the availability of resources. Thus, Qatar is investing heavily in desalination and in-tandem power generation using Reverse Osmosis (RO) or Forward Osmosis (FO) membrane technologies[46, 47]. Research has also considered the lifecycle impacts of such technologies on Qatar's fragile ecosystem, which is at the brunt of harsh climates, e.g., desertification and increased land salt content. QEERI and the QF have been at the forefront of conducting cutting-edge research in areas like solar panel efficiency, energy storage solutions, and CCUS [48].

These research endeavors are critical in overcoming the challenges specific to the region, such as high temperatures and dust, which can affect the performance of renewable energy systems. Qatar is not working in isolation; it is actively collaborating with international research institutes and universities to foster innovation in renewable energy technologies. These partnerships (also called Triple Helix '3H') enable knowledge exchange, access to state-of-the-art research facilities, and the development of tailor-made solutions for Qatar's unique energy requirements [5, 8]. The engagement of the private sector and international partnerships are vital in realizing Qatar's renewable energy potential. The government encourages private investments in renewable energy projects through public-private partnerships (PPPs) and favorable investment conditions [45].

Additionally, Qatar collaborates with international entities, such as the International Renewable Energy Agency (IRENA) and various global energy firms, to bring expertise and technology to its renewable energy projects [49]. Qatar's policy framework is pivotal in permitting a streamlined direct investment in renewable energy projects, which is reflected by large-scale renewable energy projects like the Qatar Solar Energy Program, the development of the Al Kharsaah Solar PV Plant [5], and the proposed wind power station in Northern Qatar [32]. These projects contribute to increasing renewable energy capacity and catalyze further investments in the sector.

3.6.3 Techno-Economic Challenges

Transitioning to renewable energy requires substantial initial investment, particularly in the development of new infrastructure and technology. International financing and collaborations to fund these large-scale projects cover major costs, though integrating a significant proportion of renewable energy into the existing power grid poses technical challenges. Renewable sources like solar and wind are intermittent and can lead to grid instability [39]. Smart grid technology can better manage the variability of renewable energy, whereas energy storage technologies, like battery systems and pumped hydro storage, are being explored [5, 8, 29] to store excess energy and balance the grid.

Renewable sources like solar and wind are intermittent and can lead to grid instability. To address this, Qatar is investing in smart grid technology that can better manage the variability of renewable energy. Additionally, advancements in energy storage technologies, like battery systems and pumped hydro storage, are being explored to store excess energy and balance the grid[10, 11]. The extreme heat and dust prevalent in Qatar pose a significant challenge to the efficiency and maintenance of renewable energy systems, particularly solar panels. Research and development efforts focus on creating more robust and efficient systems to withstand such conditions. Innovations in solar panel materials and protective coatings are being explored to enhance durability and performance.

3.6.4 Leveraging Geography and International Role and Investment in Qatar’s Energy Transition

As a major oil and gas exporter, Qatar's energy transition is influenced by international market dynamics and global energy policies. Active

participation in international energy dialogues and aligning its energy transition with global trends has allowed Qatar to position itself as a rising sustainable innovator in the GCC/MENA region [5]. Qatar's continual reforms and coordination with stakeholders, policymakers and sustainability experts have allowed it to formulate a relatively robust policy framework to support renewable energy adoption and transition [13]. Qatar's role at an international level has been responsive and dynamic, being the key focus of various sustainability investment firms in the Global North, such as Iberdrola S.A., the world's largest owner of wind farms [50]. Developing and implementing policies that effectively support the transition to renewable energy can be complex, especially in aligning them with existing economic and energy strategies.

Balancing rapid development with sustainability goals poses a challenge, as it requires a holistic approach to urban planning, resource management, and environmental conservation. This includes revising existing regulations such as labor and *Kafala* reforms, introducing carbon audits, enforcing provisions for low- or near-zero carbon generation across petrochemical and petroleum industries, and provisions for green construction [51]. Additionally, incentivizing renewable energy investments and clear target-setting have boosted stakeholder and investor confidence in Qatar [26]. Qatar addresses this by adopting sustainable development practices in its urban and industrial projects [1, 3]. This includes green building standards, efficient water and waste management systems, and the preservation of natural habitats.

3.6.5 Improving Public Engagement and Awareness

Qatar strongly emphasizes education and public awareness in its energy transition. Initiatives such as community workshops, educational campaigns, and school programs have been instrumental in raising awareness about renewable energy and sustainability [5]. Public awareness and engagement are crucial for the energy transition's success, which in Qatar requires substantial efforts to improve upon [51]. These efforts are critical in cultivating a culture that supports and participates in the energy transition. A lack of understanding and support from the public can hinder progress as the public would either be resistive or less likely to adapt to the changes to non-hydrocarbon fuels and energy [1]. Public engagement is necessary for hydrocarbon-dependent economies such as Qatar to on board potential dissidents or elements that could likely resist a substantial change from the norm. This would mean that the Qatari public, much like their GCC

peers are likely to be subject to uncertainty concerns associated with the so-called post-hydrocarbon world.

Involvement of communities in local renewable projects and educational initiatives is also being promoted via community-driven sustainability initiatives such as recycling, clean drives and energy-saving programs [52]. Implementing educational and awareness campaigns is essential for Qatar to inform the public about the benefits of renewable energy and sustainable practices. The Qatari economy in the current age still extensively relies on its oil rents and gas exports, which given the complex geopolitics and fuel market dynamics, are being paced up rather than down as compared to renewable energy products [39]. Such instances, result in a lower public engagement in the GCC and Qatar with governmental efforts to boost sustainable energy transition acceptance across the norm [53]. Notwithstanding, the Qatari public is responding appropriately to recent government incentivization and induction of sustainable energy programs. This owes to their perception that they are good substitutes for now-inflating hydrocarbon products.

While the potential for renewable energy in Qatar is immense, some challenges must be addressed. These include integrating renewable energy sources into the existing power grid, managing the intermittency of solar and wind energy, and optimizing the performance of renewable energy technologies in harsh desert conditions [5]. In addition to the comprehensive review performed above, and in light of the opportunities and challenges identified above (in Section 3), a summary table is provided below.

4. Qatar's Role in Global Energy Governance

Global energy governance can be defined as the management or coordination of international collective decisions over issues of the global energy system. As one of the largest liquefied Natural Gas (LNG) exporters and an influential actor in the world energy segment, Qatar occupies a sensitive place within this governance structure. Knowing Qatar's impact on the global energy regimes and agreements is crucial if one has to appreciate global energy management in the current and emerging global climate change [54].

4.1 Qatar's Involvement in Global Energy Organizations

Qatar is also involved in several premier global Energy Forums, such as the Organization of the Petroleum Exporting Countries OPEC, the International Renewable Energy Agency IRENA, and other international

energy forums. Through OPEC membership, Qatar has, over time, affected the oil production allowances and the pricing mechanism of the global commodity; nonetheless, in the recent past, the focus has been toward the LNG and the natural gas market. IRENA membership enables Qatar to engage in dialogue and make decisions about using renewable energy sources in countries that rely mostly on oil and gas exports [55]. Through such organizations, it has demonstrated its interest in influencing the energy policies within the international system, especially those that will benefit the country's strategic and newfound interests in sustainable energy.

4.2 Influence of Qatar's Energy Transition on Global Policies

Due to Qatar's ongoing energy transition variables, such as investment in renewable energy and the ongoing efforts towards generation diversification, Qatar can bring about several changes in providing structures for energy governance from the global perspective. Thus, as Qatar plans to diversify energy sources and aims at adopting the sustainable kind of energy, there are chances it will be doing so to influence other fossil fuel-reliant nations, especially those in the GCC [13]. This background of Qatar in managing the transition from the hydrocarbon-intensive model to the sustainable model will be useful in interacting with the future energy policy framework of the state, especially in facets such as renewable energy integration, energy efficiency, and carbon management [56]. Furthermore, it means that Qatar can be a leader and promote the use of more renewable energy sources in areas where they still depend on oil and gas goods, which will contribute to the development of global sustainability plans and strategies.

4.3 Strategic Implications for Qatar

Qatar's active participation in global energy governance has strategic consequences for the country's energy policies. Suppose Qatar synchronizes its domestic plans with global patterns. In that case, it will significantly impact global energy policy and a place of prominence in the new world order of energy severities [57]. Therefore, for Qatar to maintain its strategic positioning, the country should keep participating in global energy talks, especially those pertaining to energy transitions. Furthermore, Qatar can use its leadership in LNG markets to promote the use of natural gas as a transition fuel in energy policies at the international level and, simultaneously, invest in renewable energy technologies and

infrastructure to establish itself as a leader in the clean energy industry [18, 55].

5. Scenario Planning for 2050

Strategic management and planning include a real-life activity known as scenario planning which directs a company or organization to work out several possible events likely to unfold in the future. As for the energy sector in Qatar, analysing key scenarios is valuable in foreseeing further problems and opportunities from the perspective of further transformation in the global energy industry [58]. Therefore, if Qatar formulates long-term energy plans consistent with various possible scenarios, it would be better positioned to respond to contingencies to manufacture its sustainability efforts.

5.1 Developing Scenarios for Qatar's Energy Future

Qatar can identify several potential future trends that could happen in the sector in Qatar by 2050. These, would depend on various aspects such as technology evolution, policies, and global energy patterns. For instance, one of the plausible scenarios could be a very fast advancement in technology as far as renewable energy is concerned and a noticeable shift to the use of solar and wind energy and, therefore, very minimal use of natural gas[59]. In another instance, the shift can be gradual and slow, where natural gas continues to be predominant with the addition of intermittent increments in renewable energy facilities [35]. Each of them would take into account the different risks, uncertainties and assumptions, for example, the speed of technology development, changes in legislation, trends in the energy consumption in the world and the rest of them.

Qatar's direct participation in the international energy regime has certainly pledged deep geostrategic implications for its domestic energy regime. Thus, in order to increase its impact on the future development of foreign energy policy and become more advantageous in the new world energy structure, Qatar needs to adapt its domestic energy policy to the international level. Therefore, Qatar should continue participating in international energy talks to maintain its strategic position, especially on the transition to sustainable energy [17, 60, 61]. Moreover, Qatar, as the leader in LNG markets, can promote natural gas as a transition fuel for worldwide

energy strategies and simultaneously invest in renewable technologies and facilities to pioneer the digital economy.

5.2 Implications of Developing Scenarios

In each case, the analysed conditions and factors have different prospects for the growth of Qatar's economy, environmental impact, and energy security. For instance, a predominantly renewable scenario would lead to a high level of investment in new technologies and generation capacity, with likely social effects on employment and the overall economy [56, 61]. On the other hand, a scenario wherein natural gas remains a dominant source could highlight CCS as a critical means of managing adverse environmental impacts. Various levels of management, government, industry and the public would have to learn how to overcome various opportunities and challenges of the four scenarios [62, 63]. This adaptation could occur at the policy, business, and community levels, where people's perceptions towards energy utilization and stewardship of resources may need to change [64].

5.3 Strategic Recommendations

Thus, Qatar needs to have rather adjustable strategies and invest in projects viable for several scenarios of the country's future energy landscape. The authorities should ensure funding for the further exploration of promising technologies that can become critical in different scenarios, including advanced energy storage and CCS [65]. Furthermore, Qatar needs to press on with policies that would help it open up its energy sources so that the country can be flexible enough to respond to changes in the global energy markets and technological advancement [13, 66]. Thus, preparing various scenarios for further development will help Qatar ensure energy security, enhance economic growth, and develop sustainable goals.

6. Limitations of the Study

The review article has considered literature from the 2014 – 2024 period, and Qatar's efforts in the sustainable energy transition are fairly recent (since the 2020s). The review is limited regarding its access to the proposed initiative as part of the energy transition. However, the review mentions significant projects that will likely manifest in the coming decade. The time

currency issue is also prevalent for the review, in that the data before Qatar's reforms on the energy transition is uncommon and relatively scarce.

7. Recommendations

While the governmental focus is improving public interest and awareness of Qatar's energy transition, much remains to be covered in domestic capacity building and skill gap coverage for Qatar's workforce [1, 5]. Relevant recommendations are as follows in brief retrospect:

1. Developing policy and enforcing monitoring and evaluation mechanisms.
2. Managing Hydrocarbon Asset Desertification Risks via incentivizing renewable energy investments can help Qatar offset its losses in reduced O&G production.
3. Streamlining PPP (3H) for continued sustainable energy innovation
4. Managing cost factors on a data-driven basis associated with sustainable energy projects on large scales
5. Leverage the techno-economic benefits of projects to diversify the energy mix

The effectiveness of Qatar's policy framework can only be improved by enforcement and ramping up monitoring and evaluation mechanisms to track progress and make necessary adjustments [5]. Monitoring mechanisms enable the government to assess the impact of its policies and strategies, identify challenges, and develop responsive measures to achieve its energy transition goals. Regulations should encourage the use of renewable energy in public and private sectors, incentives for green building practices, and guidelines for energy-efficient appliances and equipment. The government must continue to facilitate lower tariffs and subsidies on renewable energy mixes for energy producers, which would favour renewable energy production and consumption.

To this end, sustainability-oriented curricula, knowledge creation (RD&I) and research-led employment opportunities can help foster the upskilling of Qatar's domestic and migrant workforce. As with policy enforcement, continued incentivizing renewable energy investments can help Qatar offset its losses in reduced O&G production [4]. Hydrocarbon Asset Desertification poses a significant economic loss risk to Qatar should the sustainable energy transition occur slowly and the dependence on hydrocarbons not lowered substantially in the coming decades.

The involvement of the private sector in Public-Private Partnerships (Triple Helix) 'PPP (3H)' collaborations in Qatar's renewable energy initiatives has been a key factor in the success of projects such as Al-Kharsaah.

These partnerships are crucial in mobilizing the necessary resources and expertise for large-scale renewable energy initiatives, which the QF has been aiming for [45]. Partnerships with international and local companies such as Iberdrola S.A., GE and ENI can help develop and implement renewable energy projects with optimal lifecycles and lower environmental impact [50].

8. Potential Impact on Future Research

This way, as Qatar progresses toward the manufacturing of a sustainable energy future, it points to an ideal model for other nation-states, specifically those of the GCC and the MENA region, which share similar economic and environmental characteristics. This study brings out the importance of transitioning to green energy by highlighting the technological, operational, economic, policy, and social changes required in the nation. Thus, the concept of sustainability in the O&G sector may seem quite paradoxical; however, it is quite possible. For Qatar it has been a remarkable accomplishment; for example, zero-flaring and carbon audits across the chemicals industry.

The factors driving Qatar towards energy transition are somewhat multiple and, therefore, systemic, giving a true meaning to Qatar's holistic approach on the adoption of renewable sources of energy. Ranging from environmental responsibility to economic plan diversification, technological development, and the quest for a national vision and leadership in the global arena, every one of them is important for Qatar in the achievement of the sustainable energy outlook. Despite these challenges, it is crucial to acknowledge that the shift is also filled with opportunity for Qatar to reimagine its energy sector and become a framework for sustainable growth in the region and beyond.

It can therefore be suggested that although there has been progress in Qatar's transition away from energy, it has not been smooth. Some of the challenges that have come with the concept include deploying power to the grid, high up-front costs, and the need for trained workforce have been addressed with commendable strategies. Therefore, it is important for other countries aspiring to perform similar transformations to learn from the measures that Qatar has undertaken to mitigate these challenges through research, participation in international organizations, and policy adjustments.

One of the most significant barriers to the implementation of renewable energy is the fact that it is often intermittent due to varied weather. In response to this, Qatar has embraced the development of efficient energy storage technologies. Some examples are battery storage systems for

efficiently storing excess energy produced from renewable energy for use at other times when production is low. Investigations into other possibilities of energy storage including pumped hydro storage and thermal energy storage are also being carried out owing to the fact that they could be a more sustainable and reliable means of energy storage. Therefore, it is feasible to analyse the social and environmental advantages of Qatar's energy transition. This is contrary to the cost which now has a blurred meaning as including the environmental cost or the social cost which is worse, health cost, benefits such as improved air quality, reduction of greenhouse emissions, and generation of employment opportunities within the renewable sector. Such changes bring direct benefits for the population and correlate with the requirements of the world in the fight against climate change.

9. Conclusion

Qatar is diversifying its energy portfolio by reducing its reliance on oil and gas revenues, and mitigating risks associated with volatile global oil markets. This shift is beneficial for energy security and creates a foundation for making the economy and energy infrastructure less vulnerable and more sustainable. Qatar's strategic policies put into action by respective national visions toward diversification of the country's economy has led to significant advancement in renewable energy technologies. However, sustainability transition is constrained by factors such as dependence on fossil energy sources, Infrastructure factors, and lack of congruence between policy goals and practical steps on implementation. Thus, the future of sustainable energy system in Qatar will depend on the enhanced application of novel technologies, efficient legislation, and collaboration between the government and private companies. It underlines the need for flexibility to meet global energy dynamics and local socio-political and economic environments to maintain Qatar's leadership in the global sustainable energy revolution, Additionally, it creates new opportunities for development, including green technology, sustainable tourism, and export of renewable power.

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Table 1. **Summary of Opportunity and Challenges Evident for Qatar in its Sustainable Energy Transition**

		Opportunity	Challenge	References (Name, Year, Type)		
1	Techno-economic	• Good solar potential • Relatively viable wind potential • Cost abatement is substantial (80%) if Qatar transitions 10% of its energy production to solar. • Desalination leads to higher desertification. • Non-hydrocarbon GDP per capita increased at a higher rate than other GCC members (+5%) last decade. • Hydrogen production has more economic potential than that of Australia and other countries. • Low adaptability of renewables to the national grid. • Significant projects at a large scale with higher energy and cost-efficiency than conventional power plants, e.g. Al-Kharsaah, yielding $14.03/MWh cost instead of the expected $24.6 – $39.2/MWh. • Hydrogen production is marred by distribution problems and the ammonia transport option is highly viable. • Wind farms at Haloul could outperform gas-operated turbines by +366 kWh/kW/yr. At a total cost of USD 289,000	• Reducing the economy's 'heavy' reliance on conventional hydrocarbon mix (primarily gas) • Slowed energy diversification will incur higher costs in the long-term • Poor performances in terms of renewable energy mix and consumption per capita • High water consumption • Hydrocarbon asset desertification leads to substantial economic loss • Solar power projects are vulnerable to technical failures in harsh climates and incur high R&D costs to stay resilient. • The renewable energy mix is too dependent on solar (lower energy security and resilience). • Wind power is less viable than solar.	Alashqar et al.	2022	Article
				Hasid et al.	2023	Case Review
				Perez-Astudillo et al.	2022	Article
				Munawwar & Ghedira	2014	Article
				Al-Mohannadi & Al-Mohannadi	2022	Case Review

Table 2 (continued)

		Opportunity	Challenge	References (Name, Year, Type)		
2	Socio-economic	• Social discontent with higher prices of hydrocarbon fuels • Qatari consumers are relatively more aware and likely to adopt cheaper, renewable alternatives, unlike their GCC peers • Employment opportunities are expected to continue to rise in Qatar owing to the non-hydrocarbon/renewable sectors • High investments in infrastructure, e.g., student housing, introducing carbon audits for lowering CO_2e, and GHGe inventorisation	• Vulnerability for continued investment owing to human rights indices and stakeholder trust regarding labor welfare. • Lack of an agile, skilled workforce in the short or medium term to cope with energy transition at a rapid pace • Increasing focus on education, awareness and engagement is needed.	Richer	2015	Article
				Sever & Tok	2022	Article
				Al-Musalmani & Maalouf	2022	Article
3	Politics and Policy	• O&G dependence influences policymaking, though investor pressure has improved renewable energy incentivization • Adequate and robust policy framework defined by the QNV 2030, the NDS 2018-2022, QEECS 2021 and other regulations • Increasing PPP (3H) • The policy promotes technological innovation and sustainability improvements across Qatari O&G industries (e.g., zero-flaring) • Gradual increase in renewable energy investments and compliance with carbon-neutral targets • Compliance with binding agreements such as COP21 and Paris.	• The policy is not adequately enforced and only provisions are effective to date. • The policy can potentially offset losses due to hydrocarbon asset desertification as investment and capital influx increases in the renewable sector. • Tight monetary policy, e.g., fixed investments	Wright	2021	Case Review
				Kaminekar & Stewart	2015	Report