HYDROGEN, FUEL CELL & ENERGY STORAGE

Future prospects for solar energy production and storage in Iran

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Abstract

Iran possesses 10% of the world's oil and 15% of global gas resources, with an energy intensity of 8 MJ per dollar of Gross Domestic Product (GDP). Over the past decade, Iran has become one of the highest emitters of carbon dioxide (CO_2), following Japan and Germany. Additionally, the global climate change-induced water crisis has impacted the generation of electricity from hydropower. With 300 sunny days per year and an average solar irradiance of 5.5 kWh/m^2 per day, Iran has substantial potential for solar energy. This potential could play a crucial role in transitioning from fossil-based energy systems to achieve long-term energy security and sustainability. Supporting renewable energy systems and technologies in Iran requires robust research and development efforts. In this context, the Niroo Research Institute (NRI), affiliated with the Iranian Ministry of Energy (MoE), is at the forefront of advancing renewable energy technologies. The Niroo Research Institute (NRI) has developed a national strategy and action plan aimed at advancing and localizing renewable energy systems. This study provides an overview of Iran's renewable energy potential, current status, strategies, perspectives, promotion policies, major achievements, and energy options. It includes a detailed action plan, offering a framework for designing a roadmap for Iran's energy transition.

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1 Introduction

The development of renewable energy is crucial for ensuring energy security, especially during disruptions [1]. Issues in energy systems can arise from technical problems, human error, or natural events [2]. Threats to the energy sector include natural disasters, cyberattacks, geopolitical tensions, fuel price fluctuations, and long-term climate change. Renewable energy can help address these challenges by diversifying the power generation mix, reducing water usage, enabling rapid deployment and modularity [3]. Distributed electricity generation plays a key role in energy security, with renewable energy making significant contributions to these systems [4, 5]. Despite the Middle East's reputation for abundant and inexpensive fossil resources, renewable energy is gaining political attention due to the rising power demand in the region. Among neighboring countries, Iran has a notably high level of energy consumption per capita, estimated to be 80% above the global average [6]. This is largely due to substantial energy and fuel subsidies for consumers and businesses, which reduce incentives for energy efficiency. However, following the lifting of sanctions, Iran offers significant opportunities for companies looking to invest in its renewable energy sector [7].

To assess the sustainability of a country's energy-related activities, various indicators are outlined in the literature. Sabetghadam [2] proposed the following indicators for evaluating sustainability: (1) Environmental sustainability: Per capita carbon emissions and most significant energy-related local pollutant, (2) Social sustainability: Households with access to electricity and clean energy investment, (3) Economic sustainability: Resilience to external impacts: energy trade and burden of energy investments, and (4) Technological sustainability: Energy intensity and the deployment of renewable energy. With appropriate policies and strategies, renewable energy can enhance all these sustainability indicators. Figures 1 and 2 illustrate the job creation and costs associated with various electricity generation resources.

Recent studies have demonstrated the technical and economic feasibility of incorporating a substantial share of renewable energy into the energy mix of countries worldwide [8, 9]. One study [10] assessed solar energy's potential for climate change mitigation and highlighted that Photovoltaic (PV) systems could supply 30-50% of the required electricity. Bahrami and Abbaszadeh [11] recommended: (1) Focusing on cultural and educational efforts to raise community awareness about environmental issues, (2) Ensuring guaranteed purchase of renewable power generation, and (3) Including guaranteed prices for renewable power in subscribers' bills.

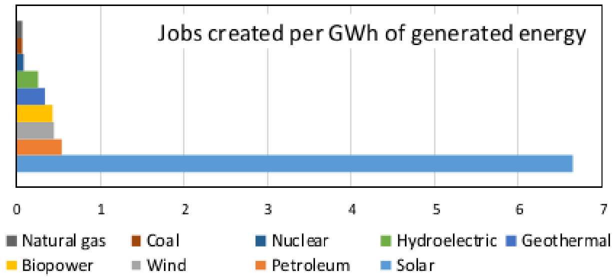

Fig. 1. Job created per GWh of energy generated [12, 13].

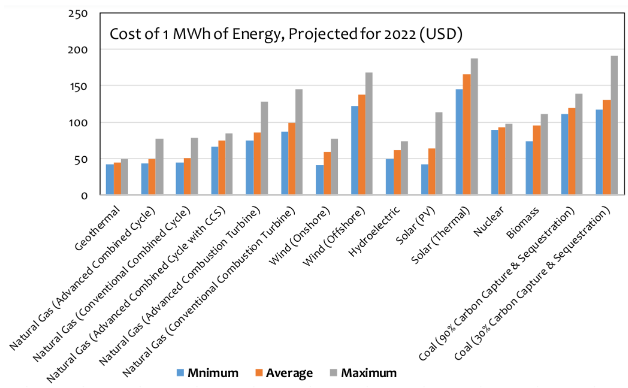

Fig. 2. Cost of one MWh of energy, projected for 2022 [14].

Further, Iran faces a water crisis due to insufficient water resources to meet demand [15]. Contributing factors include rapid population growth, uneven population distribution, poor water management, inefficient agricultural practices, frequent droughts, and high climatic variability [16]. Over the lifecycle of the solar PV and wind turbine systems, water withdrawal and consumption are between 2-15% of that used by coal and 0.1-14% of that used by nuclear power plants for power generation [17]. Therefore, renewable energy is a viable alternative to fossil fuel-based power generation. (See Figure 3).

Figure 4 illustrates the percentage of CO_2 emissions from the Middle East, highlighting Iran, Saudi Arabia, and the United Arab Emirates as the top three emitters. This underscores the urgent need for these countries to advance renewable energy development as a key strategy for reducing greenhouse gas emissions and fulfilling their commitments under the Paris Agreement. By 2030, Iran must reduce greenhouse gas emissions by 4 to 12% according to the Paris Agreement terms [18]. Despite having some of the world's lowest shares of low-carbon energy, many countries in this group possess abundant and inexpensive solar resources. These resources can aid in diversifying their energy mix, reducing greenhouse gas emissions, and potentially generating additional revenue from hydrogen exports. Green hydrogen has significant potential in both Iran [19] and the broader Middle East [20].

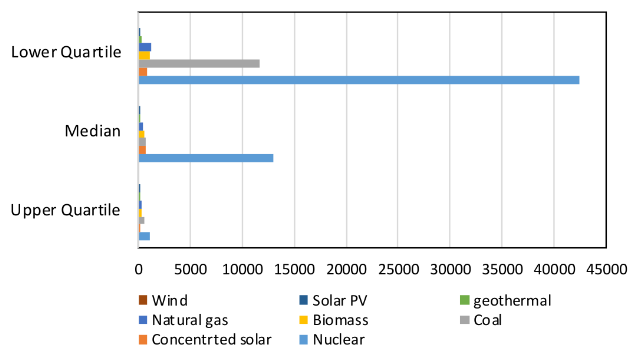

Fig. 3. Water withdrawal to produce 1 MWh of electricity [21].

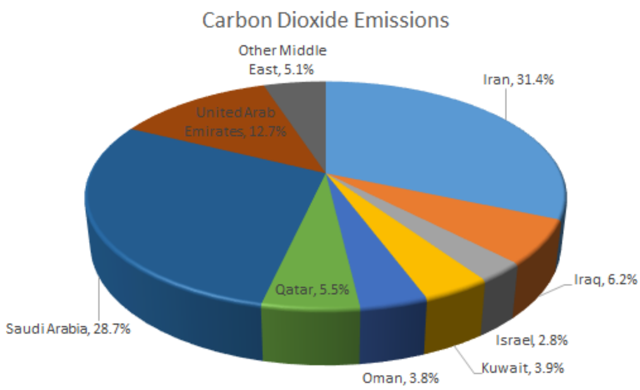

Fig. 4. Percentage of CO2 emissions in the Middle East in 2023 (data was collected from EI 2024 [18]).

For major producer economies, recent years have seen only a minor shift in the energy mix, with a slight increase in natural gas usage compared to oil. Given Iran's substantial solar energy potential and the decreasing costs of conversion technologies, this paper explores how leveraging these factors can create a synergy to facilitate a successful transition from fossil-based infrastructure. It provides a comprehensive review of Iran's energy status, evaluating the energy transition to support sustainable planning and policy-making. This assessment is likely to impact the geography of energy relations.

2 Overview of energy status in Iran

Iran is one of the world's major fossil fuel producers. Petroleum and natural gas are extensively used in the transportation, power, and industrial sectors due to their low prices and existing infrastructure [22]. This reliance results in high levels of pollution and greenhouse gas (GHG) emissions. As a result, Iran's renewable energy resources have not been significantly utilized. To diversify its energy mix, the country has various renewable resources awaiting development, including solar, wind, hydropower, biofuel, and geothermal energy across different regions and sectors. Figure 5 illustrates the rising trend in primary energy consumption and primary energy consumption per capita, as reported by the Energy Institute (EI) [18]. Over the years, Iran's economic situation has experienced significant fluctuations, including periods of growth, recession, revolution, and conflict. However, per capita, energy consumption has consistently increased, with a generally upward slope in the chart.

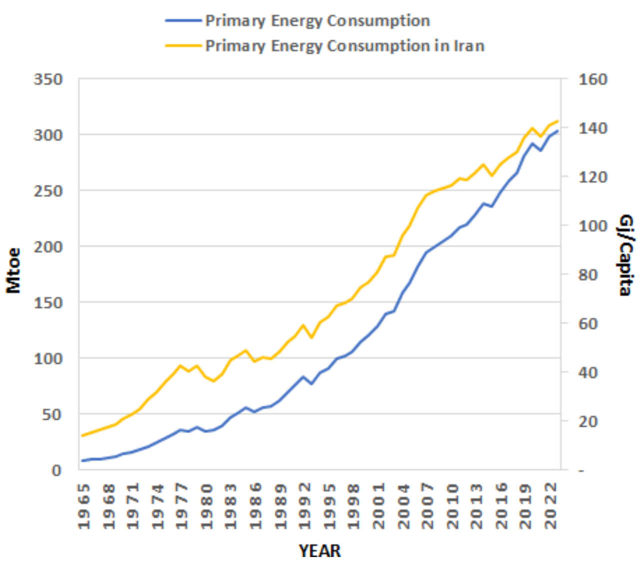

Fig. 5. The trend of primary energy consumption and per capita energy consumption in Iran (data was collected from EI, 2024 [18]).

Figure 6 highlights the crucial role of natural gas in Iran's energy economy, as the country possesses the world's largest natural gas reserves. Together, natural gas, crude oil, and coal account for over 98% of Iran's primary energy consumption, contributing to rising greenhouse gas emissions.

Iran holds the second-largest oil reserves in the Middle East, following Saudi Arabia, with 18.88% of proven oil resources. It also ranks second in power generation in the region, with 25.06% of the total. Figure 7 illustrates the trends in oil and natural gas production and consumption in Iran, showing a significant decline after the revolution, largely due to its reliance on exports. However, fossil fuel consumption in the country has consistently increased, with a particularly sharp rise in natural gas consumption. This trend is driven by policymakers' focus on expanding natural gas use across various sectors. The chart shows that nearly all of Iran's natural gas production is directed towards domestic consumption, largely due to the growth of subsidized natural gas use, which is predominantly for non-productive purposes.

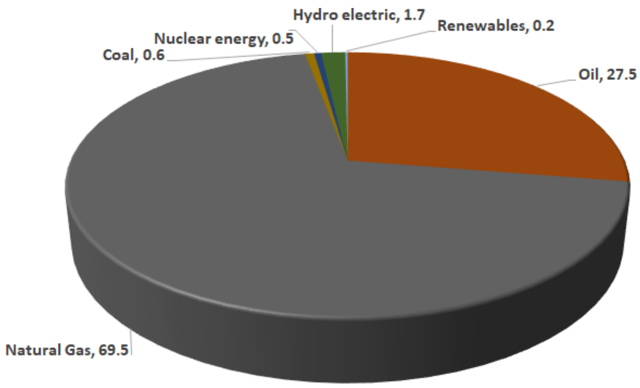

Fig. 6. The amount of primary energy consumption in Iran in terms of fuel in 2023 (data was collected from EI, 2024 [18]).

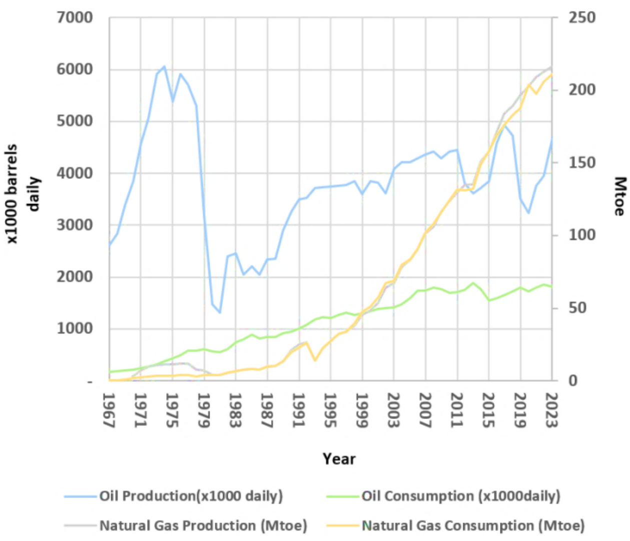

Fig. 7. The trend of production and consumption of fossil fuels of crude oil and natural gas in Iran (data was collected from EI, 2024 [18]).

Figure 8 shows displays power generation from various renewable energy resources, including hydropower, in Iran. Hydropower generation is mainly affected by annual rainfall fluctuations, leading to significant variations in its output. The production of solar and wind energy has increased significantly in recent years due to government support. However, it still does not match the electricity generated from fossil fuels and hydropower.

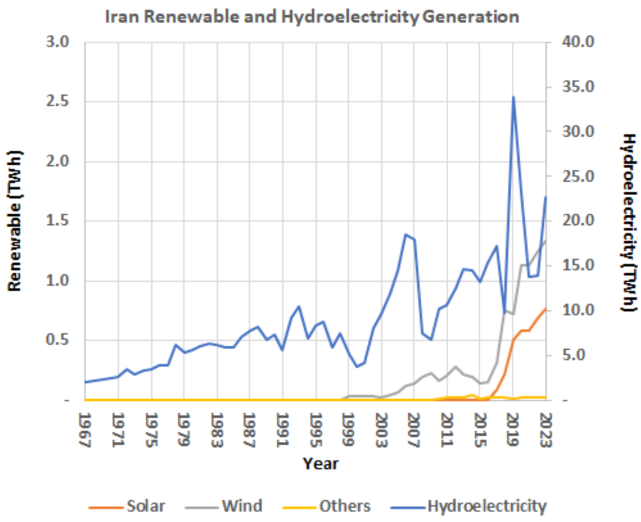

Fig. 8. Trend of renewable and hydroelectric power generation in Iran (data was collected from EI, 2024 [18]).

Figure 9 shows the types of fuel used for electricity generation. It shows that Middle Eastern countries predominantly focus on generating electricity from natural gas and crude oil, while renewable energy sources have significant potential for development in the region. Figure 10 depicts the electricity generation process across various renewable, hydro, and fossil sources. Power generation from oil in Iran has decreased in recent years, while the trend for power generation from natural gas has been increasing. Additionally, renewable power generation remains significantly lower compared to fossil-based sources.

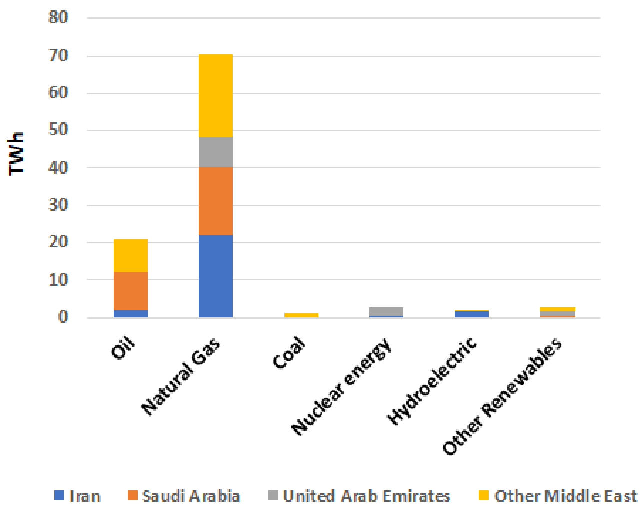

Fig. 9. The amount of energy consumption in power generation in the Middle East in 2023 (data was collected from EI, 2024 [18]).

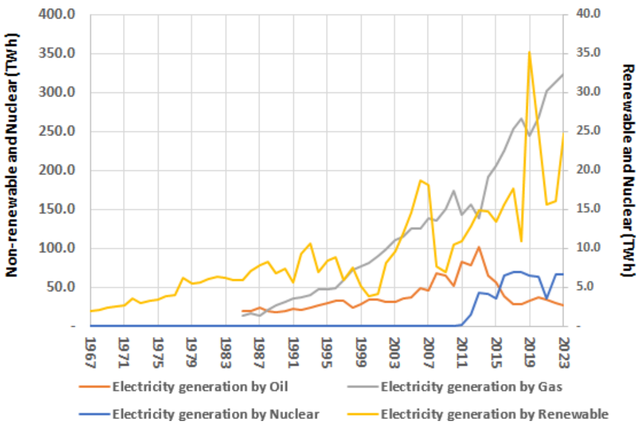

Fig. 10. The trend of fossil and renewable power generation in Iran (data was collected from EI, 2024 [18]).

Figure 11 shows the trend of CO_2 emissions in Iran. Up until 2008, CO_2 emissions were increasing, but they declined following the imposition of stringent economic sanctions in the subsequent years. After the Joint Comprehensive Plan of Action (JCPoA) agreement, the slope of the CO_2 emission curve began to rise once more. This indicates the ineffectiveness of current policies in reducing GHG emissions and highlights the need for more effective measures, such as promoting renewable energy development and improving energy efficiency.

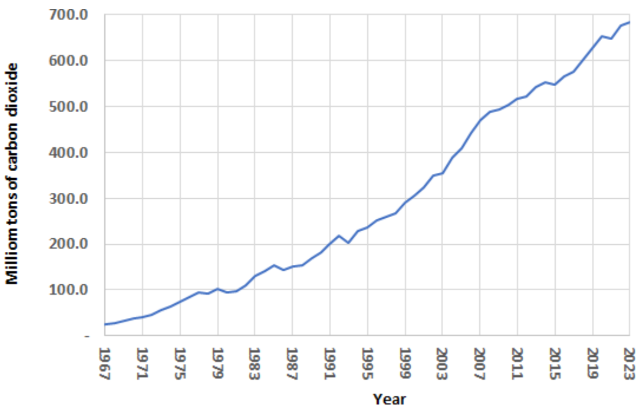

Fig. 11. Emission of CO_2 in Iran from energy (data was collected from EI, 2024 [18]).

As mentioned earlier, distributed power generation is crucial for energy security, and renewable energy plays a significant role in these systems [4]. García-Gusano and Iribarren [23] explored future scenarios for energy security and utilized the Renewable Energy Security Index (RESI) in their power generation model to evaluate the energy security of various power generation mixes. Extensive use of RESI [24] as an energy security index is practical for energy policy-makers, as it addresses various aspects of energy security. Additionally, electrification enhances power generation security, which can be achieved through the deployment of renewable energy [25], a key factor in the decarbonization of power generation. At the Niroo Research Institute (NRI), a study was conducted to explore the potential of renewable power plants to generate electricity as a competitive alternative to conventional fossil-fuel power plants. Thus, the findings of this study significantly influenced future initiatives commissioned and/or sponsored by various organizations within the Ministry of Energy (MoE) and other government authorities. Additionally, during the project's implementation, efforts were made to leverage local expertise and secure key components domestically.

3 Solar energy in Iran

Figure 12 displays regions with similar solar potential based on maps and data provided by SOLARGIS in 2020 [26]. Many areas in the country receive radiation levels exceeding 1800 kWh/m^2 and more than 300 sunny days annually. Regions with an annual mean daily global radiation of 5.2 to 5.4 kWh are located in the provinces of Isfahan, Kerman, Yazd, and Fars. It was found that the highest capacity factor, approximately 21.5%, is observed in Zabol and Nimroz cities in Sistan and Baluchestan province, Sirjan city in Kerman, and Taft, Anar, and Abarkooh cities in Yazd province, as well as Hajiabad city in Hormozgan province. This high capacity factor can reduce the return on investment and economically justify the development of solar thermal power and photovoltaic power plants. Moreover, a high capacity factor increases the production of power plant units and reduces the overall capacity needed for installation.

PV and thermal technologies are widely used to exploit solar energy. The key difference between these technologies lies in the type of energy they produce: solar thermal systems generate heat, while photovoltaic (PV) systems produce electricity. The applications, economics, and complexity of solar thermal systems vary widely. For example, power generation and air conditioning technologies are generally more expensive and complex compared to simpler and more cost-effective applications like water and space heating [27]. In this context, solar thermal technology is primarily classified based on operating temperature, which determines its applications. Solar thermal power plants fall into the high-temperature category and include various technologies such as linear Fresnel, solar tower (heliostat), parabolic trough, and parabolic dish [28, 29]. This category of solar thermal technology can play a significant role in Iran. In particular, concentrating collectors are well-suited for regions with high solar irradiation. Various studies have shown that Iran's annual solar irradiation exceeds 2800 kWh/m^2 [29–32].

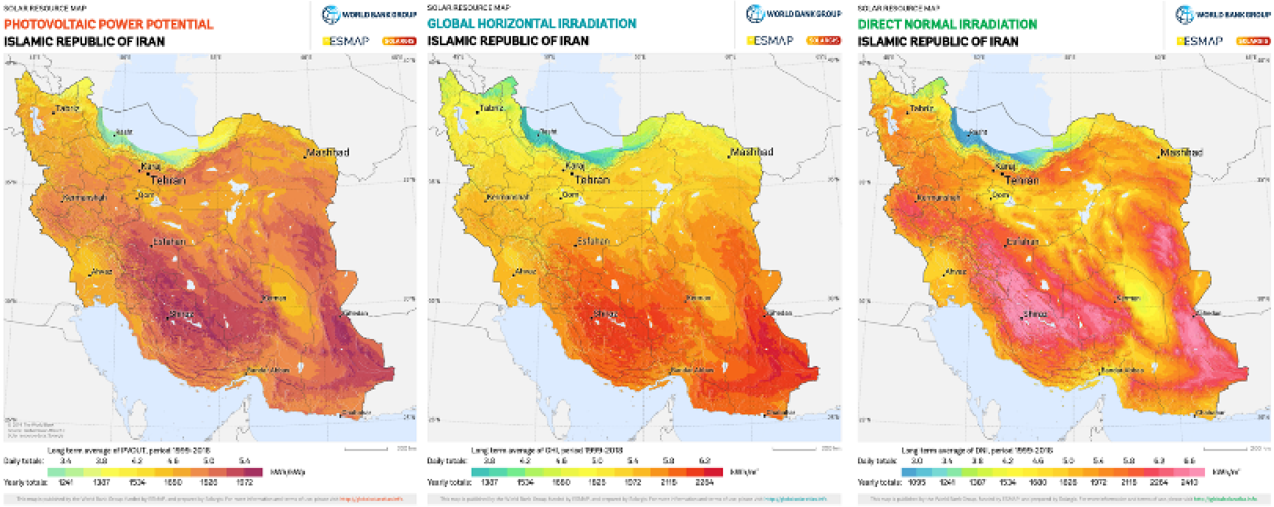

Fig. 12. Solar heat map of Iran [26].

Although Iran has the potential to generate over 60 GW of solar power, the country currently has less than 0.5 GW of installed solar capacity. To address poverty and expand solar energy access, a project funded by the Imam Khomeini Relief Foundation and the Ministry of Energy (MoE) aimed to deploy small PV units for electricity generation under a feed-in tariff scheme. Additionally, thousands of small energy storage systems, powered by 100 W PV panels, were provided to remote off-grid areas.

Despite these efforts, solar energy accounts for less than 0.5% of the total energy consumption. Given the high radiation levels (exceeding 1800 kWh/m^2 in some areas) and more than 300 sunny days annually in Iran [33], there is substantial potential for solar thermal power plants. Despite this, approximately 6.5 GW of thermal solar power plant capacity has been planned globally, with over 1 GW currently under construction. The largest solar thermal power plant under construction is in the United Arab Emirates, with a capacity of 0.7 GW, utilizing a combination of parabolic trough and solar tower technologies. Among solar thermal technologies, the parabolic trough is the most mature and has the lowest capital expenditures (CapEx) [34]. Another promising option is solar towers, which are rapidly advancing and could play a significant role in the future of thermal power plants.

However, the levelized cost of electricity (LCOE) for solar thermal technology remains higher than that of photovoltaic (PV) systems. This disparity has limited its development, leading to ongoing research aimed at making the technology more competitive and reducing its LCOE. Additionally, the storage system for solar thermal power plants is a critical limiting factor, which will be discussed in detail in the next section.

Various design and simulation studies conducted by universities and research institutes have highlighted Iran's potential for solar thermal energy [35–39]. At the Niroo Research Institute (NRI), a project was planned to design and construct a 20 kW thermal parabolic trough solar collector. This project builds on previous studies, which demonstrate that similar power plants have been successfully built and operated at scales of tens of megawatts globally. The ten-meter-long, 20 kW thermal parabolic trough pilot plant is the first of its kind designed and constructed using domestic expertise and locally available components and supplies. Additionally, a pilot solar chimney power plant was developed in Kerman, featuring a chimney with a height of 60 meters and a diameter of 3 meters [36]. This solar chimney power plant has the potential to generate over 400 MWh [38]. However, the high technological and investment costs remain significant barriers to the success of solar power plants in Iran. Despite the challenges, solar thermal power plants have been designed in Shiraz and Yazd (see Figure 13). Notably, the Shiraz plant, which began operation of its steam generation system in 2008, is a concentrating solar power (CSP) plant with a nominal capacity of 250 MW. It is considered the most significant solar thermal project in Iran [33, 39–41]. This plant is not operational and functions as a demonstrative power plant.

Given the development trends of solar thermal technologies and Iran's significant potential, this technology could become a part of the country's energy production sector by 2030. However, challenges such as thermal storage, materials, and costs need to be addressed first. Ongoing activities in thermochemical energy storage in Iran, which will be discussed in detail in the next section, are steps in this direction.

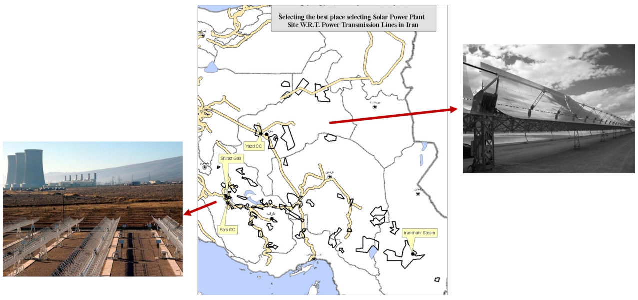

Fig. 13. Solar thermal power plants in IRAN (Shiraz and Yazd) [25].

4 Solar thermochemical energy storage in Iran

An inherent drawback of electricity is that it cannot be stored on a large scale. This limitation makes the grid vulnerable to imbalances between production and consumption, a risk that is heightened when relying on renewable electricity sources, which are not always entirely reliable. The challenges of renewable electricity become even more critical due to its deep dependence on climatic conditions, which makes it difficult to guarantee and balance production output. Surplus production or shortfalls on the power grid can cause fluctuations in frequency and voltage, potentially leading to equipment damage and blackouts. As a result, the current expansion of renewable energy raises significant questions about how to effectively manage the power grid. In this context, electricity storage in chemical forms, particularly as liquid carriers, becomes crucial for the superior management of the energy network. On the other hand, while electricity consumption accounts for only 20% of final energy, it represents 38% of primary resource consumption due to the significant energy losses and CO_2 emissions during the conversion to electricity [42]. In this context, shifting from more carbon-intensive fossil fuels to natural gas – the cleanest fossil fuel – becomes essential. By 2040, natural gas, combined with renewables, is expected to account for 75% of global energy growth [43]. To fully realize the potential of natural gas as a substantial alternative to coal on a large scale, it will be necessary to convert it into energy carriers that offer the logistical advantages of liquid carriers [44].

The BP Statistical Review [43] highlights the abundance and geographic diversity of natural gas supplies (Figure 14). Natural gas serves as an alternative to coal and oil, enhancing the energy efficiency and security of suppliers, though it remains costly to ship or pipe. Similarly, transmitting renewable electricity over long distances, whether regionally or globally, is either prohibitively expensive or technically unfeasible. Converting natural gas into liquid hydrogen carriers using solar energy systems offers an alternative for integrating these easily transportable fuels into the electricity market. This approach leverages the benefits of transportability via ships or pipelines [45]. Iran is rich in both solar and natural gas resources, with an estimated 34 trillion cubic meters (TCM) of natural gas. These resources can be harnessed to produce liquid fuels from natural gas by deploying solar energy on a large scale. The utilization of solar thermochemical systems offers a low-emissions method for producing liquid fuels, serving as feedstock that supports the integration of renewable electricity into global markets [46–50]. This approach provides a 'bridge' from traditional fossil fuel technologies to the large-scale production of green chemicals and fuels.

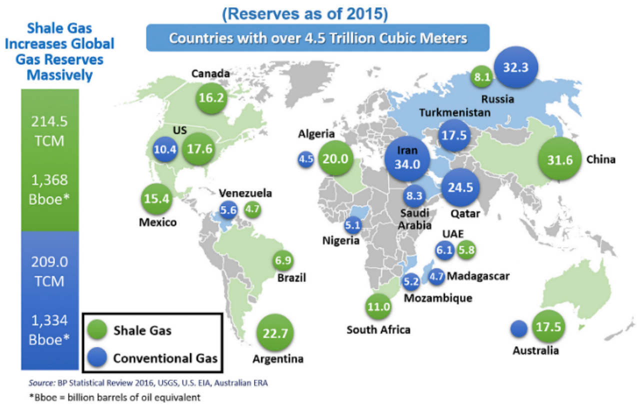

Fig. 14. Distribution of proven natural gas reservoirs in the world [43].

For a long time, methanol (CH_3OH) has been one of the fuels with the lowest GHG emissions produced on a large industrial scale. The production of Methanol from syngas ($CO + H_2$) is a highly mature technology, with more than $200,000\,Nm^3/h$ of syngas being generated worldwide through steam methane reforming (SMR: $CH_4 + H_2O \xrightarrow{700-900\,^{\circ}C} CO + H_2 \xrightarrow{250\,^{\circ}C} CH_3OH$ method in the world [51]. In Iran, the annual capacity for methanol production through this pathway is expected to reach approximately 23 million tons by 2025 [52]. To meet the required heat loads for the SMR process, solar-driven steam reforming is one of the most extensively studied solar thermochemical options, with considerable experience in Australia and other regions [47]. Nevertheless, an important consideration for constructing a solar-driven steam reforming system is the location's suitability, which includes having adequate solar irradiation potential and necessary infrastructure, such as access to the national electricity transmission network. Considering all the above specifications, optimal locations have been identified based on detailed research conducted by NRI [53], as illustrated in Figure 14. The hatched areas represent suitable locations for constructing solar power plants, where key infrastructure such as main and secondary routes, cities, district centers, heating power plants, gas or combined cycle plants, and meteorological stations are present. Integrating Figures 13 and 14 provides a particularly revealing and insightful perspective. It highlights the potential for integrating solar energy with chemical complexes and a decentralized market, thereby enhancing the country's energy security. Given the significant CO_2 emissions in these areas and their proximity to international seas, using this renewable energy carrier in chemical form $CO_2 + H_2 \xrightarrow{\text{Solar}} CH_3OH$) could serve as a viable alternative to Liquefied Natural Gas (LNG) for shipping to countries like China and India, which have substantial methanol demand as feedstock. [54]. It also highlights an important consideration: the gradual transition from natural gas to methanol, and eventually to carbon-neutral technologies. While this shift may be economically attractive and potentially viable with the proper development of technology and infrastructure, the question remains whether it is feasible from a climate change perspective. In 2020, Iran was ranked eighth among the top ten countries worldwide for CO_2 emissions, with 8.87 metric tons per capita [55], and was also among the top seven for gas flaring [56]. In the upstream oil industry, flare gas contributes significantly to greenhouse gas emissions [57].

This scenario offers a promising step towards preventing major environmental collapse. However, unless we develop more innovative methods for reducing carbon emissions or achieve a more rapid decline in carbon usage, transitioning to a post-carbon world will remain a challenge. Integrating renewable energy systems with fossil fuel technologies presents a novel approach to sustainable energy policy to address impending crises, but it will require modifications to existing infrastructure. To address the challenges of creating a sustainable world, three key pillars are considered: Storing renewable energy in chemical form, primarily as H_2 or CO_2 carriers in liquid forms such as methanol, formic acid, or ammonia [58–61]. These methods highlight the desired qualities of an ideal storage medium: Low volume and high energy density. They also allow us to develop an 'idealness factor', which measures how close we are to achieving the optimal conditions for energy storage.

5 Conclusion

Solar energy development in Iran has been progressing in recent years, with the government establishing ambitious targets for renewable energy production. As of 2024, Iran had approximately 1120 MW of installed solar capacity, but plans are in place to expand this to 10 GW in the near future. The country benefits from abundant solar resources, experiencing around 300 sunny days per year in many regions. The Iranian government has been providing incentives for solar energy development, such as feed-in tariffs and tax exemptions. Foreign companies have played a significant role in many of Iran's solar projects, contributing essential expertise and technology. With its substantial solar resources, Iran has the potential to become a major player in the global solar energy market. However, challenges related to technology access and financing need to be addressed to fully realize this potential. Table 1 summarizes the challenges, opportunities, and suggested solutions for solar energy development in Iran. Iran also has substantial potential for solar fuels, a type of renewable energy source that uses sunlight to produce fuels like hydrogen or methane. Solar fuels can be generated through various technologies, including photoelectrochemical cells, photocatalytic reactors, and concentrated solar power systems. Solar fuels have the potential to play a significant role in Iran's energy mix, especially in reducing the country's dependence on fossil fuels. However, challenges such as the high cost of production and the need for more efficient technologies remain. Overall, solar fuels present a promising opportunity for Iran to enhance its renewable energy use and decrease its carbon footprint.

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Table 1. Challenges, potentials, and suggested solutions for solar energy development in Iran [29, 62, 63].

Challenges	Potentials	Suggested Solutions
Lack of a Comprehensive Policy Framework	Abundant Solar Resources	Develop Integrated Renewable Energy Policies
Iran's renewable energy policies are fragmented and lack coherence, which hinders effective implementation.	Iran enjoys over 300 sunny days a year, providing a strong basis for solar energy generation.	Establish a centralized authority to streamline policy-making and implementation processes.
High Dependency on Fossil Fuels	Growing Global Interest in Renewable Energy	Incentivize Private Sector Participation
The economy's reliance on oil and gas limits investment in renewables.	The global shift towards renewables creates opportunities for technology transfer and investment.	Create favorable conditions for private investment through subsidies and tax incentives.
Insufficient Infrastructure and Technology	Potential for Technological Innovation	Invest in Research and Development
Existing renewable energy infrastructure is minimal, with less than 1 GW capacity.	Advances in solar technology can enhance efficiency and reduce costs.	Increase funding for research in renewable technologies and support local innovation.
Regulatory and Bureaucratic Barriers	Strategic Geographic Position	Simplify Regulatory Processes
Complex regulations and bureaucratic hurdles impede project development.	Iran's geographical diversity allows for various renewable energy applications, including solar and wind.	Streamline the approval processes for renewable projects to encourage faster implementation.
Public Awareness and Acceptance	Regional Leadership Potential	Enhance Public Awareness Campaigns
Low public knowledge about the benefits of solar energy limits its adoption.	Iran has the potential to become a leader in renewable energy in the region, competing with neighbors.	Launch educational initiatives to raise awareness of renewable energy benefits and opportunities

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