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Energy imbalance in Iran: Modern technologies, challenges, and the transition to a sustainable future with global insights

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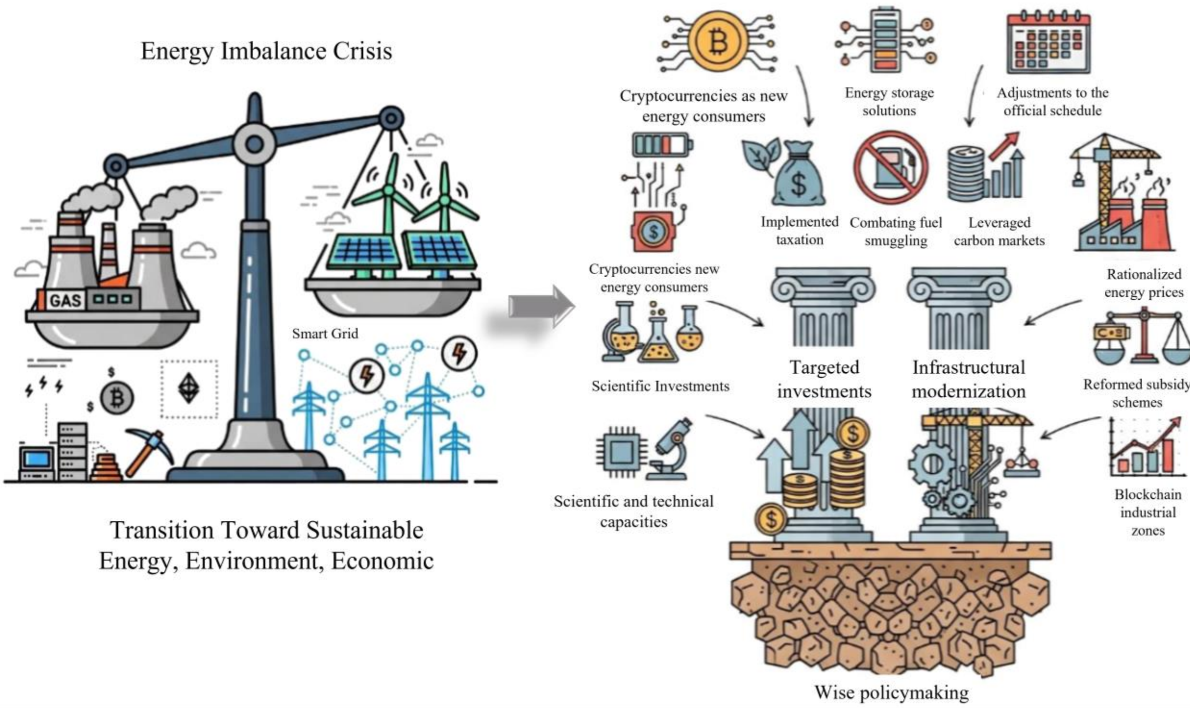
Abstract

The energy imbalance in Iran stands as one of the fundamental challenges in the country's energy supply and consumption sectors, exerting profound impacts on its economic, social, and environmental sustainability. This study examines the historical trajectory of energy imbalance in Iran, analyzing key contributing factors such as inefficiencies in energy distribution and consumption, resource wastage, and insufficient development of renewable energy infrastructure. Additionally, the experiences of several developed countries in optimizing energy consumption management are reviewed to identify successful models for mitigating energy imbalance in Iran.

Based on this analysis, a range of solutions is proposed, including the optimization of energy consumption in industrial sectors, the advancement of innovative energy production technologies, the reform of supportive policies, and the adoption of renewable energy sources. The findings of this study demonstrate that a combination of structural reforms, appropriate economic policies, and the utilization of cutting-edge technologies can play a pivotal role in reducing energy imbalance and achieving sustainable development in the country.

Graphical Abstract



1. Introduction

In today's world, energy is one of the most critical drivers of economic growth, industrial development, and social welfare. Optimal management of energy resources not only directly impacts economic sustainability but also enhances energy efficiency, leading to cost reduction, improved energy security, and minimized environmental impacts. Despite being endowed with abundant fossil fuel resources, Iran faces significant challenges, including energy imbalance, unsustainable consumption patterns, and inefficiencies in energy distribution and production systems.

This section presents an overview of Iran's energy production and consumption trends over the past three years, along with future projections, to provide a deeper understanding of the country's energy imbalance and underscore the importance of addressing this issue.

1.1. Summary of Iran's Electricity Supply During Peak Demand Periods

According to the Iran Chamber of Commerce Research Center, the nominal capacity of thermal power plants in Iran reached 92.8 megawatts by the end of the year 2023-24, marking a 2-megawatt increase from the year 2022-23 (**Fig. 1**) [1]. Here, thermal power plants refer to small-scale and large-scale power plants that use fossil fuels to generate electricity. It should be noted that thermal power plants include gas, steam, combined cycle, and diesel power plants [2].

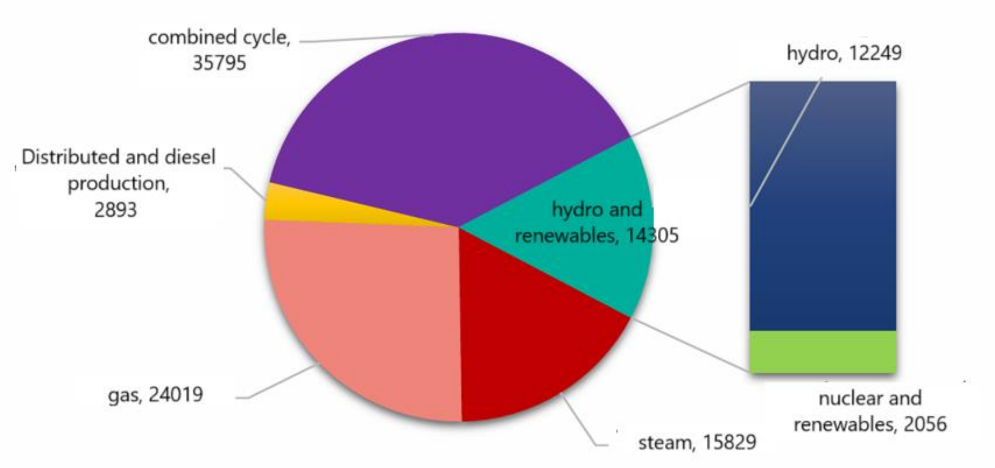


Fig. 1. Installed capacity of various power plant types in Iran as of the end of 2023.

Despite an average annual growth rate of 2.8% in power plant capacity during 2017-2023, peak demand increased by 4.8% during the same period. This disparity has resulted in an annual deficit exceeding 12.4 gigawatts between installed capacity and peak demand. As shown in **Fig. 2**, the electricity shortfall has intensified in recent years, with its absolute magnitude showing a continuous upward trend [1].

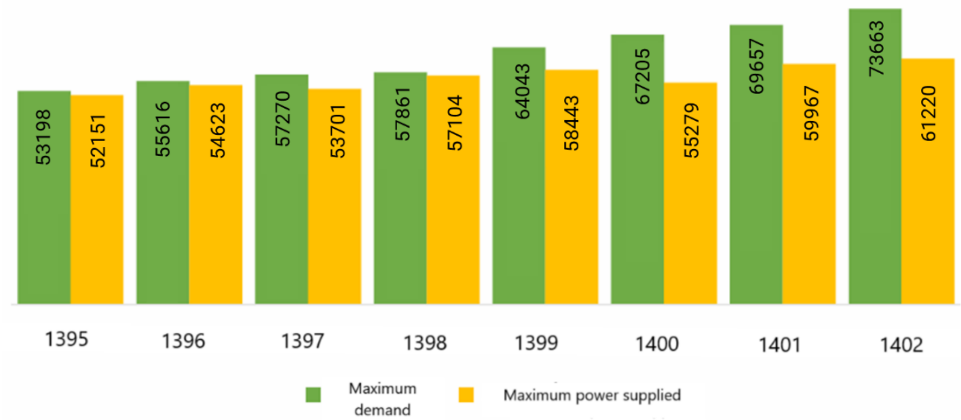


Fig. 2. Peak demand and maximum supply capacity from 2017 to 2023.

The electricity consumption and demand of consumers are influenced by various factors, including weather conditions, socio-cultural variables, and economic status, with varying degrees of impact on consumption growth depending on the type of consumer. According to **Fig. 3**, while residential consumers account for approximately 32% of annual electricity consumption, data from the Iran Research Center indicates that during the summer of 2024, this sector contributed to over 48% of peak electricity demand. Meanwhile, the industrial and agricultural sectors consumed 36% and 15% of electricity in 2023, respectively, with their shares of peak demand in the same year being 28% and 12% [1].

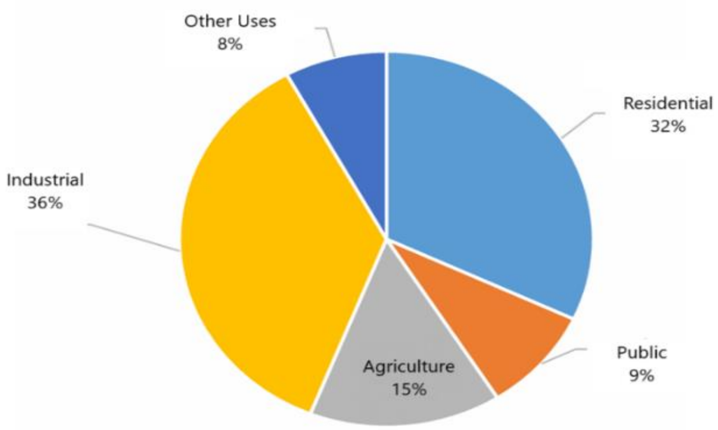


Fig. 3. Electricity consumption share by customer type.

1.2. Evaluation of Power Plants in Operation and Electricity Supply in Iran

Fig. 4 presents the estimated load curve for different weeks of the year and the method of meeting demand based on the capacity of thermal and hydropower plants, with the remainder supplied through demand-side management programs and imposed restrictions. According to this chart, due to the country's climatic conditions, the average electricity deficit peaks during weeks 17 to 23 (mid-summer) and may necessitate consumption restrictions to meet national demand [1-2].

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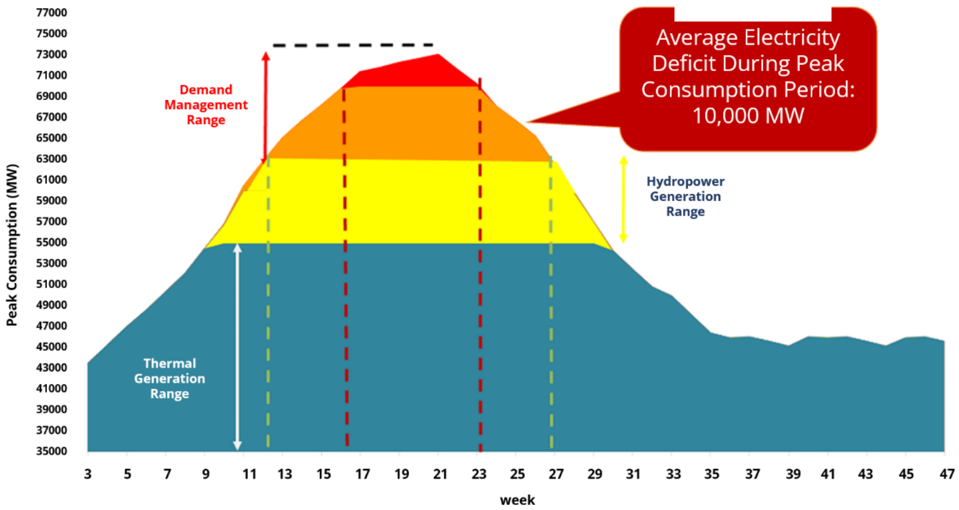

Fig. 4. Weekly load curve estimation of the national grid and generation level.

As shown in **Fig. 5**, during the 2010s, the nominal capacity of power plants in the country increased by only 3.5% annually, while electricity consumption grew by over 45%. From 2013 to 2021, the growth in power plant capacity was merely 21% [3].

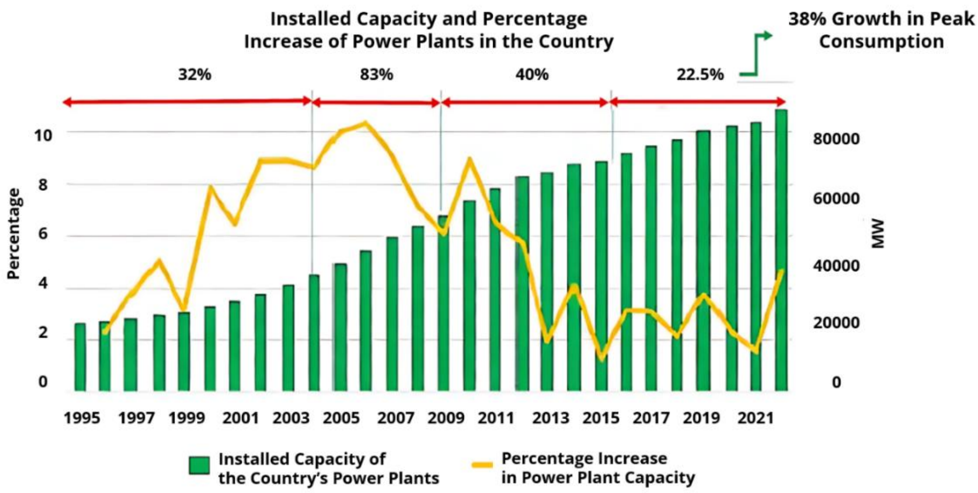

Fig. 5. Nominal capacity and percentage increase in the country's power plant capacities.

1.3. Forecasting Iran's Future Energy Imbalance

The energy imbalance in Iran has emerged due to multiple factors, including rising energy demand, extensive fossil fuel subsidies, inefficient tariff policies, and insufficient development of renewable energy sources. This issue has not only intensified pressure on the power distribution network and fuel resources but has also constrained opportunities for energy exports and new investment attraction [4].

According to **Fig. 6**, based on data from the Iranian Ministry of Energy, there is a significant discrepancy between the peak electricity demand during the hot season and the instantaneous generation capacity of the country's power plants. This mismatch has led to an increase in electricity shortages, and it is predicted that if the current trend continues, this deficit will intensify annually, reaching between 32 and 61 gigawatts by the year 2021. Moreover, according to the Secretary of the Renewable Energy Association, the electricity deficit in 2024 has already reached 18 gigawatts [3].

Based on the reported statistics, it can be concluded that Iran will face an energy shortfall of approximately 25 gigawatts in the summer of 2025.

This study aims to analyze the primary causes of energy imbalance in Iran and propose practical solutions to mitigate this challenge. The ultimate goal is to develop a system that not only meets current demands but also ensures a more sustainable future for the country.

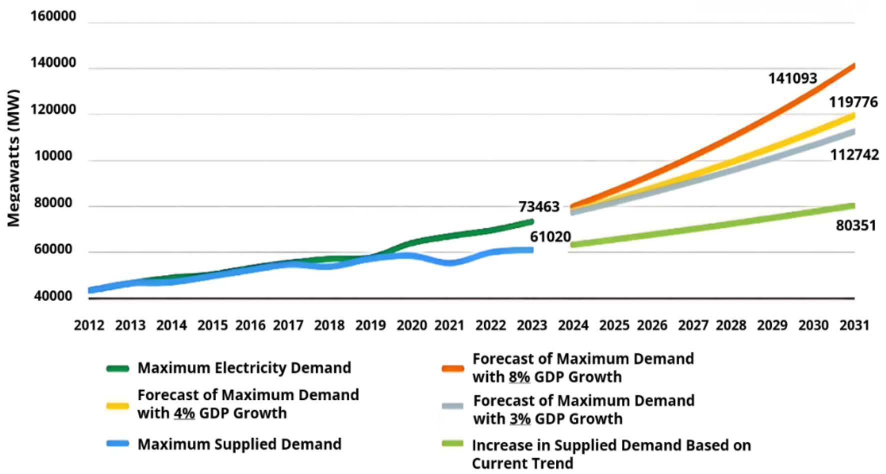

Fig. 6. Peak load growth trend and projected consumption demand in Iran up to the year 2031.

2. Technological Transformation in Energy Management

Technological advancements in energy management serve as a key strategy, playing a vital role in optimizing consumption and enhancing efficiency. The development of innovative technologies in energy production, transmission, and consumption constitutes essential tools for achieving sustainable development goals, reducing energy intensity, and improving overall productivity.

2.1. A General Overview of Energy Technologies in Iran

Understanding the status of energy technologies in Iran requires a comprehensive overview of current trends, existing achievements, and forthcoming challenges. This section reviews the key indicators, capacities, and technological weaknesses within Iran's energy sector, providing a foundation for more detailed analyses presented later.

2.1.1. Plant Life Cycle and Operational Utilization

Many power plants in Iran face reduced efficiency due to improper operation and aging. According to data, approximately 30% of Iran's power generation capacity is more than 30 years old. This aging results in higher emergency shutdown rates and diminishes the effective utilization of resources (see **Fig. 7**) [1]. The average age of thermal power plants is estimated to be between 28 and 32 years, with about 35% of the plants exceeding 30 years in operational age [2, 5].

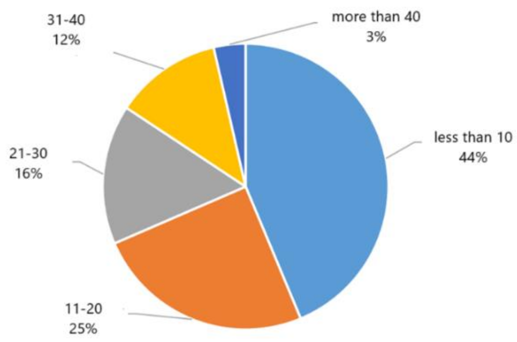

Fig. 7. Distribution of the operational ages of installed power plants in Iran.

2.1.2. Age and Capacity of the Power Grid

Another operational risk associated with the electrical infrastructure is related to the capacity and aging of the transmission network. The data presented in **Table 1** indicate that a substantial portion of the country's substations and transmission lines are over 30 years old. Additionally, approximately 20% of the network capacity has been in operation for more than 30 years, and 15.3% of the substations are over 35 years old. The emergency outage rate for these infrastructures has been reported as very high [1].

Table 1. Age distribution of substations and transmission lines in Iran (by percentage).

Age	Percentage of Transmission Substation Capacity by Age	Percentage of Network Transmission Lines by Age
1-5	19.7	6.3
6-10	13.9	4.9
11-15	18.1	15.8
16-20	12.0	16.1
21-25	10.6	17
26-30	6.1	12.1
31-35	4.2	6.4
Over 35	15.3	21.4

2.2. Analysis of Innovative Approaches in Gas Turbine Optimization

Developing countries have implemented various measures to reduce energy consumption in power generation processes. Among these, gas turbine (GT)-based power plants have garnered particular attention due to their lower capital costs compared to steam plants. However, conventional industrial gas turbines, especially under partial load conditions, exhibit low efficiency, which leads to environmental issues and increased pollutant emissions.

In recent years, one of the technologies developed to enhance efficiency and produce cleaner electricity (with minimal pollutants) is the combined cycle (CC) technology. The thermal efficiency of gas turbine power plants with combined cycle (CCGT) can reach up to approximately 60%, which is a significant improvement compared to the efficiency of traditional coal-based steam power plants. These power plants not only contribute to conserving limited energy resources but also play an effective role in reducing emissions and protecting the environment. The following section discusses various techniques to improve the efficiency of gas turbines [5].

2.2.1. Air Intake Cooling and STIG Cycles

The IAC and STIG cycles are among the innovative technologies that have significantly improved the efficiency of industrial gas turbines. In the IAC system, incoming air is cooled before compression, which has been proven as an effective method to boost the turbine's power output. This approach particularly benefits the grid during peak summer demand. The IAC cycle technology reduces the temperature of the air entering the compressor section, leading to increased density and mass flow rate, resulting in higher gas turbine power output. This method is especially advantageous in hot climatic conditions, where it enhances overall efficiency [6].

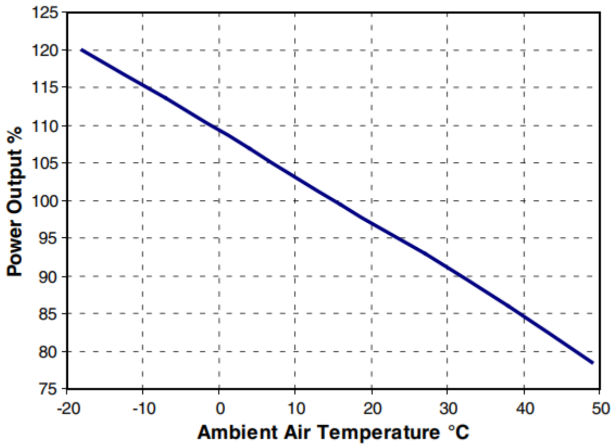

Fig. 8. Percentage relationship between ambient temperature and turbine output for a standard gas turbine.

Analysis of the data in **Fig. 8** indicates that the power output of the gas turbine can increase by approximately 0.7% for each one-degree Celsius reduction in inlet air temperature [6]. Conversely, an increase in air temperature negatively impacts turbine performance, resulting in a significant decrease in power output. This performance drop is particularly noticeable during the hot summer months when electricity demand peaks. Therefore, maintaining a lower inlet air temperature through ambient air cooling is considered an effective and desirable measure to enhance gas turbine performance.

The two most common IAC systems are evaporative cooling and chillers. Evaporative cooling is widely used due to its simplicity and cost-effectiveness but has two main limitations: first, its performance significantly decreases under high relative humidity conditions; second, the ingress of water droplets into the compressor section can lead to excessive blade erosion. In contrast, chiller systems, which are less dependent on ambient humidity and do not pose a risk of blade erosion, are considered a safer alternative. However, these systems consume additional electrical power and cause greater pressure drops compared to evaporative methods.

STIG technology is another innovative approach to efficiency enhancement, involving the direct injection of steam into the combustion chamber. When a simple cycle power generation unit is used as a baseline and STIG and IAC technologies are integrated continuously into the system to facilitate performance parameter simulation, the results show that upgrading from a simple cycle to a combined system incorporating IAC and STIG can increase the power output from 30 MW to 48.25 MW, while the thermal efficiency can be improved from 29.9% to 33.4% [6].

2.2.2. Improving Gas Turbine Efficiency through Advanced Alloys

Achieving maximum efficiency in modern gas turbines necessitates a significant increase in the inlet gas temperature. However, this temperature escalation introduces more challenging operational conditions that intensify corrosion of turbine blades. Currently, turbine blades used in aerospace, marine, and industrial applications are primarily made from nickel-based superalloys, as these components endure the highest levels of stress and operational temperatures compared to other engine parts.

This issue is particularly pronounced in turbines installed in marine environments, where the presence of compounds such as sulfur, sodium in the fuel, and halides dissolved in seawater can have detrimental effects on the lifespan and reliability of superalloy components. These factors may lead to a decrease in the load-bearing capacity of the parts and an increased risk of severe system failures.

Therefore, alongside maintaining mechanical strength at high temperatures, enhancing the corrosion resistance of superalloys plays a key role in improving turbine performance efficiency. Nickel-based superalloys, possessing high resistance to creep, thermal stability, suitable tensile strength, structural stability at elevated temperatures, and corrosion and oxidation resistance, are considered primary materials for manufacturing hot-section components of gas turbines [6]

Table 2. Chemical composition of superalloys used in gas turbine blades.

Superalloy	%Cr	%Co	%Ti	%W	%Al	%Ta	%Mo	%Fe	%C	%B	%Nb	%Re	%Ru	%Hf	%Ni
SC: AM1	7.8	6.5	1.1	5.7	5.2	7.9	2	-	-	-	-	-	-	-	Balance
SC: René N6	4.5	12	-	5.7	6	7.5	1.1	-	0.05	0.04	-	5.3	-	0.15	Balance
MC-534	4	-	-	5	5.8	6	4	-	-	-	-	3	4	0.1	Balance
GTD-111	13.5	9.5	4.75	3.8	3.3	2.7	1.53	0.23	0.09	0.01	-	-	-	-	Balance
Allvac® 718Plus	17.9	9	0.74	1.04	1.5	-	2.68	9.3	0.02	0.003	5.51	-	-	-	Balance

As shown in **Table 2**, nickel serves as the primary base in all the introduced alloys, and each of these alloys contributes to enhancing performance and increasing resistance against harsh thermal conditions and mechanical stresses in gas turbine engines [6].

2.2.3. Efficiency Improvement of Gas Turbines through Thermal Barrier Coatings (TBC)

Thermal Barrier Coatings (TBC) are multilayer systems consisting of an insulating ceramic layer combined with a metallic bonding layer that bonds the ceramic to the substrate. The primary objective of these coatings is to reduce the surface temperature of components, control and diminish oxidation and corrosion, and also alleviate thermal stresses in high-pressure and high-temperature parts. The ceramic top layer protects the metallic substrate from high-temperature environments, thereby extending the service life of components in gas turbines.

Typically, these coatings are applied using methods such as plasma spraying, sputtering, and Electron Beam Physical Vapor Deposition (EBPVD). However, TBC systems can fail through three main pathways: 1) delamination between layers, 2) inadequate bonding between the ceramic layer and the protective oxide, and 3) mechanical disruptions that cause displacement or loss of the coatings. The development of growth of thermally grown oxide (TGO) layers within deposited coatings has been proposed as an effective measure to enhance durability and system performance. Removing the bond layer can also extend operational lifespan, as in this case, the TGO layer directly forms on the substrate surface, offering greater resistance to thermally induced warping during thermal cycling. Overall, employing these technologies can lead to weight and cost reduction as well as improve the efficiency and longevity of gas turbine components [5].

In continuation of this approach, another study conducted at the Montazer Gaem Power Plant in Iran [7] replaced a conventional pressure reducing valve with an expansion turbine to produce mechanical power. This power was subsequently used to operate a mechanical chiller, reducing the inlet air temperature to the compressor.

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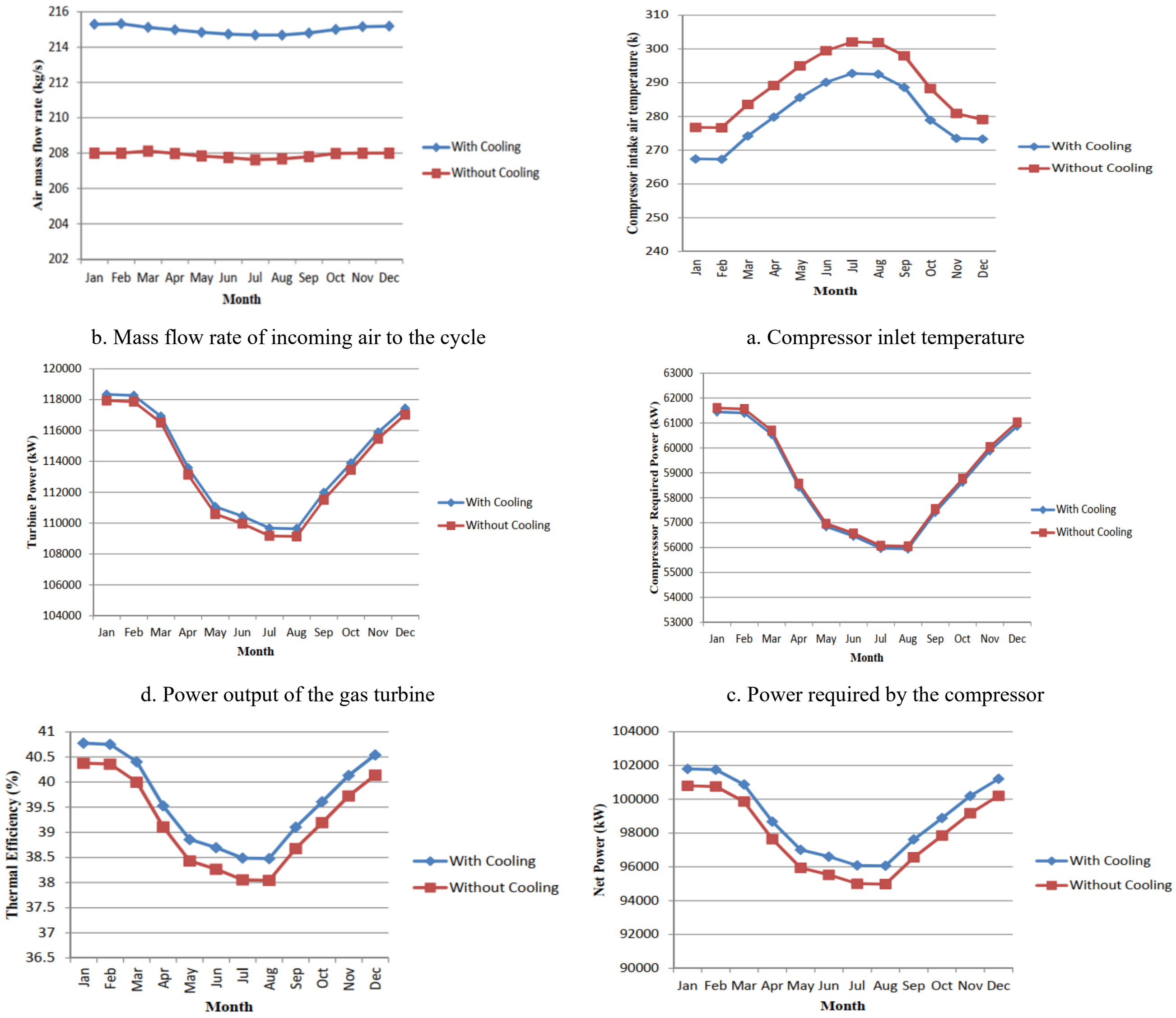

b. Mass flow rate of incoming air to the cycle

a. Compressor inlet temperature

d. Power output of the gas turbine

c. Power required by the compressor

f. Thermal efficiency of the cycle

e. Net cycle output power

Fig. 9. Effects of implementing a mechanical chiller.

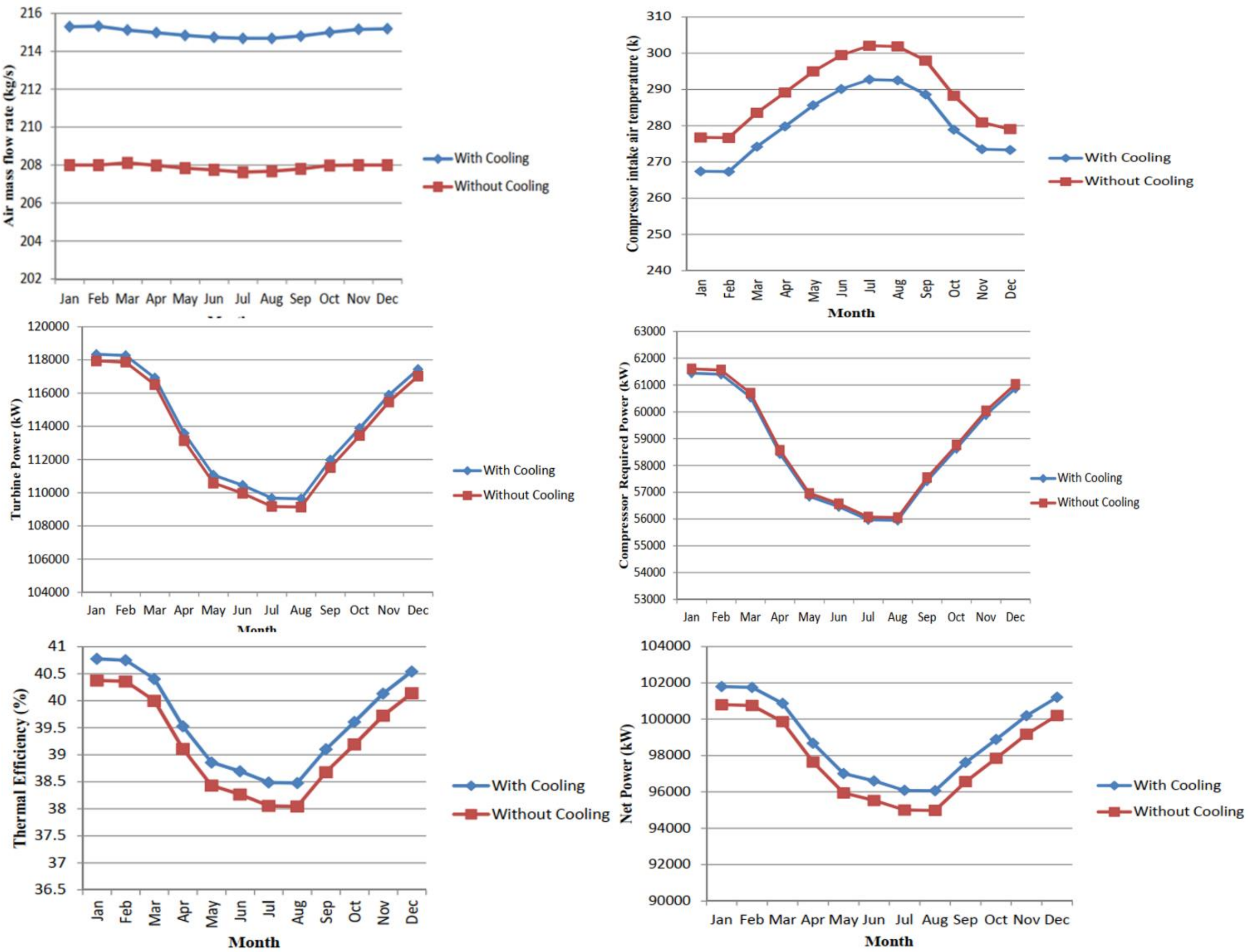

Fig. 9. Effects of implementing a mechanical chiller. a. Compressor inlet temperature, b. Mass flow rate of incoming air to the cycle, c. Power required by the compressor, d. Power output of the gas turbine, e. Net cycle output power, f. Thermal efficiency of the cycle.

The use of a mechanical chiller results in the following effects [7]:

— Temperature reduction: This system decreases the compressor inlet temperature by approximately 3.2% (**Fig. 9a**).

— Increased inlet mass: Lower temperatures increase air density, resulting in an approximately 3.4% increase in air mass entering the compressor (**Fig. 9b**).

— Reduced compressor power consumption: Due to lower inlet temperatures, less energy is required for compression, reducing the compressor power demand by up to 0.26% (**Fig. 9c**).

— Increased gas turbine power: The higher air intake into the combustion chamber leads to more efficient combustion, increasing turbine output by about 0.45% in summer conditions (**Fig. 9d**).

— Increased net cycle power: The net power output of the system increases by 1.138%. If this system is installed across all six units in the power plant, it could increase capacity by approximately 6484 kW in July (**Fig. 9e**).

Improved thermal efficiency: Ultimately, the increase in net generated power, with constant fuel consumption, results in a 1.138% rise in the system’s thermal efficiency (**Fig. 9f**).

The implementation of mechanical chillers yields several benefits, including increased plant power output and efficiency, reduced energy consumption, and improved environmental performance of the system. This approach can serve as a practical model for other power plants operating in hot and arid climates.

2.3. The Impact of Smart Electricity Meters and Remote Control Equipment on Energy Consumption Management

Historically, electricity consumption management relied primarily on incentive policies or temporary restrictions. However, today, smart meters and remote control devices serve as strategic tools that enable real-time monitoring and management of energy usage. These technologies play a particularly significant role in reducing grid load for governmental entities.

2.3.1. Operation of Smart Electricity Meters

Smart meters measure instantaneous energy consumption and transmit this data in real-time to monitoring centers. They are capable of analyzing consumption patterns, issuing alerts, and even disconnecting or limiting usage during peak load hours. Additionally, remote switching equipment can control the operation of unnecessary devices to optimize energy use.

2.3.2. International Experiences with Smart Meters

Developed countries have been utilizing smart meters for years. In Italy, the installation of over 35 million meters from 2001 to 2006 resulted in a 5.5% reduction in residential consumption and decreased operational costs for distribution companies. Similarly, in Japan, the application of Internet of Things (IoT) technology in government and educational buildings has led to a 10% reduction in electricity use over five years [8-9].

2.3.3. Technical and Economic Benefits of Smart Meters

These technologies offer several critical advantages in managing the electricity supply-demand gap:

- Real-time load management: issuing alerts or automatically cutting power during peak periods.
- Economic incentives for conservation: through time-based tariff differentiation.
- Reducing investment needs in generation and transmission: by postponing the construction of new power plants through peak load reduction.
- Monitoring high-consumption offices in real-time: enabling incentive-based or punitive policies based on precise data.

It can be concluded that the deployment of smart meters and remote switching equipment constitutes a key element in the digital transformation of energy consumption management. This approach has yielded tangible and significant results in reducing electricity consumption and improving energy balance both in developed countries and within Iran.

3. The Role of Cryptocurrencies in Iran's Energy Balance

In recent years, cryptocurrencies have become one of the most heated topics in both economic and technological discussions. They have influenced profound changes in the global financial system and have played a role across various industries. As a burgeoning phenomenon, cryptocurrencies continue to evolve. A significant topic within this domain is the concept of "Green Cryptocurrency," which aims to reduce the environmental impacts of cryptocurrency mining and optimize energy consumption in this industry. This section will explore this concept, its applications in the industry, the role of government incentive policies, and the potential future of such digital assets.

3.1. Green Cryptocurrencies and Production Trends

Green cryptocurrencies are digital assets designed to lower energy consumption and promote environmental sustainability. These cryptocurrencies utilize more efficient methods for transaction validation.

3.1.1. Analysis of Energy Consumption Trends of Cryptocurrencies in Iran

In 2017, coinciding with the surge in Bitcoin prices globally, cryptocurrency mining in Iran experienced a remarkable increase, leading to a significant rise in energy consumption within this sector. Due to the relatively low electricity prices in Iran compared to international standards, cryptocurrency mining became highly profitable and attractive to the general public. As a result, electricity consumption for mining reached 500 *MW* in 2017 [10].

With the substantial rise of unregulated cryptocurrency mining activities, the Iranian government recognized mining as an official industry in 2019 and began issuing licenses to various organizations. This development further contributed to an increase in energy consumption in the sector.

Based on the data in **Fig. 10**, Iran ranks eighth worldwide in Bitcoin mining energy consumption, with a total of 5.13 gigawatt-hours, representing a substantial and non-negligible figure [11, 12]. The Iranian government, through measures such as shutting down illegal mining operations, increasing electricity tariffs, and concurrently, the decline in Bitcoin's global value, has managed to reverse the increasing trend in electricity consumption associated with these activities.

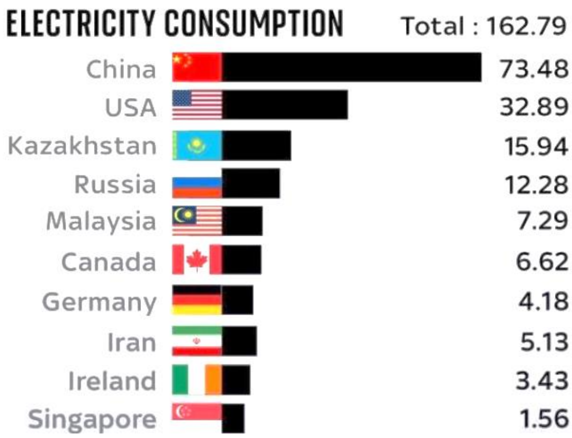

Fig. 10. Global energy consumption for Bitcoin mining (in gigawatt-hours in 2021).

3.1.2. Impact of the 12-Day Iran-Israel Conflict on Bitcoin Mining and Electricity Consumption

In cryptocurrency mining, the network's computational power is represented by a unit called "hashrate", which indicates the level of mining activity within the network. A higher hashrate signifies a greater number of calculations per second and is generally associated with increased electricity consumption.

During the military tensions between Iran and Israel in June 2025, a report indicated a 5% decline in the global Bitcoin hashrate. Concurrently, Iran experienced widespread internet disruptions, abruptly removing many data centers and mining operations from operation. As shown in **Fig. 11**, within a short period in June, the network's hashrate suddenly decreased, while the network's difficulty for Bitcoin mining remained relatively unchanged [13]. This discrepancy suggests a sudden reduction in computational capacity without any change in the network's algorithm. Assuming that this 5% hashrate decline resulted from the shutdown of Iranian mining farms, it can be inferred that Iran's contribution to the global hashrate is approximately 5%.

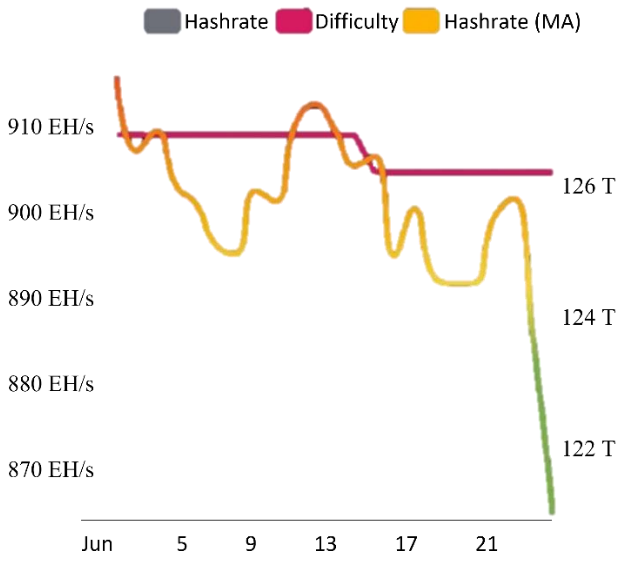

Fig. 11. Variations in Bitcoin network hash rate during the 12-day Iran-Israel conflict period.

Subsequently, an estimate of the electricity consumption associated with this 5% of the global hashrate was conducted, along with an approximation of the total electricity used in Iran to meet this demand. To refine this estimate, it is essential to know that at the time of this decline, the global Bitcoin hashrate was approximately 900 *EH/s*, of which 5%, or 45 *EH/s*, belonged to Iran.

To understand energy consumption, one can consider the efficiency of mining devices. A common and reasonably efficient device is the Antminer S19 Pro (2020), which consumes about 3000 watts and has an output of 110 *TH/s*. Simple calculations indicate that approximately 409,000 units of the S19 Pro are required to achieve the specified hashrate. Assuming each consumes 3000 watts, the total power required to support 5% of the global hashrate would be about 1200 *MW*, equivalent to the consumption of several industrial cities or a large power plant.

In simple terms, if 5% of Bitcoin's hashrate genuinely belongs to Iran, its mining operations would continuously consume about 1200 *MW* of electricity, covering approximately 7% of the country's power deficit in 2024. However, on June 28 (2025), Mohammad Alah dad, Deputy of Transmission and Foreign Trade at Tavanir Co (Iran Power Generation Transmission & Distribution Company), announced that internet shutdowns during the 12-day conflict reduced the national grid's load by 2400 *MW*, accounting for about 15% of last year's power deficit; notably, the reported electricity consumption by Tavanir is double the predictions made in this study. This discrepancy highlights new dimensions of the issue and suggests that most mining devices and equipment in these farms, often old and outdated models with lower-than-standard efficiency, are likely contributing to this gap. Many of these devices are typically high-energy-consuming Chinese second-hand models, which are prevalent and popular in sanctioning countries like Iran due to their low prices.

Moreover, according to Tavanir's estimates, illegal miners cause annual damages exceeding $2 billion to Iran's power sector. The presence of such an issue within Iran's energy imbalance, particularly during summers when residential consumption peaks, poses serious risks to the stability and sustainability of the national power grid. However, through the promotion of green cryptocurrencies, Iran could reduce electricity consumption while fostering the development of clean energy sources to meet the energy demands of these digital assets. Additionally, attracting foreign investment could strengthen the country's digital and blockchain sectors.

3.1.3. Sources of Energy Supply for Green Cryptocurrency Mining

Utilizing renewable and clean energy sources is particularly important for the mining of green cryptocurrencies. In Iran, the following resources can be exploited [14, 15]:

- Solar Energy: Given the adequate sunlight in many regions of Iran, deploying solar panels to supply electricity is a highly viable option.
- Wind Energy: Wind-rich areas, especially in the northwest and southeast of the country, provide opportunities for harnessing wind turbines.
- Purchasing Green Electricity from the Energy Exchange: Miners can procure their required electricity from the Green Panel on the Energy Exchange, which is dedicated to trading electricity generated from renewable sources.

A noteworthy aspect of green cryptocurrencies is that, unlike conventional cryptocurrencies, they do not require high-power hardware. This distinction can lead to a decline in demand for energy-intensive equipment and a significant reduction in overall energy consumption within the country.

3.2. The Role of Green Cryptocurrencies in Industry

The high energy consumption associated with cryptocurrency mining presents a fundamental challenge for this technology. However, through innovative approaches, it is possible to utilize this energy efficiently within industry sectors and simultaneously contribute to economic and industrial growth. The following sections explore some proposed strategies in this regard.

3.2.1. Utilizing the Heat Generated by Mining Devices

Cryptocurrency mining equipment (miners) produce a significant amount of heat, which can be utilized in various industrial and agricultural sectors. Examples of such applications in several countries include:

- Norway: The heat from miners is used to warm greenhouses via heat exchangers, aiming to reduce fossil fuel consumption [16].
- The Netherlands: Mining heat is used to power tulip greenhouses and reduce dependence on natural gas following energy crises [17].
- Sweden: A company utilizes 600 kW miners to maintain a stable temperature in a 300-square-meter greenhouse in cold regions [17].
- Canada: Extensive use of mining heat in greenhouses, offices, and even electric vehicles has been a successful strategy since 2013 to reduce carbon footprint [18].

In Iran, particularly in regions with harsh winters such as Ardabil and Zanjan, mining farms could be established alongside greenhouses to utilize this heat for agricultural energy needs [17].

3.2.2. Using Excess Energy from Mining Systems for Power Generation and Industry Support

The energy consumption of mining operations can serve as a complementary resource for industries or even for power generation:

- Technologies such as steam turbines and thermoelectric systems enable conversion of mining heat into electrical energy.
- Excess energy can be stored in batteries and used during peak consumption hours to prevent industrial power outages and mitigate potential equipment damages.

- This energy can also be employed in cooling systems for industrial equipment and miners, enhancing efficiency and reducing overall electricity usage.

3.2.3. Industry Financing through Cryptocurrencies

In countries like Russia and Venezuela, cryptocurrencies serve as tools for financing industrial projects and importing equipment. For sanctions-affected countries such as Iran, this approach could be a viable alternative to traditional banking systems.

3.2.4. Exploiting Surplus Power from Power Plants

Some power plants produce electricity above domestic demand, which cannot be exported. One proposed solution is to use this surplus energy for cryptocurrency mining, generating additional revenue. In Kazakhstan, some coal-fired plants have turned to mining and reinvested the proceeds in expanding their infrastructure.

3.2.5. Establishing Blockchain Industrial Parks

One of the challenges of energy imbalance is the uneven distribution of electricity across different regions. In areas with surplus power, blockchain-based industrial parks could be established. This strategy optimizes energy consumption and facilitates the use of mined cryptocurrencies to bolster industrial development. In Canada, regions such as Quebec, with abundant hydroelectric power, have implemented this approach. Iran could similarly develop blockchain industrial zones in regions with excess electricity production, such as the Zagros and Alborz hydroelectric plants, to optimize energy utilization and generate income for infrastructure development.

3.3. Government Incentive Policies for Cryptocurrency Mining

Government policies regarding cryptocurrency mining vary based on economic priorities, energy resources, and environmental considerations. Some countries have introduced incentives to attract investment in this sector, as outlined below:

- *Uzbekistan* [19]: The country has legalised solar-powered cryptocurrency mining and offers tax discounts to miners utilizing solar panels. Given Iran's substantial solar energy capacity in central regions such as Yazd and Kerman, establishing solar-based mining projects and providing tax incentives to miners could be advantageous.
- *Russia* [20]: Russia provides various tax incentives to attract investment in cryptocurrency mining. For instance, in Buryatia, miners benefit from land and property tax exemptions, reduced income tax rates, and a 50% discount on electricity costs. Similarly, Iran could establish special economic zones dedicated to cryptocurrency mining, akin to free trade zones, to increase sector investment and lower production costs.
- *Georgia, Switzerland, and Portugal* [21-24]: These countries have successfully attracted cryptocurrency investments by reducing or eliminating crypto-related taxes. Iran could follow suit by lowering or abolishing taxes on legal mining activities, encouraging miners to transition from underground operations to formal registration and participation in the national economy. Additionally, abolishing capital gains taxes on cryptocurrency transactions could serve as an incentive to attract foreign investment and foster the growth of the blockchain ecosystem.

Supportive policies and strategic utilization of energy resources can significantly influence the development of the cryptocurrency industry. Implementing effective management strategies for energy consumption, leveraging existing capacities, and establishing sound policy frameworks can transform this technology into a powerful tool for economic growth and industrial development.

4. Governance and Macro Energy Policies in the Iranian Government

The issue of energy imbalance in Iran is one of the fundamental challenges in the country's economic and industrial policy-making. However, effective policy formulation in the energy sector can not only contribute to alleviating this imbalance but also create a foundation for economic development, reduce dependence on oil revenues, and optimize the utilization of national energy resources.

This section reviews various strategies employed by different countries to manage energy supply and demand. The aim of this review is to provide practical recommendations for optimizing Iran's macro energy policies and establishing a sustainable and efficient framework for energy supply in the country.

4.1. Energy Export and Import

One of the effective strategies to reduce energy imbalance is leveraging the potentials of energy exports and imports. Many countries have managed to balance their energy accounts through optimized management of these processes. This section discusses the experiences of several countries in this domain.

4.1.1. Examination of the Status of Energy Export and Import in Iran

Iran has faced various challenges in energy export and import over recent years. Primarily, the electricity sector must fulfill domestic demand while simultaneously meeting its export commitments to neighboring countries, particularly Iraq. Additionally, a portion of the country's demand is satisfied through electricity imports [25].

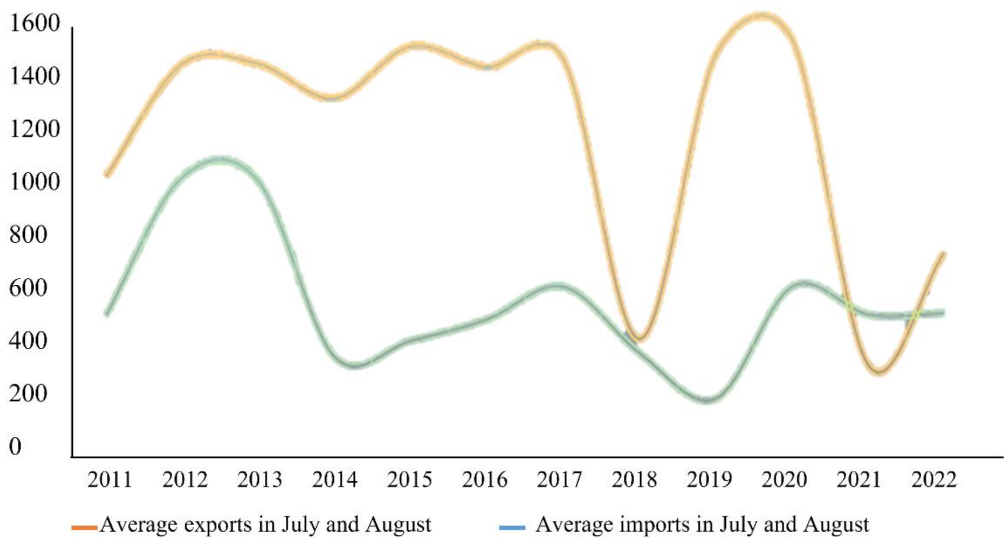

Fig. 12. Average exchanged power with neighboring countries during July and August over the past ten years.

Fig. 12 illustrates the average export and import capacities during July and August from 2011 to 2021 [26]. As observed, the average export capacity to neighboring countries was approximately 900 *MW* in 2011, increasing to a range of 1,170–1,300 *MW* until 2017. These figures decreased to around 344 *MW* in 2018 and further to 252 *MW* in 2021, with exports exceeding imports in 2021.

Aside from cross-border trade performance, export capacity should be considered as an integral part of overall demand management. One potential approach to mitigating Iran's energy imbalance involves importing gas from Russia and Turkmenistan, up to 30 million cubic meters per day, which could reduce the country's gas deficit by up to 10%. Conversely, increasing electricity exports to countries such as Pakistan (which generated revenues of 651 billion Toman in the first half of 2022) could help offset some import costs.

The expansion of Iran's electricity exports need not be limited to neighboring countries. By leveraging projects like "IR" and "Ager," export opportunities could extend to Europe. However, the energy export sector faces significant challenges. A primary obstacle is the relatively low energy prices in Iran compared to global market rates, leading to undervaluation of resources and encouraging overinvestment in energy-intensive industries such as cement and steel. This has resulted in increased production capacities without regard to energy efficiency; for example, Iran's steel industry currently consumes 1.5 times the global standard electricity. Furthermore, low electricity prices diminish incentives for investment in the power sector, resulting in frequent power outages.

Additionally, the development of energy-intensive industries raises concerns about environmental costs, including increased pollution and greenhouse gas emissions, which Iran will likely be pressured to address by international organizations. Therefore, rationalizing energy prices not only can enhance foreign exchange revenues but also prevent unnecessary resource wastage.

Currently, Iran purchases energy at global market rates but exports it at prices below international levels, which exacerbates the country's energy imbalance. Additionally, Iran faces financial challenges, and energy exports constitute a significant portion of its foreign currency earnings. Therefore, a complete cessation of energy exports is impractical. However, alternative strategies can be employed to reduce the country's reliance on energy exports to meet its domestic needs.

4.2. Government Incentive Policies to Reduce Imbalance

To achieve a sustainable and balanced energy system, governments and international institutions implement a set of incentive policies. These policies not only reduce dependence on fossil fuels but also contribute to optimizing energy consumption and strengthening renewable energy infrastructure. Below, some of the most significant policies are examined.

4.2.1. Support for Renewable Energy

Governments provide financial incentives to renewable energy producers, such as tax reductions for clean energy projects and the allocation of land for the development of renewable energy. Countries like Germany, Chile, the UAE, and South Africa have implemented supportive policies to create favorable conditions for renewable energy expansion.

For instance, Germany has enhanced investment security in this sector through policies like feed-in tariffs, which guarantee the purchase of generated electricity. On the other hand, countries such as Chile, the UAE, and South Africa have allocated state-owned land for solar and wind projects. By leveraging their natural resources, these nations have reduced initial costs and facilitated investor participation in renewable energy initiatives.

4.2.2. Phasing Out Fossil Fuel Subsidies and Redirecting Resources to Clean Energy

Reducing fossil fuel subsidies is a key policy for addressing energy imbalances. Such subsidies often lead to excessive fossil fuel consumption and undermine the competitiveness of renewable energy sources [27, 28].

- According to the International Energy Agency (IEA) 2023 report, fossil fuel subsidies should be gradually phased out, with the reallocated funds directed toward renewable energy development. However, subsidy reductions may impose economic burdens on households, necessitating a gradual and balanced implementation by governments.
- Carbon pricing has also been proposed as a strategy to reflect the true costs of fossil fuels. This policy incentivizes energy producers to adopt cleaner resources and reduce environmental pollutants.

As illustrated in **Fig. 13**, Iran ranks among the top countries—alongside Russia and China—providing the highest fossil fuel subsidies [29]. Moreover, Iran's fossil fuel subsidies account for a significant share of its Gross Domestic Product (GDP at Market Exchange Rates, MER). This highlights the substantial fiscal burden these subsidies place on Iran's economy, which could hinder sustainable development and investments in clean energy. These findings underscore the urgency of subsidy reform and resource reallocation toward renewables, a topic explored in-depth in the study's chapter on fossil fuel subsidy reduction.

4.2.3. Establishing Carbon Markets and Carbon Trading Systems

Carbon markets are an effective approach to reducing environmental pollutants and optimizing energy consumption. These markets operate under a cap-and-trade mechanism. Governments set an upper limit (cap) on carbon emissions, and companies exceeding this limit are required to purchase carbon credits from low-emission firms.

— Advantages of Carbon Markets in Mitigating Energy Imbalance

1. Promoting Clean Energy Adoption: Carbon pricing incentivizes energy producers to transition toward renewable resources.
2. Reducing Long-Term Costs: Shifting to renewable energy lowers both economic and environmental costs over the long term.
3. Generating Revenue for Clean Energy Projects: Income from carbon credits can be reinvested in renewable energy initiatives.
4. Driving Innovation in Clean Technologies: Higher carbon emission costs encourage companies to develop low-carbon and more efficient technologies.

The implementation of these incentive policies can reduce energy imbalances and facilitate the transition to a sustainable and efficient energy system.

4.2.4. Incentive Program for Replacing Outdated Household Appliances with Energy-Efficient Iranian Models

A practical strategy to reduce energy consumption and address national energy imbalances is replacing outdated household appliances with energy-efficient models. Due to Iran's economic challenges, replacing household appliances has become difficult and costly for citizens. Meanwhile, the high energy consumption of obsolete appliances contributes significantly to rising energy demand and exacerbates the country's energy imbalance.

To address this, a compelling proposal is implementing a nationwide appliance replacement program, offering energy-efficient Iranian products with installment payment plans to consumers. Below are the key benefits of this initiative:

1. Reduced Electricity Consumption: Older appliances often lack energy-efficient technologies and consume excessive electricity. Replacing them with modern, energy-saving models can reduce energy usage by up to 30%. This not only benefits the environment but also lowers electricity bills over time.
2. Boosting Domestic Production: The program can directly stimulate national manufacturing. Increased demand for energy-efficient Iranian appliances encourages domestic producers to expand production and improve product quality. This can create jobs and enhance the household appliance industry's contribution to GDP.
3. Easier Recycling of Old Appliances: Replacing outdated appliances facilitates more effective recycling. Delivering old devices to recycling centers minimizes environmental harm and allows reusable materials to re-enter the production cycle.

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In conclusion, this program can serve as an effective solution for reducing energy consumption, revitalizing domestic production, and protecting the environment. However, its successful implementation requires coordinated efforts from the government, manufacturers, and consumers to achieve the goals of improved energy efficiency and sustainable development.

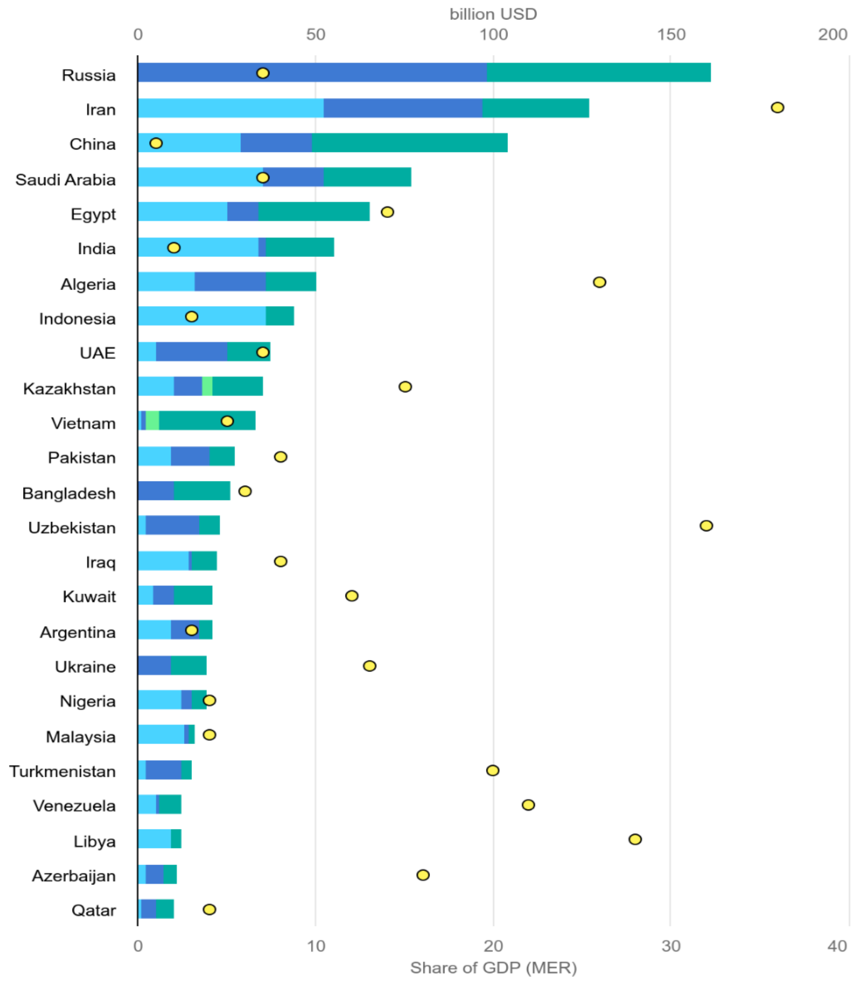

Fig. 13. Comparison of energy subsidies and their share of gross domestic product in selected countries.

4.3. The Impact of Daylight Saving Time (DST) on Energy Consumption

Another strategy for reducing energy consumption and improving efficiency is adjusting the official national time under the Daylight Saving Time policy. The primary objective of this policy is to maximize natural daylight utilization and reduce dependence on artificial lighting and heating.

In general, implementing time adjustments can lead to significant energy savings in the following sectors:

1. Reduced Lighting Consumption: During summer months, increased use of natural daylight decreases the need for artificial lighting.
2. Optimized Heating and Cooling: In certain regions, DST can facilitate more efficient energy use in heating and cooling systems.
3. Lower Transportation Energy Use: Extended daylight hours reduce fuel consumption in vehicles and street lighting.

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This policy has been implemented in various countries with differing effects on energy consumption. While some nations have observed reduced energy use for lighting and cooling, others have experienced less pronounced impacts than anticipated. **Fig. 14** illustrates the energy savings achieved through DST adjustments in various countries [30]. As shown, Iran (if DST were implemented) would achieve the highest energy savings at 1.8%, surpassing other nations. In contrast, developed countries such as the United States, the European Union, and Canada—which already implement DST—exhibit lower energy savings compared to Iran.

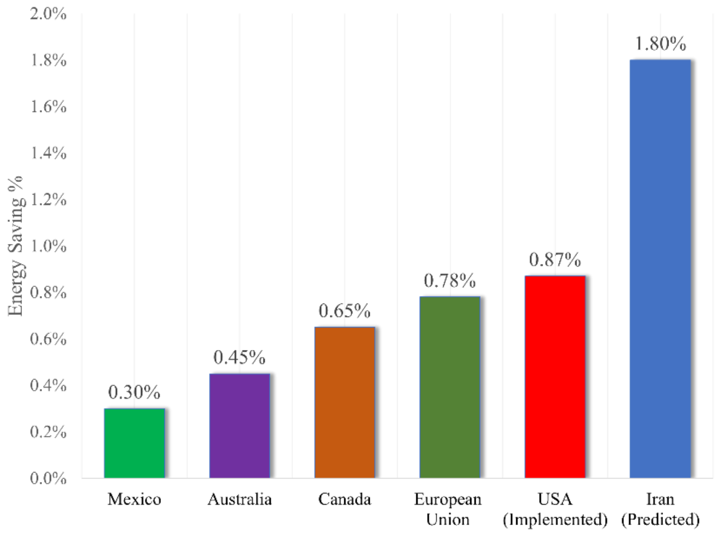

Fig. 14. Energy savings resulting from the implementation of daylight saving time in various countries (Data from Mahdi Arabsadegh).

This finding highlights Iran's unique energy consumption structure, which is heavily dependent on daylight hours. Synchronizing daily activities with natural daylight plays a pivotal role in reducing energy demand. Thus, adopting DST in Iran could significantly optimize energy consumption, lower associated costs, and improve load distribution.

Post-cancellation data on energy consumption reveal a notable surge in electricity demand. According to Iran's Tavanir CEO, the average annual growth in electricity consumption in 2023 doubled compared to the past decade, adding over 700 MW to the grid's peak load. This spike is primarily attributed to the overlap of residential peak usage hours with peak summer temperatures.

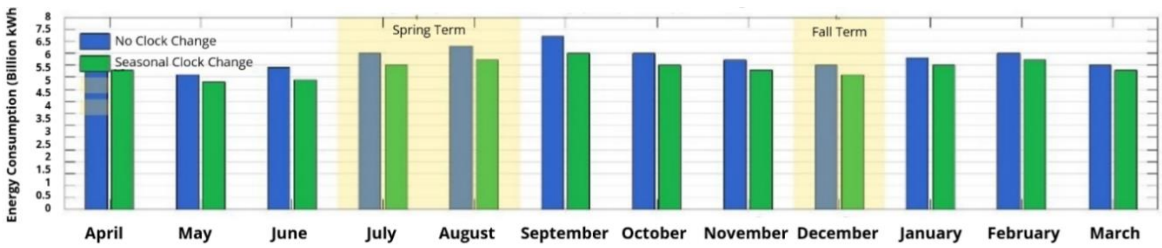

Fig. 15. Comparison of energy consumption with and without daylight saving time in the year 2024.

Fig. 15 demonstrates the direct impact of not implementing DST in 2024, which has led to a measurable increase in energy consumption [6], which if Iran adopted DST, it could have achieved annual energy savings exceeding 4.2 billion kilowatt-hours (*kWh*).

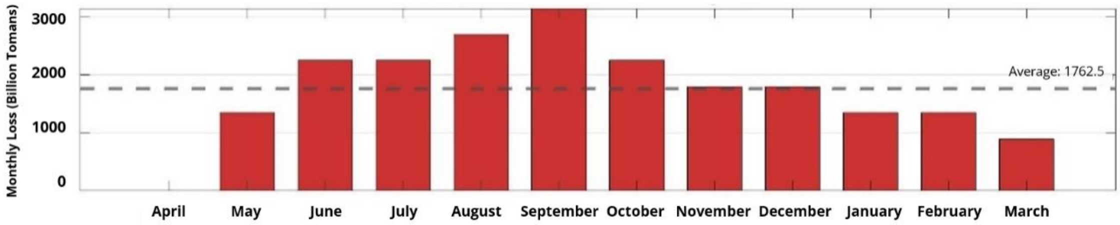

Fig. 16. Estimated financial losses due to the non-implementation of daylight saving time policy in the year 2024 (Data from Mahdi Arabsadegh).

As shown in **Fig. 16**, which analyzes the financial losses due to increased energy consumption across different months, the highest economic damage occurs during the warmer months of the year [30]. The total financial loss amounts to 21,150 billion tomans annually, highlighting the economic consequences of decisions regarding DST.

Furthermore, according to the CEO of Iran's Tavanir Company in April 2025, implementing DST would reduce electricity consumption equivalent to the output of a nuclear power plant.

The cancellation of DST has also increased electricity consumption in the commercial and industrial sectors. Shifting working hours in offices and businesses has aligned peak operational times with periods of high temperatures, escalating the demand for cooling systems. Consequently, energy consumption in these sectors has risen sharply.

Global experiences and Iranian data suggest that reinstating DST could positively address energy imbalances. Key benefits of this policy include reduced electricity consumption, decreased reliance on surplus generation during peak hours, and enhanced energy efficiency. Given Iran's current challenges in electricity supply, revisiting this decision could play a pivotal role in optimizing consumption and ensuring the sustainability of the energy grid.

Given Iran's current electricity supply challenges, revisiting this policy could significantly optimize consumption and enhance grid stability.

4.4. Government Energy Taxation

Taxation in the energy sector can serve multiple purposes, including reducing consumption, mitigating environmental pollution, and increasing government revenue. Taxing fossil fuel consumption is one of the most significant policy measures in this regard. However, in Iran, the effectiveness of such taxation has been limited due to extensive energy subsidies. Below are some proposed strategies to address this issue.

4.4.1. Taxation on Excessive Energy Consumption

Imposing taxes on excessive energy use can incentivize consumers to improve efficiency and reduce consumption. By increasing the cost of unnecessary consumption, this policy encourages optimal use of energy resources. In some countries, taxes on high electricity and gas consumption have led to reduced usage and enhanced energy efficiency. For example, Germany implemented electricity taxes in the industrial sector alongside the Energy Management System (ISO 50000), resulting in a 90% reduction in electricity consumption in this sector.

4.4.2. Implementation of Green Taxes

Green taxes aim to reduce environmental pollution and promote the use of clean energy. Research in Iran indicates that green taxes could reduce fossil fuel consumption and improve environmental quality. However, to mitigate adverse effects on income distribution, mechanisms must be designed to ensure wealthier households bear a larger tax burden.

International experience demonstrates that countries with well-designed energy taxation systems motivate citizens and businesses to reduce energy consumption and adopt cleaner alternatives. Nations with higher energy tax rates exhibit lower energy intensity. For instance, in 1990, Finland became the first country to introduce a carbon tax, which significantly reduced greenhouse gas emissions and encouraged the adoption of renewable energy sources [31].

4.4.3. Reforming Energy Subsidies

Extensive energy subsidies in Iran have led to excessive and inefficient consumption. By gradually reducing subsidies and implementing appropriate taxes, the necessary financial resources for developing clean energy infrastructure can be secured. This policy can curb unnecessary consumption and enhance energy efficiency. For instance, Georgia, after implementing tax reforms and reducing exemptions, saw its tax revenue share of GDP rise to 25% in 2008 [32].

4.4.4. Tax Substitution

In some countries, energy taxes have replaced other taxes, such as payroll taxes. This shift can incentivize producers to hire more labor rather than increasing energy use. Research indicates that such policies can improve employment rates and reduce energy consumption. For example, Germany's 1999 environmental tax reforms increased taxes on oil and gas while introducing a new electricity tax, encouraging renewable energy adoption and reducing fossil fuel dependence [33].

4.4.5. Carbon Taxation

Many European countries have successfully reduced greenhouse gas emissions and promoted cleaner energy sources by imposing carbon taxes. These taxes can cover a wide range of pollutants, including carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), and fluorinated compounds. However, the scope of implementation varies by country, depending on economic structures, environmental policies, and international commitments [31].

As a country with high greenhouse gas emission intensity, Iran can emulate successful European carbon tax policies to address energy imbalances and improve efficiency. A critical first step is phasing out tax exemptions for energy-intensive and polluting industries, similar to Norway's approach. This measure can effectively reduce fossil fuel consumption and optimize energy use in industrial sectors [5].

Additionally, Iran could establish a domestic Emissions Trading System (ETS), requiring industries to purchase carbon emission permits, as practiced in the European Union. This not only incentivizes emission reductions but also generates revenue for renewable energy development. Furthermore, a gradual, tiered carbon tax—particularly in transportation and building sectors, akin to Austria's policies—can help regulate consumption and lower pollutant emissions [31].

Finally, to ensure the success of these policies, Iran must design support mechanisms to mitigate economic impacts on vulnerable populations, balancing fossil fuel dependency reduction with social and economic sustainability.

4.5. Combating Energy Smuggling

Energy smuggling is a critical factor contributing to Iran's energy imbalance, leading to reduced government revenue, market instability, and increased consumer costs. Due to the exceptionally low prices of energy carriers in Iran, smuggling these products and selling them illegally to neighboring countries has become highly prevalent [34-35].

In March 2025, the spokesperson for the Iranian Parliament's Energy Commission announced the seizure of over 80 million liters of smuggled fuel along with related equipment. Simultaneously, the Chief Justice of Hormozgan Province reported the discovery of four illegal taps siphoning fuel from the national oil pipeline network. Additionally, the former CEO of Iranian Fuel Conservation Company estimated the value of smuggled fuel in the country at $5–7 billion annually.

Smugglers frequently exploit single-use commercial cards to bypass customs regulations and evade government duties. Reports indicate that 30 million liters of fuel are smuggled daily, resulting in an annual loss of $9 billion.

While the Iranian government has taken steps to address fuel smuggling—including specialized meetings and inter-agency coordination to identify smuggling hotspots and implement border trade regulations—these efforts have not been entirely successful. Below are proposed measures to enhance these initiatives.

4.5.1. Implementing Advanced Monitoring and Control Technologies

Deploying cutting-edge technologies such as smart monitoring systems and fuel distribution fleet management systems can significantly improve oversight of fuel distribution and consumption. For instance, Iran's "SIPAAD" system, designed to monitor urban heavy vehicles, could be leveraged to combat fuel smuggling. This system imposes restrictions and allocates fuel based on predefined routes and fleet requirements, preventing misuse.

4.5.2. Strengthening Border Surveillance and Inspections

Border crossings are critical hotspots for fuel smuggling. Equipping these areas with advanced surveillance technologies, increasing the number of trained and specialized personnel, and fostering close cooperation with neighboring countries can significantly curb smuggling activities. Implementing joint inspection initiatives and information-sharing mechanisms with bordering nations can further enhance the effectiveness of these measures.

4.5.3. Enacting and Enforcing Stricter Laws

Revising and tightening laws related to fuel smuggling—including harsher penalties and punitive measures—can serve as a strong deterrent. Additionally, expediting judicial proceedings and establishing specialized courts for fuel smuggling cases can help address this issue more efficiently.

4.5.4. Enhancing Transparency in the Fuel Supply Chain

Ensuring transparency across all stages of the fuel supply chain—from production to consumption—can help identify vulnerabilities and prevent smuggling. The adoption of integrated and traceable information systems will enable more precise monitoring and accountability.

4.5.5. Strengthening International Cooperation

Fuel smuggling is a transnational challenge that requires international collaboration. Iran can improve its anti-smuggling efforts by: — Joining international agreements, — Exchanging intelligence and best practices with other nations, — Participating in joint programs to combat cross-border fuel smuggling. These steps will bolster Iran's ability to tackle smuggling while fostering regional and global partnerships.

5. Transition to Sustainable and Renewable Energy

The transition to sustainable and renewable energy is no longer a choice but an imperative for ensuring energy security and sustainable development. Despite its vast fossil fuel resources, Iran faces challenges such as energy imbalance, rising demand, and environmental obligations. Renewable energy, particularly solar and wind power, stands out as one of the most effective solutions to address this imbalance. This section aims to outline a clear pathway for Iran's transition to sustainable energy and evaluate practical strategies to maximize the potential of renewables.

5.1. Statistical Overview of Renewable Energy in 2024

The Office of Planning and Regulation of the Renewable Energy and Energy Efficiency Organization of Iran (SATBA) publishes annual aggregated statistics on the renewable energy sector. These statistics are instrumental in identifying solutions to reduce energy imbalance. Below are key highlights from the 2024 report [36].

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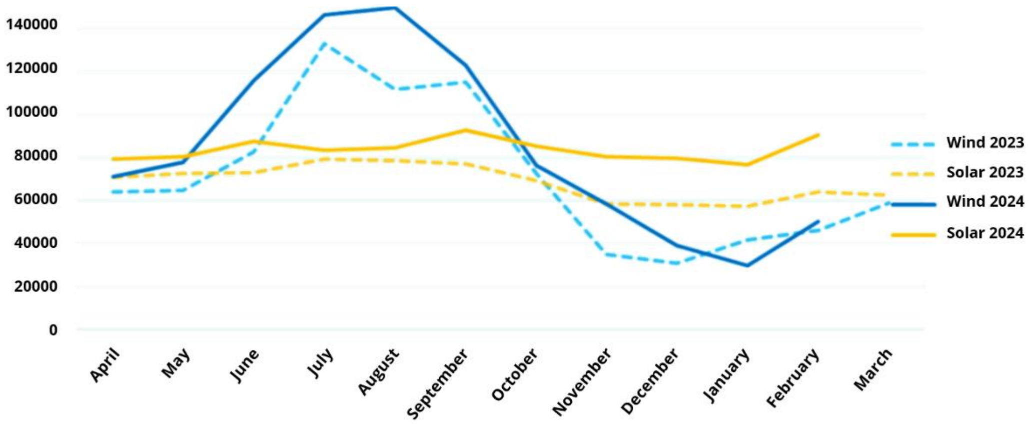

Fig. 17. Electricity Generation from Renewable and Clean Power Plants.

The data in **Fig. 17** illustrates the share of electricity generated by renewable power plants in Iran from the beginning of 2023 to February 2024. Key observations include: — A 30% increase in electricity production from solar and wind power plants compared to the same period in the previous year. — The highest production surge for wind power occurred in August 2024, while solar power peaked in February 2024 [36].

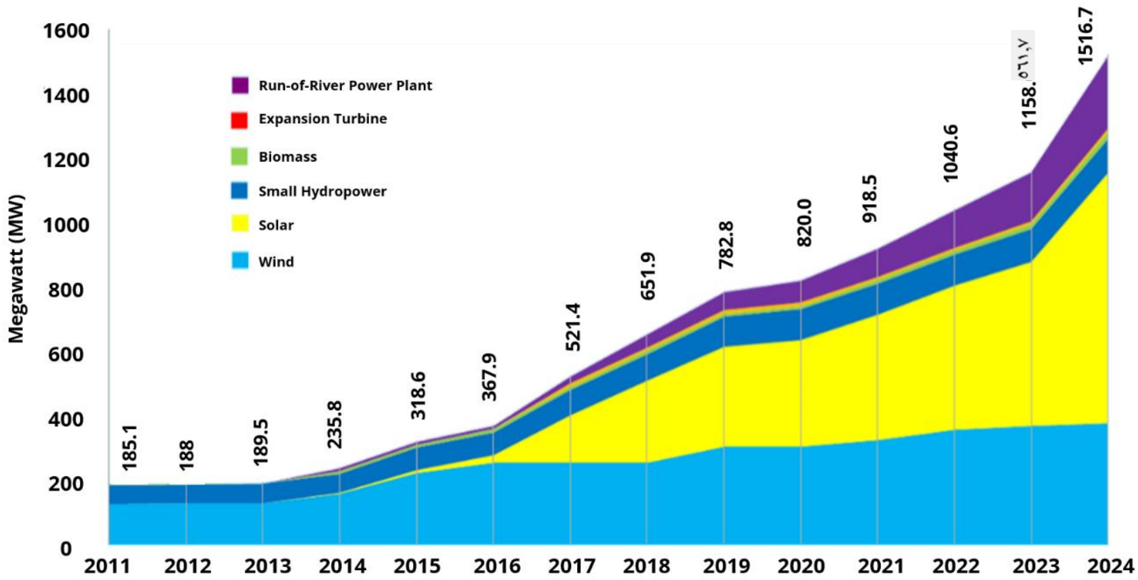

Fig. 18. Growth in Capacity of Renewable and Clean Power Plants.

Fig. 18 reveals:

— Despite wind power plants contributing more to electricity generation, their capacity growth has stagnated.

— Solar power plants, however, have experienced consistent and significant growth in capacity over the past eight years, reflecting their rising importance in Iran's energy mix [36].

— A moderate increase in capacity for distributed generation (small-scale) power plants.

— No notable growth in other renewable energy sources, with capacity remaining stagnant.

Fig. 19. Installed Capacity of Renewable and Clean Power Plants by Province (in Megawatts).

Fig. 19 highlights the distribution of renewable energy capacity across provinces:

— Top-performing provinces: Kerman (219.1 MW), Qazvin (170.8 MW), Yazd (154.4 MW), Isfahan (143.6 MW), Khorasan Razavi (117.3 MW) [36].

— These regions benefit from high solar irradiation, favorable geographic conditions, government incentives, and targeted investments**.**

5.2. Assessment of Solar Energy Potential in Iran

Solar energy, as a renewable resource, has garnered significant attention worldwide. Estimates indicate that converting merely 0.1% of the solar energy reaching the Earth's surface into electricity with a 10% efficiency could yield approximately 3,000 gigawatts of power. This amount is nearly four times the total annual energy consumption globally.

Iran, situated between 25 and 40 degrees north latitude, enjoys an exceptionally favorable position in terms of solar energy reception. The country's annual solar radiation is estimated to range between 1,800 and 2,200 kilowatt-hours per square meter, surpassing the global average. Reports reveal that over 90% of Iran's land area experiences more than 280 sunny days per year on average. This characteristic positions Iran as one of the regions with the highest potential for solar energy production.

In this section, the current status of solar energy in Iran will be examined, along with an analysis of the potential of suitable regions and the challenges associated with the development of this renewable resource.

5.2.1. Meteorological Data Analysis in Iran

Based on the data presented in **Table 3**, Mahshahr city in Khuzestan Province recorded the highest solar radiation (GHR) among the studied stations, with a horizontal radiation value of approximately 766 W/m^2 in June [36]. In contrast, Sarakhs city in Razavi Khorasan Province exhibited the lowest radiation level, with a horizontal radiation of about 185 W/m^2 in December. The overall average horizontal solar radiation (GHR) across Iran is estimated at 436 W/m^2 [37].

Studies on photovoltaic (PV) panel performance under Standard Test Conditions (STC) indicate that regions with horizontal radiation levels around 1,000 W/m^2 should be considered economically viable for PV system deployment. Furthermore, the minimum required radiation for a site to be deemed suitable for solar panel installation is 500 W/m^2.

According to these criteria, the meteorological stations in Dalgan (Sistan and Baluchistan Province), Mahshahr and Shushtar (Khuzestan Province), Abadeh (Fars Province), and Fadashk (South Khorasan Province) exhibit average radiation levels exceeding the minimum threshold. This underscores the high potential of these regions for PV-based solar power generation and highlights the need for further investigations to advance this technology.

Table 3. Solar Radiation Values at Meteorological Stations in Iran.

Site	Maximum irradiation (W/m^2)	Minimum irradiation (W/m^2)	Avg irradiation (W/m^2)	Site	Maximum irradiation (W/m^2)	Minimum irradiation (W/m^2)	Average irradiation (W/m^2)
1. Meshkin Shahr	412	217	309	**33. Eghlid**	570	299	471
2. Namin	429	232	327	**34. Rafsanjan**	592	332	487
3. Ahar	450	252	336	**35. Arzooye**	534	380	472
4. Bonab	413	218	314	**36. Shahre Babak**	572	331	437
5. Mayan	536	282	402	**37. Kish**	519	317	450
6. Oscoo	505	320	404	**38. Jask**	548	341	464
7. Chaldoran	504	270	352	**39. Agh Ghala**	448	200	326
8. Borojeh	592	342	481	**40. Marave**	465	240	333
9. Moghar	619	272	466	**41. Behabad**	617	292	481
10. Morche khort	465	220	331	**42. Ardakan**	561	281	453
11. Varzaneh	580	339	497	**43. Abarkuh**	568	318	468
12. Eshtehard	527	219	393	**44. Korit**	547	281	444
13. Rasul Abad	571	347	463	**45. Halvan**	559	297	422
14. Delvar	555	334	622	**46. Delgan**	646	408	519
15. Bardkhoon	533	296	415	**47. Dehak**	605	305	470
16. Esfarayen	570	273	439	**48. Nosrat Abad**	617	323	489
17. Bojnurd	555	238	407	**49. Chabahar**	500	288	416
18. Davarzan	559	262	420	**50. Khash**	615	387	493
19. Sarakhs	541	185	374	**51. Lutak**	594	355	487
20. Ghadamgah	593	195	410	**52. Langarood**	539	230	365
21. Jangal	610	301	480	**53. Kahak**	433	265	370
22. Rudab	567	264	434	**54. Moalleman**	570	297	469
23. Afriz	637	289	486	**55. Haddadeh**	562	264	456
24. Khaf	611	295	484	**56. Senar**	402	216	293
25. Fadashk	634	370	575	**57. Shurjeh**	574	290	416
26. Nehbandan	602	302	486	**58. Jarandagah**	570	294	418
27. Mahi Dasht	636	322	470	**59. Abadan**	564	251	453
28. Divan dare	567	325	447	**60. Mahshahr**	766	389	604
29. Ghorveh	546	239	403	**61. Shushtar**	664	418	537
30. Joyom	573	265	431	**62. Hoseynie**	540	224	376
31. Marvdasht	631	368	499	**63. Soltanye**	550	332	454
32. Abadeh	699	432	548				

5.2.2. Analysis of Sunshine Duration in Iran

Based on the data from **Fig. 20**, the meteorological station in Arzuiyeh, Kerman Province, recorded the highest average annual sunshine duration, with approximately 285 hours per month. In contrast, the station in Bojnourd, North Khorasan Province, had the lowest value, with only about 120 hours of sunshine per month [37].

Additionally, the study reveals that the annual average monthly sunshine duration across Iran is estimated at 250.79 hours.

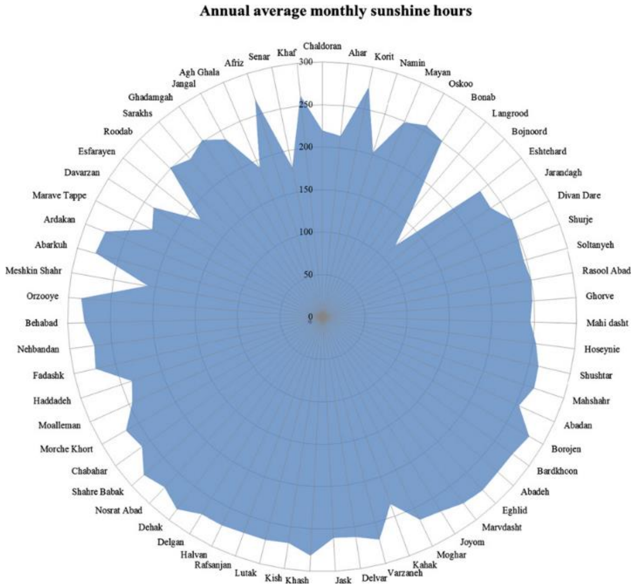

Fig. 20. Annual Average Monthly Sunshine Duration.

5.2.3. GIS-Based Analysis of Solar Radiation in Iran

In Geographic Information System (GIS) maps, solar radiation intensity is represented using color gradients. Areas with higher radiation levels are depicted in shades of red, while regions with lower intensity transition toward green [37].

The GIS maps presented in **Fig. 21-22** illustrate a clear trend of increasing solar irradiance from northern to southern Iran [37]. This pattern is primarily attributed to the decreasing latitude and closer proximity to the equator in this direction.

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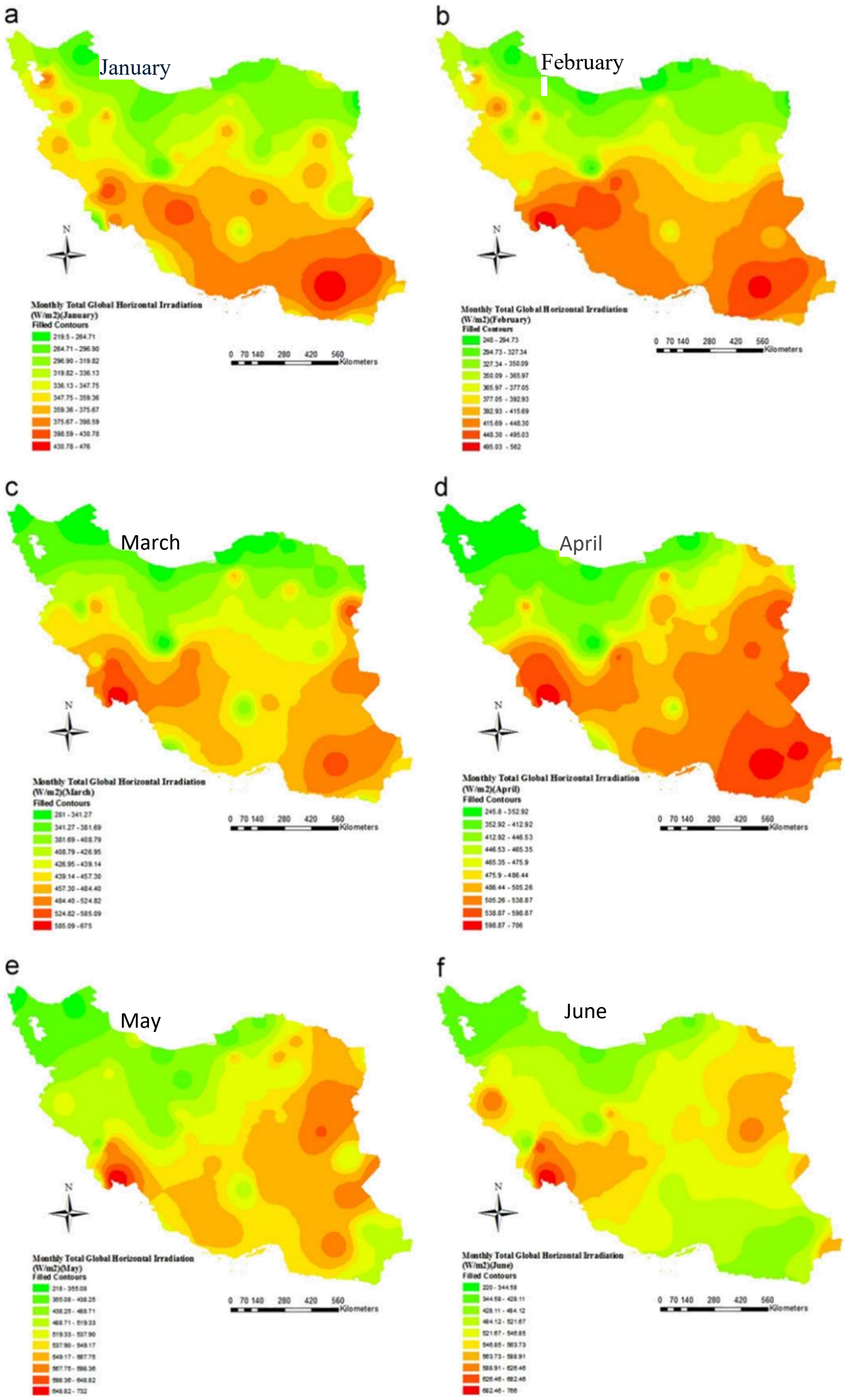

Fig. 21. Monthly Average Horizontal Solar Radiation in the First Half of the Year.

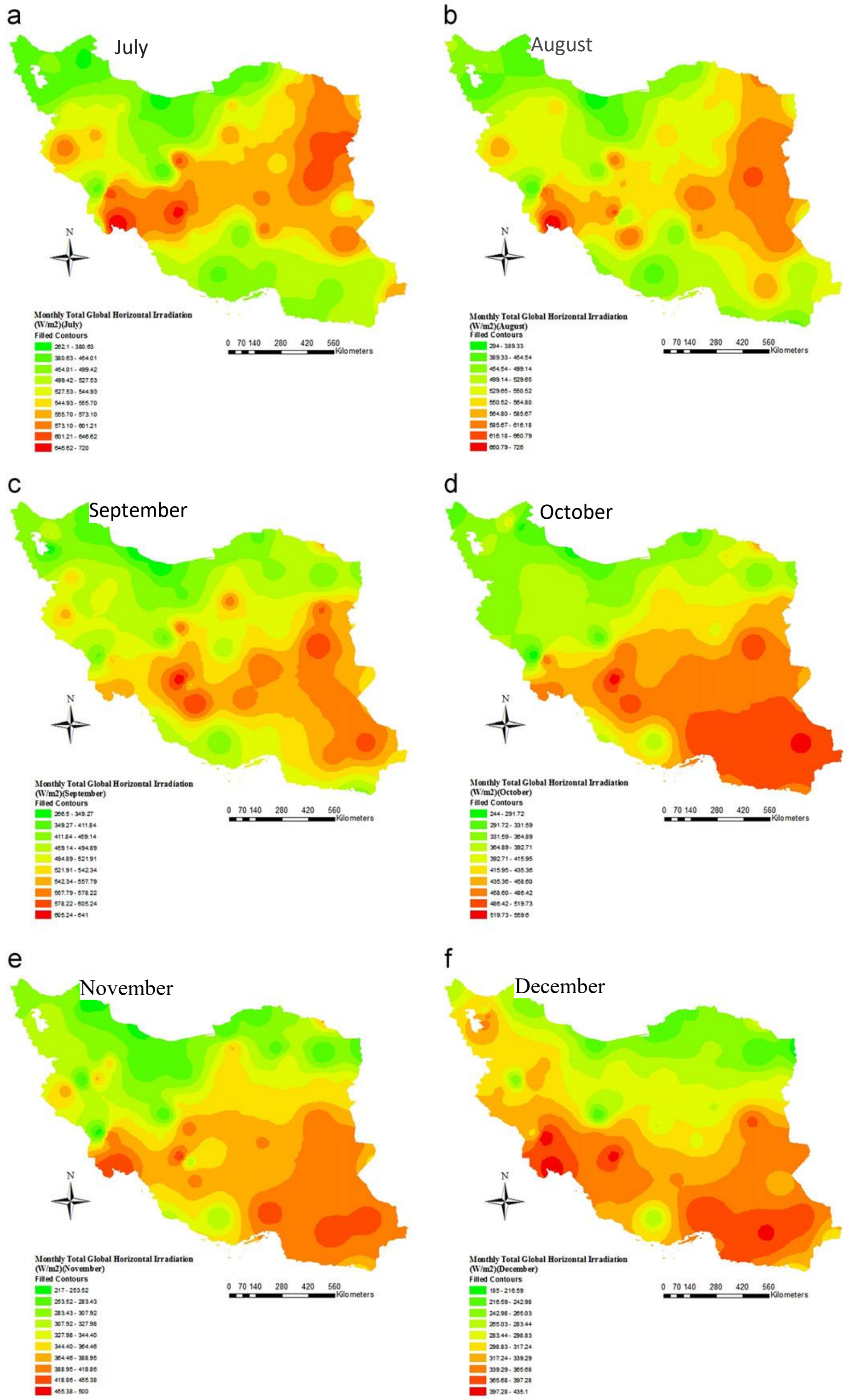

Fig. 22. Monthly Average Horizontal Solar Radiation in the Second Half of the Year.

Solar irradiance across Iran is strongly influenced by geographic location, climatic conditions, and seasonal variations. The northern and western regions, characterized by higher latitudes, greater cloud cover, and mountainous terrain, receive the lowest annual solar radiation. In contrast, the southern and eastern regions—particularly Khuzestan, South Khorasan, and Sistan and Baluchistan provinces—exhibit significantly higher irradiance levels. In the eastern areas, the 120-day winds and arid desert climate contribute to increased sunshine duration, although dust can reduce the effective solar intensity. Along the southern coastal regions, such as the Persian Gulf, despite sunny summers, peak irradiance typically occurs in April, mirroring patterns observed in neighboring Gulf countries like the UAE. This is due to high temperatures and humidity during summer, which diminish the effective solar radiation intensity.

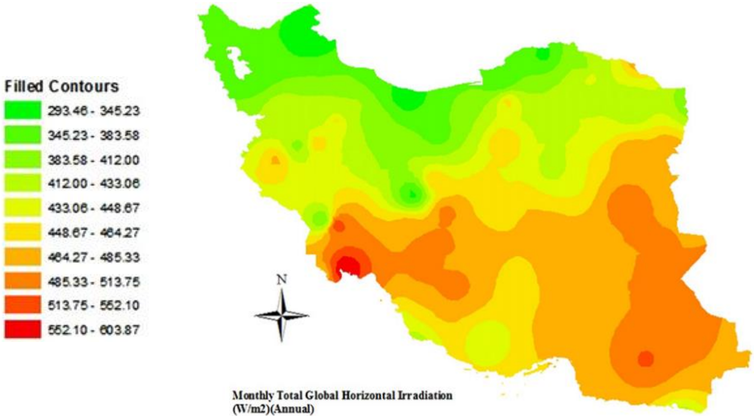

Fig. 23. Annual average of total solar radiation on horizontal surfaces.

Finally, as shown in **Fig. 23**, the annual average horizontal solar radiation recorded at the stations in Dalgan, Mahshahr, Shushtar, Abadeh, and Fadashk all exceeded 500 W/m^2 [37]. This indicates the high potential of these regions for photovoltaic applications, making them suitable candidates for further studies on solar energy development.

5.2.4. Assessment of Solar Potential in Southeastern Iran

As demonstrated in the previous section, southern Iran exhibits significant potential for the establishment of solar power plants. Below, we delve into the specifics of this potential [38].

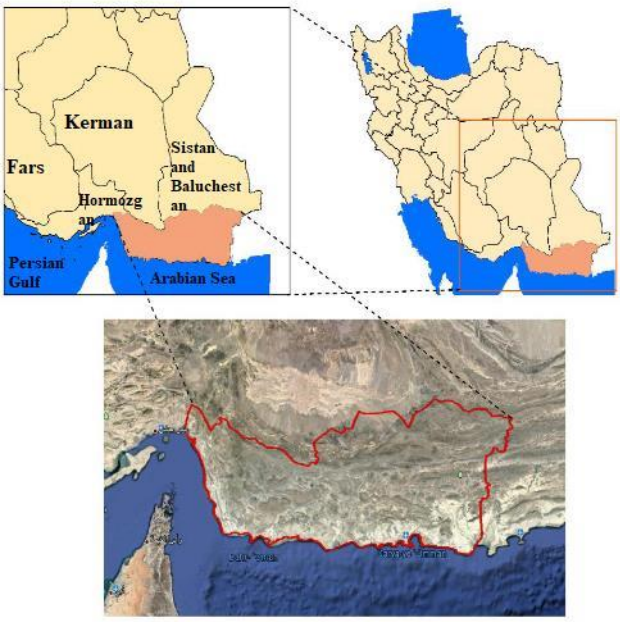

Fig. 24. Overview of the Study Area in Southeastern Iran.

As illustrated in **Fig. 24**, the study area encompasses the southeastern coastal region of Iran, covering approximately 79,406 *km²* [38]. This region includes parts of Sistan and Baluchistan and Hormozgan provinces. Major cities within this area include Chabahar, Nikshahr, Minab, Jask, and Sarbaz. The region is bounded by the Arabian Sea to the south, Pakistan to the east, the Strait of Hormuz to the west, and the cities of Saravan, Iranshahr, Kahnuj, and Bandar Abbas to the north.

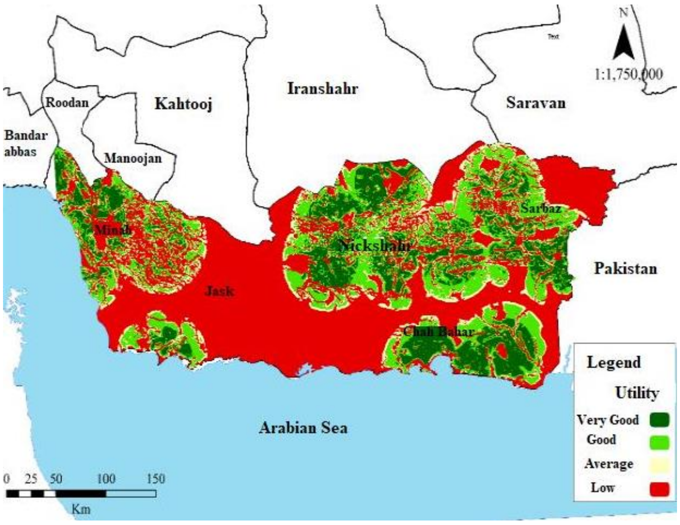

Fig. 25. Suitable Locations for Solar Power Plant Installation in the Study Area.

After evaluating various factors, including proximity to the sea, urban and non-urban areas, rivers, and other geographical features, the final map of suitable locations for solar power plant installation was developed, as shown in **Fig. 25** [13].

Table 4. Data on Potential Solar Power Plant Sites

City	Annual average Radiation (*Kw.h /m*^{2}*.day*)	Average air Temperature (˚*C*)
Baft	5.53	16.3
Jiroft	5.46	20.5
Chah bahar	7.19	28.9
Khash	5.39	19.9
Port of Jask	6.18	27.8
Saravan	5.49	22.1
Sirjan	5.46	16.6
Minab	6.07	26.7
Sarbaz	5.61	23.2
Nickshahr	5.73	21.3

Using climatic data provided by NASA and the RETScreen software, the weather conditions for these regions were analyzed and presented in **Table 4** [38].

The calculations demonstrate that constructing photovoltaic power plants with a total capacity of 3,000 *MW* in the study area—requiring only approximately 0.5% of the region's highly suitable land—could replace the total electricity generated by existing power plants in Sistan and Baluchistan Province in 2016. This finding underscores the significant solar energy potential of the Makran region in Iran, a resource that has yet to receive adequate attention.

According to the research, 37.5% of the Makran region is suitable for solar power plant development. Assuming a conversion efficiency of 15% and an effective area utilization factor of 70%, the annual electricity generation in this exploitable area is estimated at approximately 17,200 *GWh*. Thus, investment in the Makran region alone could yield 17,200 *GWh* of electricity annually, with these power plants contributing around 1,963 *MW* of power. Given Iran's 24,000 *MW* energy imbalance, this production could reduce the deficit by approximately 0.8%.

5.2.5. Assessment of Solar Potential at 102 Sites in Iran to Address Compensation of Energy Imbalance

This study evaluates the solar energy production potential at 102 stations across Iran (**Fig. 26**). The selection criteria for these sites were based on the availability of 20-year average climatic data from NASA's website [39].

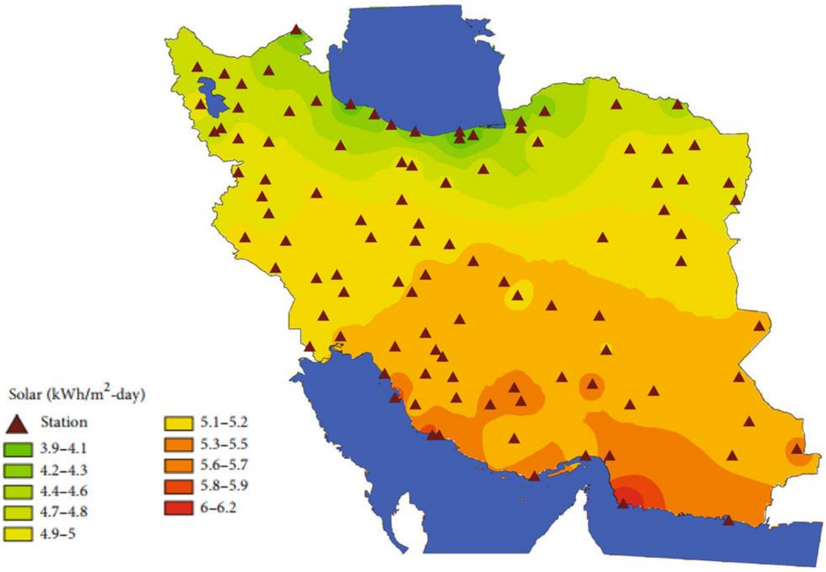

Fig. 26. Solar Radiation Intensity at the 102 Designated Sites.

As solar radiation passes through Earth's atmosphere, its intensity diminishes due to absorption, reflection, and scattering processes. This reduction is influenced by factors such as humidity, dust, cloud cover, and temperature variations between atmospheric layers. Among these, cloud cover has the most significant impact, as seasonal changes in cloudiness alter the extent of solar radiation loss. To analyze these variations, the Air Clearness Index is used, defined as the ratio of global solar radiation reaching the Earth's surface to the extraterrestrial solar radiation (at the top of the atmosphere). **Fig. 27** illustrates the Air Clearness Index for the 102 designated sites [39].

The study of these 102 locations reveals that Jask, with a levelized cost of electricity (LCOE) of $0.172 per *kWh*, and Darab, with $0.286 per *kWh*, exhibit the lowest and highest solar power generation costs, respectively.

The average LCOE across all 102 stations is estimated at $0.206. Jask and Darab stations have the highest and lowest capacity factors at 25.1% and 15.1%, respectively, while the average capacity factor for all stations is reported at 21.21%. Additionally, the top three stations in terms of solar power generation are Jask, Bushehr, and Dayyer, producing 4,401 *kWh*, 4,267 *kWh*, and 4,254 *kWh* annually. In contrast, Darab, Anzali, and Khalkhal are the lowest-performing stations, generating 2,648 *kWh*, 2,792 *kWh*, and 2,838 *kWh* per year, respectively. Collectively, the total solar power output from the 102 stations is estimated at 380 *MWh* annually.

In summary, these results indicate a potential annual production of 380 *MWh* (equivalent to 612,560 *MWh* or 612.56 *GWh*) across the 102 stations. Notably, a solar panel in Iran operates for an average of 5.2 hours per day over 310 days annually.

As previously mentioned, the country's electricity imbalance stands at approximately 24,000 *MW*, and targeted investments in these locations could fully offset this deficit.

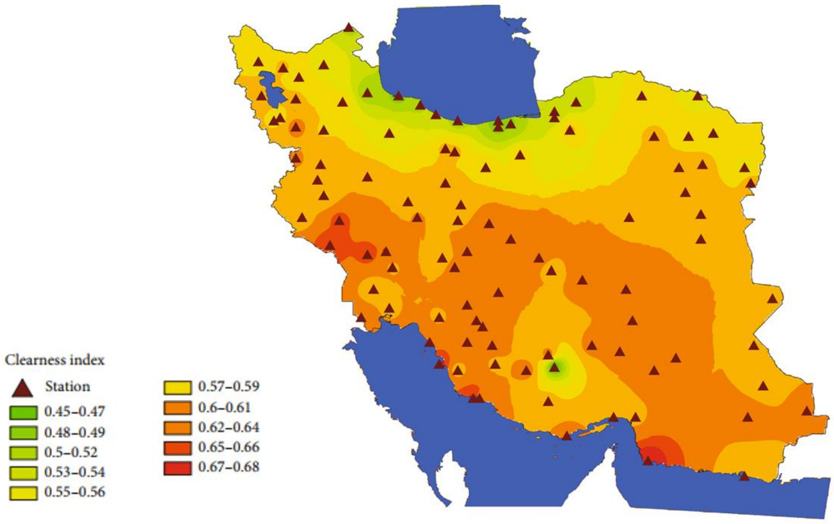

Fig. 27. Air Clearness Index at the 102 Designated Sites.

5.3. Potential Assessment of Wind Energy in Iran

Iran, with its vast regions experiencing consistent wind patterns, holds significant potential for wind energy development. Harnessing this potential can reduce reliance on fossil fuels, enhance grid stability, and mitigate environmental pollution. This section examines the current state of wind energy in Iran, identifies suitable regions, and discusses the challenges in developing this technology [40].

5.3.1. Assessment of Western Iran for Wind Energy Utilization

Due to its unique geographical position—located between low-pressure zones and adjacent to high-pressure areas in the north and northwest—Iran experiences two dominant wind patterns: —Winter winds originating from the Atlantic Ocean, moving toward the Mediterranean and Central Asia. — Summer winds blowing from the Indian Ocean and the northwest toward Iran.

The western region of Iran includes three provinces: Markazi, Lorestan, and Hamedan, covering an area of 76,522 km^2**.** This region comprises: 25 major cities, 65 towns, 212 villages, A population of 4.5 million.

Fig. 28 illustrates the electricity coverage in western Iran [40]. The region borders: North: Zanjan Regional Electric Company, West: Western Regional Electric Company, South: Khuzestan Water and Power Organization, Southeast: Isfahan Regional Electric Company, East/Northeast: Tehran Regional Electric Company. Electricity Consumption and Production (2014 Data) in this region shows:

- Peak electricity demand**:** 2,582 *MW* **(**projected to rise to 7,308 *MW* by 2025**).**
- Existing thermal power plants**:**
  - Shazand Power Plant (Arak)**:** 1,300 *MW* capacity → 8,263 *GWh* annual production
  - Mofateh Power Plant (Hamedan)**:** 1,000 *MW* → 4,850 *GWh*
  - Dorood Combined-Cycle Plant**:** 60 *MW* → 67 *GWh*

Fig. 28. Electricity Coverage in Western Iran.

The annual energy input to the Western Regional Power Grid from Tehran, West, Isfahan, Zanjan, and Khuzestan regional power companies was estimated at 9,720 million *kWh*, while the output energy transferred to adjacent regional power companies amounted to 8,571 million *kWh*.

Given an energy consumption of 14,329 million *kWh* and regional electricity generation of 13,180 million *kWh*, a production deficit of 1,149 million *kWh* is observed, which is supplied by neighboring regional power companies. Considering the growing energy demands of the region and the wind energy potential in these three provinces, strategic planning could offset this deficit through renewable energy sources.

Ultimately, the conducted studies indicate that, based on atmospheric analyses, western Iran has a wind energy production capacity of 2.09 *GW*, though the practical potential is estimated at approximately 1.9 *GW*. Furthermore, 26% of this region is deemed suitable for wind farm development. Thus, investment by local policymakers and planners in wind energy could add 1,900 *MW* to the national grid, reducing the electricity imbalance by about 0.8%.

5.4. Potential Assessment of Wave Energy in Iran

Wave energy, as a renewable resource, holds significant potential for sustainable power generation. Evaluating wave energy potential is crucial for identifying suitable locations for wave power plants [41].

5.4.1. Suitable Regions for Wave Energy Exploitation in Iran

Three major regions in Iran have been assessed for wave energy potential:

1. Caspian Sea
   - Average wave power: 5–14 *kW/m*
   - Challenges:
     - Shallow depths in the southeastern Caspian limit wave energy extraction.
     - Low practical potential for wave energy conversion systems.
2. Persian Gulf
   - Average wave power: 1–5 *kW/m*
   - Technology:

- Due to shorter wave heights, point absorber converters are the most suitable technology.

3. Oman Sea [41]

— Key locations with high potential: Sirik, Jask, Goughsar, Chabahar, and Gwadar (**Fig. 29**).

— Chabahar stands out as the most promising site due to:

- Consistent wave power (10–15 *kW/m*).
- Strategic advantages as a free trade-industrial zone.

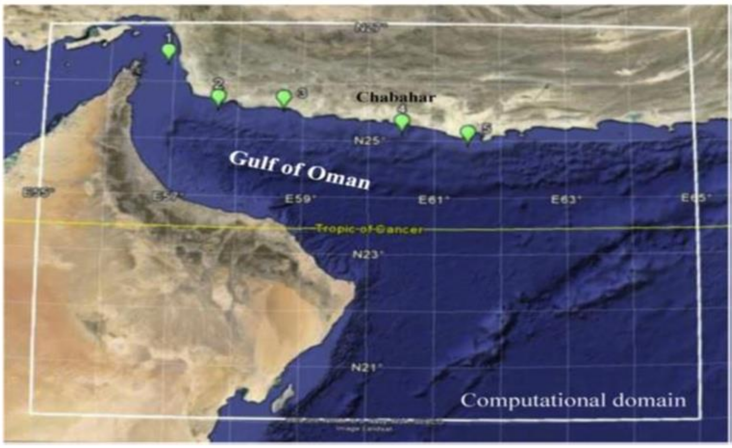

Fig. 29. Five High-Potential Sites for Wave Energy in the Oman Sea.

Table 5. Wave Power Potential Along Iran's Northern and Southern Coasts (Based on SATBA Data).

Site name	Power Per meter of the coast (*kW/m*)	Coast length (*km*)	Total power (*MW*)
Abadan	2.9	34	101
Abomosa	5.1	5	26
Anzali	3.4	124	423
Astara	0.6	83	50
Babolsar	2.2	155	341
Bandar Abbas	0.9	232	210
Lenge	3.4	359	1222
Boushehr	2.2	474	1045
Chabahar	5.8	265	1539
Jask	3.2	289	925
Mahshahr	1.7	223	380
Noushahr	1.1	99	110
Ramsar	1.4	100	141
Siri	5.3	5	27
Total			**6540**

To evaluate and characterize waves, it is typically necessary to calculate the average wave parameters over a specific time period. However, sufficient and accurate data on wave characteristics in Iran are not readily available. Since wind is the primary driver of ocean waves, coastal wind data can provide valuable insights into wave conditions. The available data from the SATBA have been utilized for this purpose.

Table 5 indicates that the Chabahar coast, with a maximum total capacity of 1,539 *MW*, possesses the highest wave energy potential in Iran [41]. Notably, the Oman Sea, where Chabahar is located, consistently exhibits wave power densities ranging between 10 and 15 *kW/m*. These values underscore the region's significant capacity for wave energy exploitation.

Table 6 compares the average and maximum wave power potential in Iran with other regions worldwide [41]. Based on available data, the Persian Gulf islands exhibit significant potential for wave energy extraction. Since these islands are not connected to the national power grid, harnessing wave energy could provide a cost-effective solution for their electricity needs. Moreover, surplus energy could potentially be transmitted to the national grid via subsea infrastructure.

Table 6. Comparison of Wave Energy Potential: Iran vs. Global Regions.

Site name	Average Power (*kW/m*)	Max. power (*kW/m*)
Persian Gulf islands	16.6	19.0
Persian Gulf coasts	3.5	6.1
Gulf of Oman coasts	10.5	12.6
Caspian Sea coasts	3.2	6.7
Japan	7.0	12.5
New Zealand	23.6	100.0
Western Europe	46.9	70.0
World (average)	**9.0**	**-**

Key regions for wave energy exploitation in Iran include the Chabahar coastline and the Persian Gulf islands. The Chabahar coast, with its high wave power density, offers substantial energy generation capacity, while the Persian Gulf islands could leverage this renewable resource to achieve energy self-sufficiency. Adopting wave energy in these regions would advance sustainable development and mitigate energy imbalances in the country.

In conclusion, this analysis demonstrates that sustainable energy development not only addresses energy imbalance challenges but also fosters economic growth and environmental improvement. By leveraging Iran's domestic potential and international collaborations in this field, the transition to a low-carbon, sustainable future can be accelerated. With strategic planning and investment, a balanced and efficient energy system can be achieved.

6. Conclusion

The issue of energy imbalance in Iran represents not only a technical and infrastructural challenge but also a multifaceted phenomenon with significant economic, environmental, and social implications. It directly influences energy security and the sustainability of the country's development trajectory. Analyzing the historical trends in energy consumption and production reveals that rapid demand growth, infrastructure obsolescence, high levels of waste, substantial subsidies, and low efficiency collectively exacerbate the gap between supply and demand.

Meanwhile, Iran possesses unparalleled potential in renewable energy sectors, particularly solar and wind, which remain underdeveloped and underutilized. Advances in innovative technologies—such as high-efficiency gas turbines, combined-cycle systems, smart meters, thermal coatings, and advanced alloys—offer promising avenues for enhancing efficiency and reducing losses.

Furthermore, comprehensive reforms in national energy policies are essential. These include rationalizing energy prices, reforming subsidy schemes, implementing green taxation, combating fuel smuggling, leveraging carbon markets, and adjusting the official schedule. Such measures can effectively restructure consumption patterns and diminish the energy imbalance.

Emerging roles, such as cryptocurrencies—while posing potential threats as new energy consumers—also present opportunities. If directed towards renewable energy utilization, they can foster digital economic growth and attract investments. Innovative applications, including utilizing miner heat in Greenhouses, energy storage solutions, and blockchain-enabled industrial zones, can facilitate energy recycling and add value to the economy.

Ultimately, the transition toward sustainable energy is not only necessary to address environmental and economic challenges but also an opportunity for technological innovation and sustainable employment creation. Achieving this transition depends on wise policymaking, targeted investments, infrastructural modernization, and leveraging the country's scientific and technological capacities.

This study demonstrates that a multidimensional and integrated approach—encompassing technological innovation, economic restructuring, and active international cooperation—is the only viable pathway to overcoming the energy imbalance crisis and realizing Iran's sustainable development vision.

Author contributions

M. S. and **S. A. M.** jointly conceived the research idea, performed the experiments, analyzed the data, and drafted the initial manuscript collaboratively on equal footing. **M. M.** supervised the entire project, provided guidance throughout the research process, critically revised the manuscript, and was responsible for finalizing and submitting the submitted version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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