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Advancing toward a sustainable future in subtropical semi-arid type climatic zone: Iraq case - The progress of solar photovoltaic energy implementation

Qusay Hassan [a,*], Sameer Algburi [b], Marek Jaszczur [c], Maha Barakat [d], Aws Zuhair Sameen [e], Bashar Mahmood Ali [f], Dunya Jameel Kassid [g]

[a] *Department of Mechanical Engineering, University of Diyala, Diyala, Iraq*
[b] *College of Engineering, Al-Kitab University, Kirkuk 36015, Iraq*
[c] *Faculty of Energy and Fuels, AGH University of Science and Technology, Krakow, Poland*
[d] *Business Administration Department, Al-Turath University College, Baghdad, Iraq*
[e] *College of Medical Techniques, Al-Farahidi University, Baghdad, Iraq*
[f] *Department of Construction Engineering and Project Management, Al-Noor University College, Nineveh, Iraq*
[g] *Mazaya University College, Iraq*

A R T I C L E I N F O

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A B S T R A C T

The study delves into Iraq's shift towards sustainable energy, focusing on solar photovoltaic energy adoption and expansion to meet rising energy demands and the need for cleaner energy solutions. It highlights the potential of harnessing solar energy, particularly through small-scale solar PV systems, supported by incentives like net metering programs that encourage surplus energy feed-in to the grid. Using Geographic Information System data, the paper examines the spatial distribution of solar PV installations and projects the capacities of rooftop solar PV systems by 2035 under various promising scenarios. It also demonstrates the link between increased solar PV capacity and meeting national energy demands, underscoring the importance of strategic policies, technological advancements, and the engagement of consumers and businesses in driving Iraq towards a sustainable energy future. By fostering an environment conducive to solar PV adoption, the results offers valuable insights for ongoing discussions and future studies on renewable energy strategies in Iraq.

1. Introduction

The global energy landscape is witnessing a profound transformation as the shift from fossil fuels to renewable energy sources gains momentum. Among the various renewable energy technologies, solar photovoltaic (PV) energy stands out as one of the most promising solutions to meet the growing global energy demands sustainably [1]. Solar PV energy harnesses sunlight, converting it directly into electricity using semiconductor materials. This technology presents a clean and inexhaustible energy source, with substantial potential for reducing greenhouse gas emissions, enhancing energy security, and fostering economic growth [2].

The roots of solar PV technology date back to the 19th century when the PV effect was first observed by Alexandre-Edmond Becquerel in 1839 [3]. The technology journey since then has been marked by continuous innovation and growth. From the development of the first silicon solar cell in the mid-20th century to the rapid expansion of solar PV capacity in the 21st century, solar energy has emerged as a critical player in the global energy market [4]. Today, solar PV is one of the fastest-growing renewable energy sources worldwide. Numerous countries have recognized its potential and are investing in its development. Governments, private sector players, and international organizations are collaborating to overcome technical, financial, and regulatory barriers to solar PV adoption. The growth in solar PV energy is not uniform across the globe, with considerable variation among regions [5]. Developing countries are increasingly embracing solar energy to address their energy access challenges, while developed countries are leveraging solar technology to achieve their carbon neutrality goals. According to the energy information administration (EIA) report 2022, as statistics presented in Fig. 1 show a comprehensive representation of the

* Corresponding author.
E-mail address: qusayhassan_eng@uodiyala.edu.iq (Q. Hassan).

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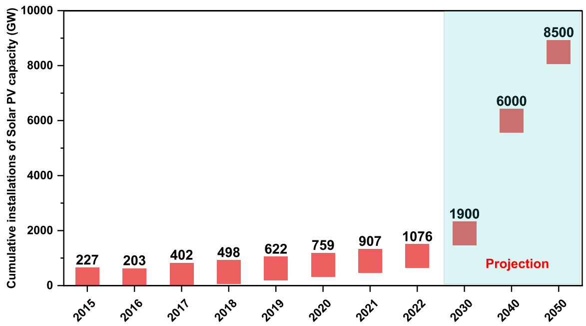

Fig. 1. The cumulative installations of Solar PV capacity projections till 2050 [6].

cumulative installations of solar PV capacity for specific years, along with projections till 2050 [6]. The showcases the substantial growth of solar PV adoption globally over the indicated time frame. In 2015, the cumulative installed capacity was 227 GW, signaling the technology increasing popularity as a clean energy source. The subsequent years witnessed impressive growth rates, with 303 GW in 2016, 402 GW in 2017, and 498 GW in 2018, reflecting the accelerating momentum of solar PV installations. The trend continued upward with 622 GW in 2019 and 759 GW in 2020, indicating a sustained expansion of solar PV capacity. By 2021, the cumulative capacity had surpassed 900 GW, and in 2022, it reached a remarkable 1076 GW, crossing the terawatt milestone. The projections for the years 2030, 2040 and 2050 are even more compelling, with an estimated cumulative capacity of 1900 GW, 6000 GW and 8500 GW, respectively. These projections highlight the significant role that solar PV is expected to play in meeting future energy demands and combatting climate change. However, to realize these ambitious projections, continued support from policymakers, advancements in technology, and increased investment in renewable energy infrastructure will be crucial to unleash the full potential of solar PV and secure a sustainable energy future.

The technological advancements in solar PV systems have been instrumental in reducing costs and improving efficiency. Innovations in materials science, manufacturing processes, and system design are contributing to the accessibility and competitiveness of solar energy [7]. New trends, such as building-integrated photovoltaics (BIPV) and floating solar farms, are further expanding the application of solar PV, allowing for its integration into various infrastructures and landscapes.

The economic aspect of solar PV energy has undergone a dramatic transformation. The declining cost of PV modules and systems has made solar electricity more affordable, thereby driving its adoption across various sectors of the economy [8,9]. Solar energy potential to create jobs and stimulate economic development is also contributing to its global appeal. Governments play a pivotal role in the growth of solar PV energy through policy formulation, incentives, and regulations. From feed-in tariffs to renewable portfolio standards, various policy instruments are being implemented to promote solar energy. International agreements such as the Paris Agreement are also pushing countries to invest in renewables such as solar PV [10,11]. Despite the tremendous progress, several challenges persist in the global development of solar PV energy. Issues related to grid integration, energy storage, environmental impact, and social acceptance must be addressed to ensure sustainable growth. The future of solar PV energy is promising, with vast untapped potential and opportunities for further innovation and growth. The transition to a sustainable, solar-powered future necessitates continued collaboration, investment, and commitment from all stakeholders. However, the global development progress of solar PV energy implementation represents a beacon of hope in the urgent quest for sustainable energy solutions. Its evolution from a scientific curiosity to a mainstream energy source is a testament to human ingenuity and determination.

1.1. Potential solar irradiance in Iraq

Despite its significant solar irradiance potential, Iraq has made relatively slow progress in solar PV installation. The geographical solar potential of the country varies between regions, with the northern territories experiencing an average solar irradiance of 11.8 $MJ/m^2/day$, while the southwestern territories record as high as 22.5 $MJ/m^2/day$. Fig. 2 illustrates the potential solar irradiance across Iraq, generated using Geographic Information System (GIS) data collected over a three-year period from 2020 to 2022. GIS, a powerful tool for spatial analysis and data visualization, was used to generate a detailed map of the solar irradiance potential across the country varied geographical regions.

However, the actual progress in harnessing this potential has been underwhelming, as highlighted in Fig. 3. The installed solar PV capacity in the country has increased gradually but modestly over the years. In 2015, the installed capacity was a mere 0.1 gigawatts (GW). By 2016, it had only doubled to 0.2 GW. The following years saw a more noticeable increase, with the installed capacity reaching 0.4 GW in 2017, 0.8 GW in 2018, and 1.2 GW in 2019. The progression continued into the next three years, with capacities reaching 1.8 GW in 2020, 2.6 GW in 2021, and 3.8 GW in 2022 [12].

Despite these increases, the pace of growth in solar PV installations has not been commensurate with Iraq vast solar potential. Given the country high solar irradiance, this represents a significant missed opportunity for sustainable energy generation and a clear area for policy intervention and investment.

1.2. Study objective

The objective of the study is to intricately explore the trajectory of solar PV energy adoption within the unique environmental and socio-economic landscape of Iraq, a nation predominantly characterized by its subtropical semi-arid climate. This analysis endeavors to systematically evaluate the current state, inherent challenges, and the potential strides made in the field of solar energy, emphasizing the pivotal role of PV technology as a cornerstone for renewable energy solutions in regions with abundant sunlight but complex climatic and geopolitical constraints. In addition to, dissect the multifaceted dimensions of solar PV implementation, including technological, regulatory, financial, and infrastructural aspects, to gauge the effectiveness, scalability, and sustainability of solar energy projects in Iraq. Moreover, seeks to unearth actionable insights and frameworks that can propel Iraq towards energy independence, ecological sustainability, and economic resilience, aligning with global sustainability goals. The ultimate overview is to craft a comprehensive narrative that not only highlights country journey towards solar energy adoption but also serves as a beacon for similar semi-arid regions grappling with the dual challenges of energy security and climate change mitigation, thus contributing to the global discourse on transitioning to a more sustainable and renewable energy-dominated future.

2. Evaluated region and demographic profile

The investigative region for this study encompasses the country of Iraq, situated in Western Asia. Geographically, Iraq is positioned approximately between latitudes 29° and 38°N, and longitudes 39° and 49°E. It spans an extensive area of about 438,317 square kilometers and houses a diverse population of approximately 40 million people, reflecting a myriad of cultural, historical, and socio-economic facets [13,14]. One of the pressing challenges faced by this country, in the context of energy, is its current reliance on conventional energy sources, with renewable energy accounting for a mere 13 % of its total power generation capacity.

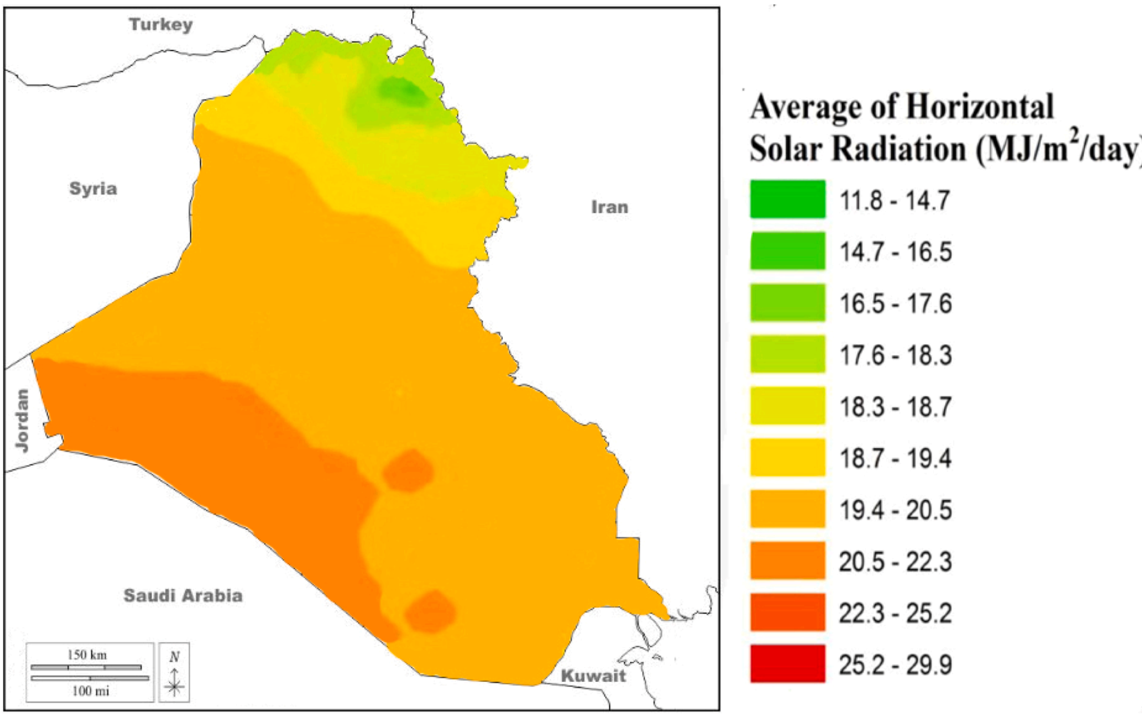

Fig. 2. The Potential solar irradiance in Iraq using data collected over a three-year period from 2020 to 2022 [10,11].

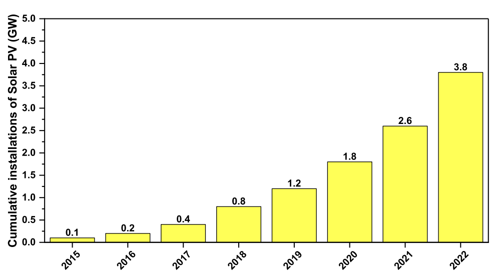

Fig. 3. The cumulative installations of Solar PV capacity in Iraq for the years 2015 to 2022 [6,12].

2.1. Electricity generation landscape

The electricity landscape of country in 2022, as illustrated in Fig. 4, delineates a diverse blend of energy resources utilized for electricity generation. Predominantly, oil takes the lead in the energy mix, equating to 38 % of the country total electricity generation. Natural Gas follows, forming 32 % of the electricity generation mix. Coal accounts for 16 % of the electricity produced. Hydropower contributes a smaller share of 5000 MW, representing 5 % of the electricity generation. Wind energy contributes 10,000 MW, making up 4 % of the total mix, while Solar Energy inputs 12,000 MW, representing 3 % of the generation mix. This diverse mix of energy resources reflects the country endeavor to balance between fossil fuels and renewable energy sources, optimizing energy sustainability and security.

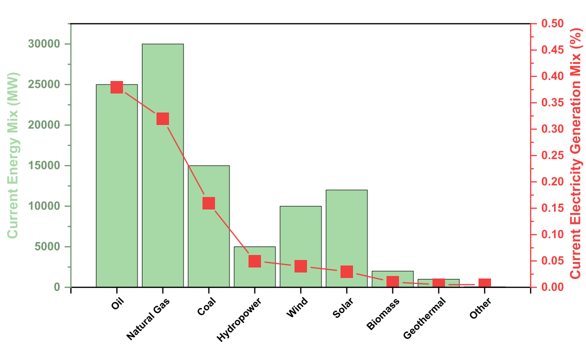

Fig. 4. Energy and electricity mix in for Iraq for the year 2022 [13,14].

2.2. Country demographic profile

The demographic profile of Iraq, as indicated by the population data and global rankings from 2000 to 2020 (presented in Fig. 5), has seen a consistent growth trend. In the year 2000, Iraq population was 23.2 million, which placed the country 40th globally in terms of population . By 2001, the population had risen to 23.8 million, advancing Iraq world ranking to the 38th position. This trend of steady growth and advancement in world rankings continued over the next few years, with the population reaching 25.1 million in 2003 (36th in the world), 26.4 million in 2005 (34th in the world), and 27.8 million by 2007, placing Iraq 32nd globally [14]. The following decade saw Iraq population climb to 29.2 million in 2009, 31.5 million in 2012, and 33.2 million in 2014, with corresponding global rankings of 30th, 28th, and 26th,

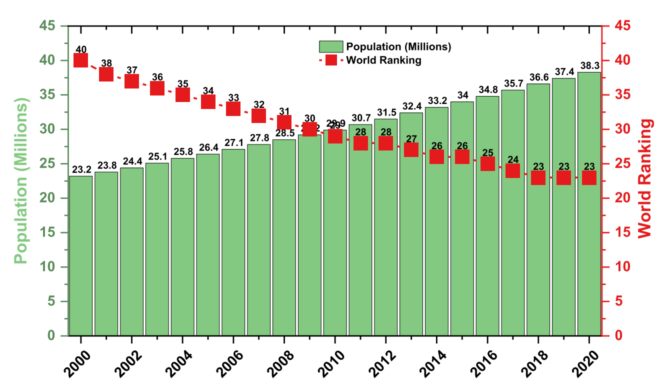

Fig. 5. Iraqi population growth and global ranking evolution (2000–2020) [14,15].

respectively. The pace of Iraq demographic expansion remained fairly consistent in the subsequent years. By 2017, the population had grown to 35.7 million, elevating Iraq to the 24th position globally. In the three years that followed, the population rose further, reaching 38.3 million by 2020 and maintaining the country global ranking at 23rd [15]. This consistent population growth highlights the increasing demographic prominence of Iraq on the global stage [16]. As the population continues to grow, ensuring access to essential services, improving socio-economic conditions, and managing resources sustainably become vital priorities for the country future.

The interconnection between population growth and electricity consumption growth is well established, demonstrating a direct proportionality. As a population grows, its demand for electricity also increases due to the greater need for residential, commercial, industrial, and other forms of energy consumption. The empirical data from 2000 to 2020, visualized in Fig. 6, lends substantial support to this assertion in the context of Iraq. In 2000, with a population growth rate of 2.92 %, the electricity demand in Iraq was 43.1 TWh. In 2001, when the population growth rate slightly dropped to 2.55 %, the electricity demand increased modestly to 43.6 TWh [17]. As the population growth rate surged to 3.24 % in 2003, the electricity demand also experienced an upward shift, reaching 46.1 TWh. This pattern of concurrent growth continued throughout the 2000s and into the next decade. For instance, in 2006, when the population growth rate hit 4.59 %, the electricity demand rose significantly to 52.6 TWh. Similarly, in 2011, the country experienced a substantial population growth rate of 8.98 %, coinciding with an increased electricity demand of 72 TWh. The trend continued in 2018, with a 6.45 % population growth rate accompanying a demand of 100.8 TWh. Interestingly, there were minor deviations from this pattern, notably in 2015 and 2016. Despite negative population growth rates of −0.66 % and −0.45 %, respectively, the electricity demand remained relatively stable, at 89.8 TWh and 89.4 TWh. By 2020, the electricity demand in Iraq had increased to 111.4 TWh, in line with a population growth rate of 5.37 % [18]. This direct proportional relationship can be attributed to several factors. As the population grows, there is an increased demand for electricity in various sectors such as residential, commercial, and industrial. More households and businesses require electricity to power their appliances, lighting, and machinery, leading to higher overall consumption. Additionally, as the standard of living improves with population growth, there is an increased use of electrical appliances and technologies, further contributing to electricity demand. Understanding this relationship is crucial for policymakers and energy planners as they develop strategies to meet the growing energy needs of a growing population [19]. It highlights the need for sustainable energy policies, investments in energy infrastructure, and efforts to improve energy efficiency to ensure a reliable and affordable electricity supply for the expanding population. Moreover, this correlation also underscores the importance of promoting renewable energy sources and energy conservation measures to meet the increasing demand while minimizing the environmental impact.

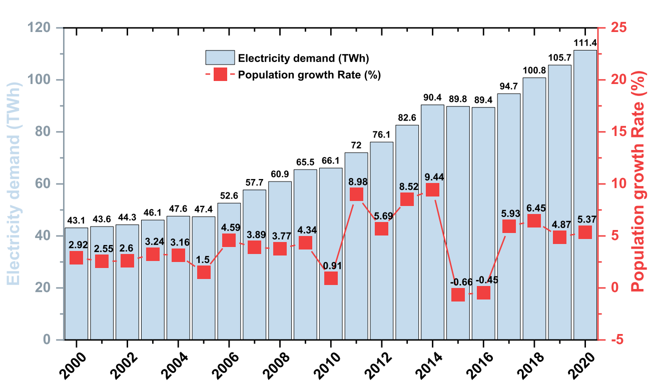

Fig. 6. The population growth and electricity consumption growth in Iraq for the years (2000–2020) [17,18].

As Iraq continues to experience population growth and further economic development, policymakers must proactively address the challenges posed by the rising electricity demand. By adopting a holistic approach to energy planning and incorporating renewable energy sources, Iraq can achieve a sustainable and resilient energy future, meeting the needs of its citizens while mitigating the impact on the environment.

2.3. Transformation of Iraqi electricity sector

The transformation of the Iraqi electricity sector has been a journey shaped by historical events, socio-political changes, and efforts to meet the country growing energy demands. Fig. 7 provides a comprehensive overview of this transformation, showcasing key milestones and developments that have shaped the sector evolution [20]. The early history of Iraq electricity sector saw its establishment in the early 1950s with the formation of the Iraq Ministry of Electricity. Subsequent years witnessed significant progress as major power plants were commissioned and the electricity grid expanded to cater to increasing urbanization and industrialization. The nationalization of the oil industry in 1974 infused much-needed investment into the sector, leading to substantial growth in power generation capacity and an extension of the electricity grid to reach remote areas [21]. However, the sector faced challenges during the Iran-Iraq war in the 1980s, which disrupted investment and resources flow, affecting the maintenance and expansion of the electricity infrastructure. The invasion of Kuwait in 1990 resulted in international sanctions that further strained the sector, limiting access to critical resources and hindering its modernization [22].

The early 2000s brought a new era of change with the invasion of Iraq by a coalition led by the United States. Post-conflict, efforts were made to rebuild and rehabilitate power plants and the electricity grid, which had suffered damage during the conflict. Subsequent years saw improvements in generation capacity, reduced power outages, and increased access to electricity for citizens [23]. In recent years, Iraq has sought to diversify its energy mix and embrace renewable energy sources, such as solar and wind power [24]. The country has also attracted foreign investments to support the development of new power projects and modernize existing infrastructure.

The transformation of the Iraqi electricity sector reflects the country resilience in overcoming challenges and its commitment to meeting the energy needs of its growing population and economy. It underscores the importance of infrastructure development, policy reforms, and investments to ensure a reliable and sustainable electricity supply. As Iraq continues on this transformative journey, it faces the dual challenge of modernizing its electricity sector while exploring cleaner and greener energy alternatives to mitigate environmental impacts. This transformation is essential for Iraq economic development, social progress, and its vision of a future powered by a diverse and sustainable energy mix. As the country moves forward, embracing innovation, technology, and international cooperation will be critical in achieving a more resilient and prosperous electricity sector that meets the aspirations of its people and contributes to a sustainable energy future.

2.4. Current status of electricity in Iraq

As of the current status, the electricity situation in Iraq continues to be a matter of concern and challenge for the country. Despite efforts made to improve the sector, Iraq faces persistent issues related to power generation, distribution, and supply. The country experiences frequent power outages and blackouts, impacting both residential and commercial consumers [25,26]. The demand for electricity has been steadily increasing due to population growth and economic development, putting immense pressure on the aging and insufficient electricity infrastructure. Moreover, technical inefficiencies, inadequate maintenance, and financial constraints further contribute to the electricity sector

1951	The modern history of the Iraqi electricity sector began in 1951 with the establishment of the Iraq Ministry of Electricity. During this period, the country embarked on developing its electricity infrastructure to cater to the increasing demand for electricity, mainly for industrial and urban centers.
1965	Iraq made notable progress in the electricity sector, with the commissioning of major power plants and grid expansion. The sector growth was fueled by increasing oil revenues, which allowed the country to invest in large-scale power generation projects.
1974	The nationalization of Iraq oil industry provided a significant boost to the electricity sector. The increased oil revenue was channeled into further expanding the power generation capacity and extending the electricity grid to reach remote areas.
1981	The prolonged Iran-Iraq war, which began in 1980, had significant implications for the electricity sector. The conflict disrupted the flow of investment and resources into the sector, leading to challenges in maintaining and expanding the electricity infrastructure.
1990	Iraq faced international sanctions following its invasion of Kuwait in 1990. These sanctions severely impacted the electricity sector, limiting access to critical resources and impeding the modernization and maintenance of power facilities.
2003-2006	The invasion of Iraq by a coalition led by the United States in 2003 brought about significant changes in the country, including its electricity sector. Efforts were made to rebuild and rehabilitate power plants and the electricity grid, which had suffered damage during the conflict.
2012	By 2012, Iraq made substantial strides in restoring and expanding its electricity infrastructure. The focus was on improving generation capacity, reducing power outages, and increasing access to electricity for citizens.
2020	Iraq has been working on diversifying its energy mix and promoting renewable energy sources, including solar and wind power. Additionally, the government has been attracting foreign investments to support the development of new power projects and modernizing the existing ones.

Fig. 7. Overview of the transformation of the Iraqi electricity sector over multiple decades [22,23].

struggles. While Iraq possesses immense potential for renewable energy, such as solar and wind power, the integration of these clean energy sources into the grid has been slow. Additionally, political instability and security concerns have hindered investments and progress in the sector [26]. To address these challenges, Iraq requires sustained commitment from the government, private sector involvement, and international support. Initiatives to modernize and expand the electricity infrastructure, improve energy efficiency, and diversify the energy mix with renewable sources are crucial steps toward achieving a reliable, sustainable, and resilient electricity sector capable of meeting the country growing energy demands and driving socio-economic development.

Fig. 8 presents an overview of power generation in gigawatts and the corresponding peak load demand, where the country power generation stood at 9.8 GW, slightly lower than the peak load demand of 11.2 GW. This trend of demand surpassing supply persisted through the following years [27,28]. In 2011, power generation was 10.6 GW compared to a higher demand of 12.4 GW, and in 2012, the data were 11.7 GW and 13.8 GW respectively. In 2020 and 2021, power generation continued its upward trend, reaching 24.3 GW and 25.8 GW, respectively. However, peak load demand was closely following, with figures at 23.1 GW and 25.2 GW, emphasizing the ongoing challenge to meet the county growing electricity needs. By 2022, power generation had grown to 27.1 GW, exactly matching the peak load demand, indicating a balance between supply and demand. This historical snapshot underscores the importance of continued investments and strategic planning in Iraq power sector to meet future demands.

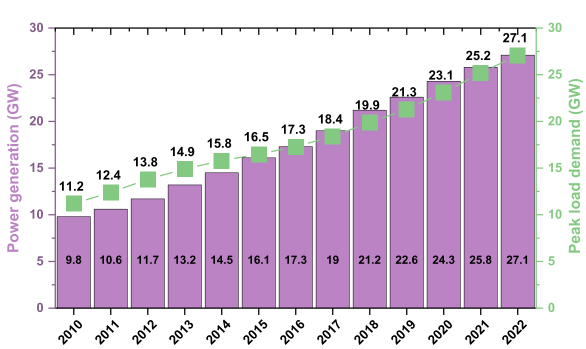

Fig. 8. Power generation vs. peak load demand in Iraq (2010–2022): tracking the balance of electricity supply and demand [27,28].

A significant shift occurred in 2012 when the government unveiled an ambitious overhaul of the electricity sector, fueled by the urgency to cater to escalating electricity demand in the face of rapid urbanization and population growth. By 2020, the sector focus pivoted towards energy mix diversification and the integration of renewable energy sources. In particular, solar PV technology emerged as a potential solution to meet the surging electricity demand and enhance energy security, heralding a new epoch in Iraq electricity sector.

2.5. Solar PV power plant projects in Iraq

As of the current status, there are several solar PV power plant projects in Iraq that aim to harness the country abundant solar resources and contribute to clean energy generation. The current vision for Iraqi solar PV power plant projects is to have significantly expanded solar capacity, contributing to a substantial portion of the country electricity generation [29]. The focus is on developing large-scale utility solar power plants in strategic locations, as well as fostering distributed solar installations on rooftops and in rural communities to enhance energy access. Iraq aims to leverage advancements in solar PV technology, energy storage, and grid integration to overcome technical challenges and improve grid stability. With supportive policies, attractive feed-in tariffs, and increased private investments, the country envisions a flourishing solar industry with local manufacturing capabilities and a skilled workforce [30]. By 2025, Iraq aims to achieve notable progress in its transition to renewable energy, reducing carbon emissions, enhancing energy security, and creating economic opportunities, ultimately paving the way for a cleaner, more sustainable energy future for the country [31,32].

As of 2021 and 2022, Iraq current vision for solar PV power plant projects focuses on the successful commissioning of several large-scale utility and distributed solar installations. Projects such as Samawah 1000 MW, Baghdad A 150 MW, and Basra 200 MW have already been turned on, contributing to the country renewable energy capacity. Additionally, smaller projects in Najaf, Dhi Qar, Diwaniyah, Hilla, and Mosul have added a cumulative capacity of 350 MW [33]. Looking ahead to 2025, the future vision for Iraqi solar PV power plants is ambitious, aiming to reach a total solar capacity of 3470 MW. The growth in solar PV capacity reflects Iraq commitment to diversifying its energy mix, reducing carbon emissions, and enhancing energy security [34,35]. The envisioned increase in solar projects showcases the country determination to embrace renewable energy and create a more

Fig. 9. Vision 2025 solar PV power plants projects in Iraq [33,34].

sustainable energy future for its citizens, as depicted in Fig. 9.

Despite the high solar radiation potential in Iraq, the vision for future solar PV power plant projects in 2025 appears to be poor compared to the abundant available solar irradiance. Several factors may account for this disparity, such as limited financial resources, complex regulatory procedures, inadequate grid infrastructure, and a lack of supportive policies and incentives. Additionally, challenges in attracting investments and addressing technical and capacity issues may have hindered the realization of a more ambitious vision. To fully capitalize on Iraq solar potential, it is crucial for policymakers and stakeholders to overcome these barriers, streamline project development processes, and create an enabling environment for solar investments. By doing so, Iraq can unlock the immense potential of solar energy, contribute to its energy security, and move closer to achieving a sustainable and renewable-powered future.

Fig. 10 illustrates the distribution of current and planned solar PV power plants across Iraq. The map showcases the geographical locations of existing solar installations and upcoming projects, providing a visual representation of the country solar energy landscape. Current solar PV power plants, such as Samawah, Baghdad A, Basra, and others, are scattered across different regions, including the central, southern, and northern parts of Iraq. Additionally, smaller projects are visible in cities such as Najaf, Dhi Qar, Diwaniyah, Hilla, and Mosul [36,37]. The map also highlights the planned solar PV power plants, which are expected to be commissioned in the future. These upcoming projects are concentrated in areas where solar irradiance is high and where the grid infrastructure can accommodate large-scale solar installations. The distribution of current and planned solar PV power plants in the map underscores the potential for solar energy in various regions of Iraq and reflects the country commitment to harnessing its solar resources for a sustainable and resilient energy future.

2.6. Solar rooftop installations as a large-scale project in Iraq

As solar PV rooftop installations become more widespread across Iraq, the benefits will be far-reaching. The reduced reliance on fossil fuels will enhance energy security, reducing the country vulnerability to fluctuations in global energy prices. Moreover, a decentralized energy generation model with solar rooftop installations can increase grid resilience, as power generation is distributed across various points, minimizing the impact of potential disruptions.

The solar rooftop installations in Iraq signify the highest solar PV across the country, demonstrating remarkable growth from 2020 to 2022. The data in Table 1 clearly illustrates this progression across 18 Iraqi governates. For instance, Baghdad installation capacity grew from 50 MW in 2020 to 70 MW in 2022, while its production capacity increased from 120,450 MWh to 164,250 MWh during the same period. Similarly, Basra, the governate with the highest capacity, saw its installation capacity rise from 80 MW to 100 MWh, and production capacity from 186,150 MW to 229,950 MW within three years. Other notable developments occurred in Mosul, Erbil, Sulaymaniyah, and Najaf, reflecting a consistent upward trend in both installation and production capacity. The installation capacity in Mosul, for example, grew from 30 MW in 2020 to 40 GW in 2022, with production capacity also rising proportionally from 70,080 MWh to 91,980 MWh. Even in regions with relatively lower capacity, such as Anbar, Muthanna, and

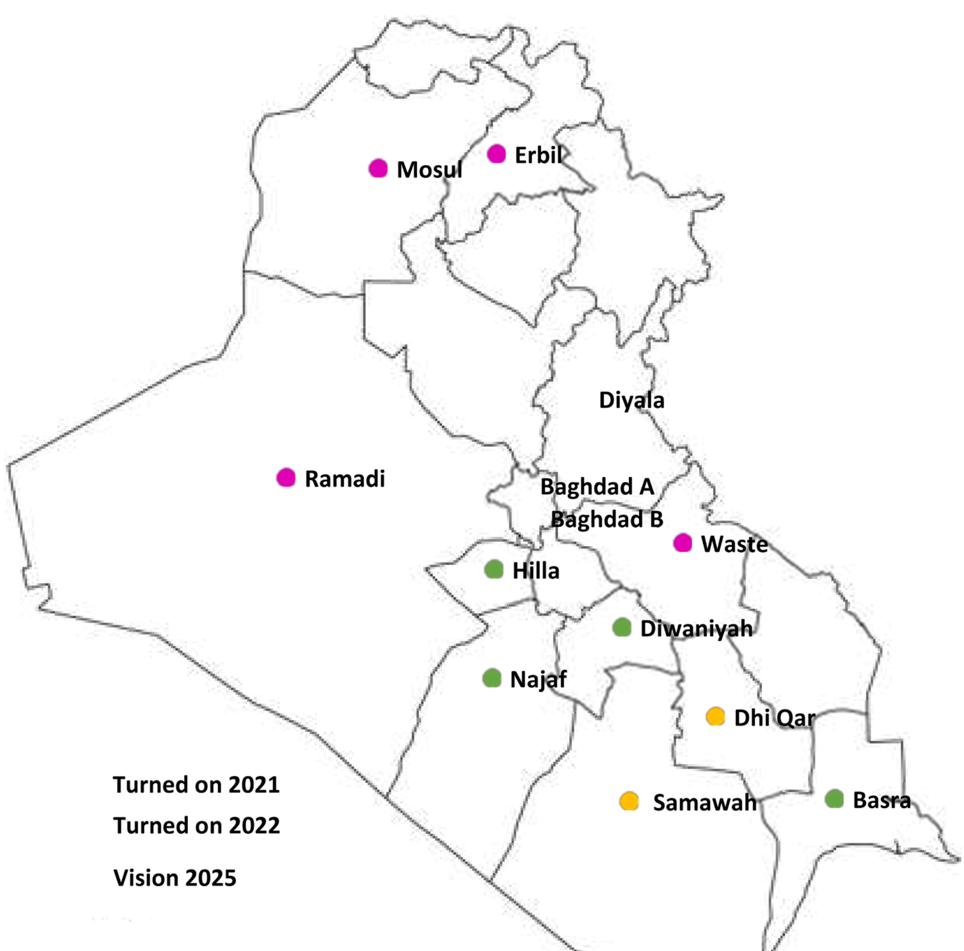

Fig. 10. Solar Current and planned power plant distribution on the map of Iraq.

Table 1
Installation capacity (MW) and production capacity (MWh) of PV solar roof across 18 Iraqi governate for the years of (2020–2022) [38–40].

Governorate	2020		2021		2022	
	Installation capacity	Production capacity	Installation capacity	Production capacity	Installation capacity	Production capacity
Baghdad	50	120,450	60	142,350	70	164,250
Basra	80	186,150	90	208,050	100	229,950
Mosul	30	70,080	35	81,030	40	91,980
Erbil	40	91,980	45	102,930	50	113,880
Sulaymaniyah	35	81,030	40	91,980	45	102,930
Najaf	25	59,130	30	70,080	35	81,030
Karbala	20	48,180	25	59,130	30	70,080
Dhi Qar	45	102,930	50	113,880	55	124,830
Maysan	30	70,080	35	81,030	40	91,980
Anbar	15	37,230	20	48,180	25	59,130
Babil	25	59,130	30	70,080	35	81,030
Wasit	30	70,080	35	81,030	40	91,980
Diyala	20	48,180	25	59,130	30	70,080
Muthanna	15	37,230	20	48,180	25	59,130
Diwaniyah	20	48,180	25	59,130	30	70,080
Kirkuk	25	59,130	30	70,080	35	81,030
Salah al-Din	35	81,030	40	91,980	45	102,930
Nineveh	40	91,980	45	102,930	50	113,880

Diwaniyah, the growth trend remains evident. In Anbar, the installation capacity increased from 15 MW to 25 MW [38,39].

The increased investment in solar rooftop installations across these governates not only contributes to sustainable energy production but also supports local economies, reduces dependency on non-renewable resources, and aligns Iraq with global renewable energy objectives.

The implementation of solar rooftop installations in Iraq as a large-scale solar PV project presents a transformative opportunity for the country. With an estimated capacity for 18 governorates and high installations in cities to power commercial and residential buildings while feeding the grid, Iraq can significantly advance its sustainability agenda. The capacity values for each city will be determined by solar irradiance levels, available rooftop space, and local electricity demand, ensuring an optimized and effective utilization of the abundant solar resource. Through collaborative efforts and community involvement, Iraq can pave the way towards a greener and more resilient energy future.

3. Methodology

The methodology for the research study is a multi-step process that integrates various data analysis techniques and tools to assess the viability and progress of solar PV implementation in Iraq as presented in Fig. 11.

Step I: Preliminary Analysis

The initial step involves a comprehensive literature review and gathering of expert technical opinions to select relevant evaluation criteria for solar PV implementation. This stage is crucial for understanding the current state of knowledge and establishing a foundation for subsequent analysis.

Step II: Data Acquisition and GIS Input

The next phase focuses on data acquisition, where spatial data layers are collected, categorized as geographic, environmental, and socioeconomic factors. These data are then input into GIS, utilizing both vector (line and point layers) and raster (Digital Elevation Models (DEMs), land cover, etc.) data formats to represent different aspects necessary for analysis.

Step III: Criteria Development and Weighting

Following data input, a list of criteria is developed to identify the best and worst conditions for solar PV installation. This involves using pairwise comparison vectors and linear models to determine the optimal weights of these criteria, ensuring that each factor is appropriately considered in the overall evaluation.

Step IV: Constraints and Modeling

Selecting constraint factors and determining buffer zones are performed using a raster calculator and Boolean logic to create a constraint model that defines unsuitable areas for PV development. This model integrates various geographical and infrastructural limitations.

Step V: Fuzzy Logic Application and Suitability Modeling

The study employs fuzzy logic techniques to reclassify the spatial data, applying a fuzzy membership function and fuzzification process to handle the uncertainty in data classification. Layer weighting and an inferential network are used to merge the geographic, environmental, and socioeconomic models into a comprehensive suitability model for solar PV sites.

Step VI: Sensitivity Analysis

Asensitivity analysis is conducted to identify the most influential criteria and to examine how input uncertainty affects the model output. This step also verifies the model compatibility with the reality of the region conditions.

Each step in this methodology represents a critical component of a thorough and systematic approach to evaluating the potential and progress of solar PV energy systems in Iraqi specific climatic zone. The use of GIS and fuzzy logic allows for a nuanced analysis that can accommodate the complexity of the factors influencing solar PV implementation.

3.1. Data compilation

In the pursuit of mapping out the solar PV energy potential in Iraq, this study methodology is anchored in a meticulous aggregation and analysis of geospatial data, encapsulated within Table 2. This table serves as a cornerstone, delineating the array of spatial variables crucial for the assessment, such as solar irradiation, land utilization, and infrastructural layouts. The analytical prowess of the ArcGIS spatial analyst toolbox is harnessed to process this data, enabling intricate tasks like overlay analysis and surface modeling, vital for interpreting solar irradiation distribution and other geographical elements. The Iraqi Meteorological Organization & Seismology enriches this study by supplying pivotal five-year solar irradiation data, facilitating a nuanced understanding of the region solar capacity. Moreover, the study introduces a GIS-based multi-hazard ranking framework that integrates the 22 primary districts of Iraq, reflecting the country administrative structure. This framework is instrumental in assessing the renewable energy prospects while judiciously accounting for various hazards that could influence solar PV project deployment. Collectively, this approach yields a holistic view of the geographic and climatic factors that could drive or deter solar energy proliferation in Iraq, guiding the identification of prime zones for solar PV installations and cognizing the

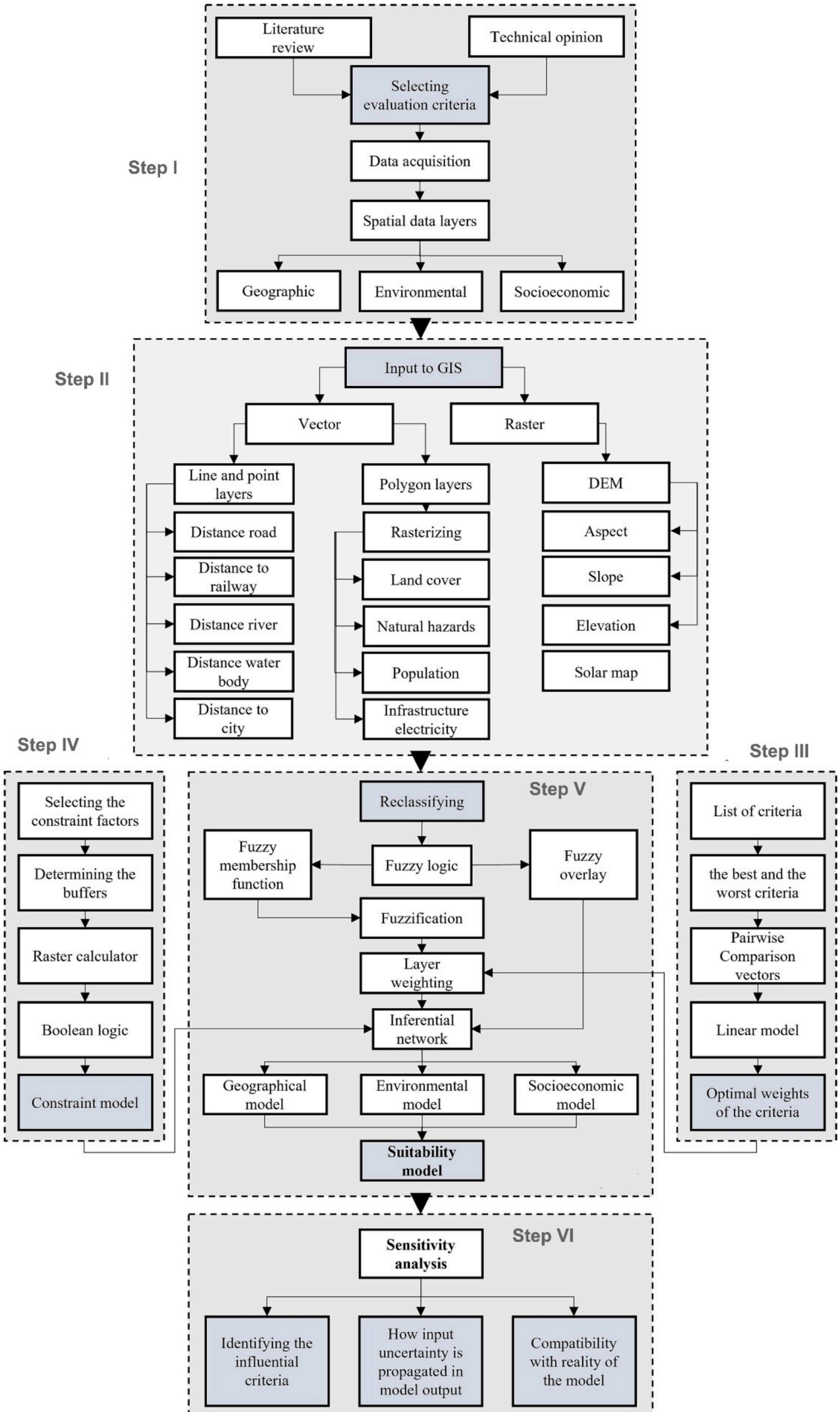

Fig. 11. Steps of GIS and Fuzzy Logic for renewable energy optimum site selection used in this study.

Table 2
The geospatial data layers used in GIS [41].

No.	Dataset description	Measurement unit
1	Terrain Elevation (DEM)	Meter
2	Terrain Gradient (Slope)	Degree
3	Terrain Orientation (Aspect)	Degree
4	Irradaince Intensity (Solar)	kW.h/m^2
5	Ground Cover Classification	–
6	Hazard Index	–
7	Demographic Distribution	–
8	Electrical Infrastructure	–
9	Transportation Pathways (Road)	–
10	Train Routes (Railway)	–
11	Stream and River Channels	–
12	Large Water Surfaces	–
13	Urban Centers (City)	–

associated risks. Through this refined geospatial data analysis, the study paints a comprehensive portrait of Iraqi solar energy landscape, considering the intricate tapestry of environmental and administrative considerations.

Vector data accuracy is contingent upon several aspects, including the characteristics of the actual objects represented (e.g., roads, rivers, city boundaries), the proficiency of the data collector, and the data origin methodology, whether it is from photogrammetry or digitalization. Raster data with quantitative attributes, such as elevation, carry intrinsic uncertainties from the unpredictable nature of their sources and the presence of control points. This uncertainty can proliferate throughout the dataset. On the other hand, raster data with qualitative attributes, such as land cover derived from remote sensing, have potential error assessments through methods such as error matrices. However, generating high-resolution data, such as solar irradiation, can invite errors from various stages of data handling, from collection to logging. This emphasizes the vital need for thorough data validation and processing in geospatial endeavors.

4. Results and discussions

The results of the study reveal significant insights into the potential of solar PV systems to meet the country future energy demands, emphasizing the crucial role of strategic planning and technological adoption. Through a detailed analysis of electric demand data and solar PV production capacities, the findings indicate that scaling up solar PV installations can substantially contribute to the national energy mix, particularly during peak solar irradiance months. The simulations, based on various projected PV capacities, demonstrate that even at the lower end of the capacity spectrum, solar PV can cover a significant portion of the energy demand, with higher capacities offering the potential to meet nearly half of the total load. This underscores the viability of solar energy as a key component in the country energy transition strategy, highlighting the importance of supportive policies, investment in technology, and public awareness to harness this clean, abundant resource.

1. Projected capacity of solar roof PV system required in 2035

The projection of solar roof PV system capacities needed in Iraq by the year 2035 provides a compelling vision of the potential role of solar energy in fulfilling the country future energy requirements. This forward-looking analysis is grounded in a detailed examination of experimental electric demand data from the year 2022, captured at one-hour intervals, alongside projections of energy demand for 2035. By conducting a simulation that incorporates this high-resolution data, researchers have been able to estimate the capacities of solar roof PV installations necessary to meet future energy needs. This simulation takes into account various potential PV capacities, ranging from 10 TWh to 40 TWh, based on the average power production from solar roof PV systems observed between 2020 and 2022. Such detailed and methodical analysis lays a solid foundation for understanding how solar energy can be scaled up to meet country growing energy demands, taking into consideration the trends and patterns in electricity consumption over recent years.

The results of this simulation, particularly highlighted in Fig. 12, offer insightful trends in monthly solar energy production, with a clear distinction between the higher outputs observed during the sunnier months of April through August, and the lower outputs during the less sunny months of September through March. This seasonal variation in solar power generation underscores the feasibility and potential effectiveness of solar roof PV systems in contributing significantly to the country energy mix. For instance, a PV system with a capacity of 10 TWh is projected to satisfy 18 % of the total energy demand, with larger capacities of 20, 30, and 40 TWh potentially meeting 23 %, 36 %, and 48 % of the total demand, respectively. These projections not only highlight the substantial role that solar energy, particularly rooftop PV installations, could play in the country energy landscape by 2035 but also provide a strategic framework for policymakers and energy planners. Emphasizing the considerable contributions solar energy could make toward satisfying country electricity needs, this analysis advocates for a transition to a more sustainable, secure, and environmentally friendly energy system, leveraging the country abundant solar resources to ensure resilience against future energy challenges.

The comprehensive analysis conducted on the potential of solar photovoltaic (PV) roof systems at varying capacities of 10, 20, 30, and 40 Terawatt-hours (TWh) across Iraq has yielded valuable insights into the scalability and effectiveness of renewable energy solutions in the region. By leveraging GIS data spanning from 2020 to 2022, the study meticulously mapped the distribution of solar PV installations and quantified their energy generation potential at each capacity level. The results, vividly depicted in Fig. 13, demonstrate a clear correlation between the installed capacity of solar PV systems and the proportion of energy they are capable of generating, with the 40 TWh capacity marking the highest energy output. This correlation not only highlights the significant benefits of expanding solar PV infrastructure but also points to the vast untapped potential of the country solar resources. The spatial analysis facilitated by GIS technology has been instrumental in identifying regions with the highest solar energy potential, thereby guiding strategic planning and investment towards areas where solar PV systems can achieve maximum efficiency and yield.

Building on these findings, the study makes a compelling case for the broader adoption and enhancement of solar PV roof systems within Iraq, advocating for an ambitious approach towards harnessing the country renewable energy resources. The observed direct relationship between system capacity and energy generation underscores the transformative impact that large-scale solar energy projects can have in meeting the country escalating energy requirements sustainably. The utilization of GIS data not only enriches the analysis with geographical insights but also serves as a crucial tool in optimizing the deployment of solar PV systems, ensuring that investments are directed towards locations with the greatest solar potential. This research underscores the critical role of solar PV roof systems in Iraqi energy landscape, advocating for increased capacities to fully leverage the renewable energy opportunities presented by the region abundant solar radiation. The implications of these findings extend beyond the immediate context of Iraq, offering valuable lessons for other regions with similar solar profiles and energy needs, and reinforcing the global imperative for investment and innovation in solar technologies to address the pressing challenges of energy sustainability and environmental stewardship.

The implications of these findings extend beyond energy generation. By harnessing the full potential of solar PV technology, Iraq can foster local industries, create employment, enhance technological prowess, and reduce greenhouse gas emissions. The strategic alignment with the country socio-economic goals, coupled with environmental stewardship, makes the push towards increased solar PV capacity all the more compelling. the energy generated percentage of solar PV roof systems at

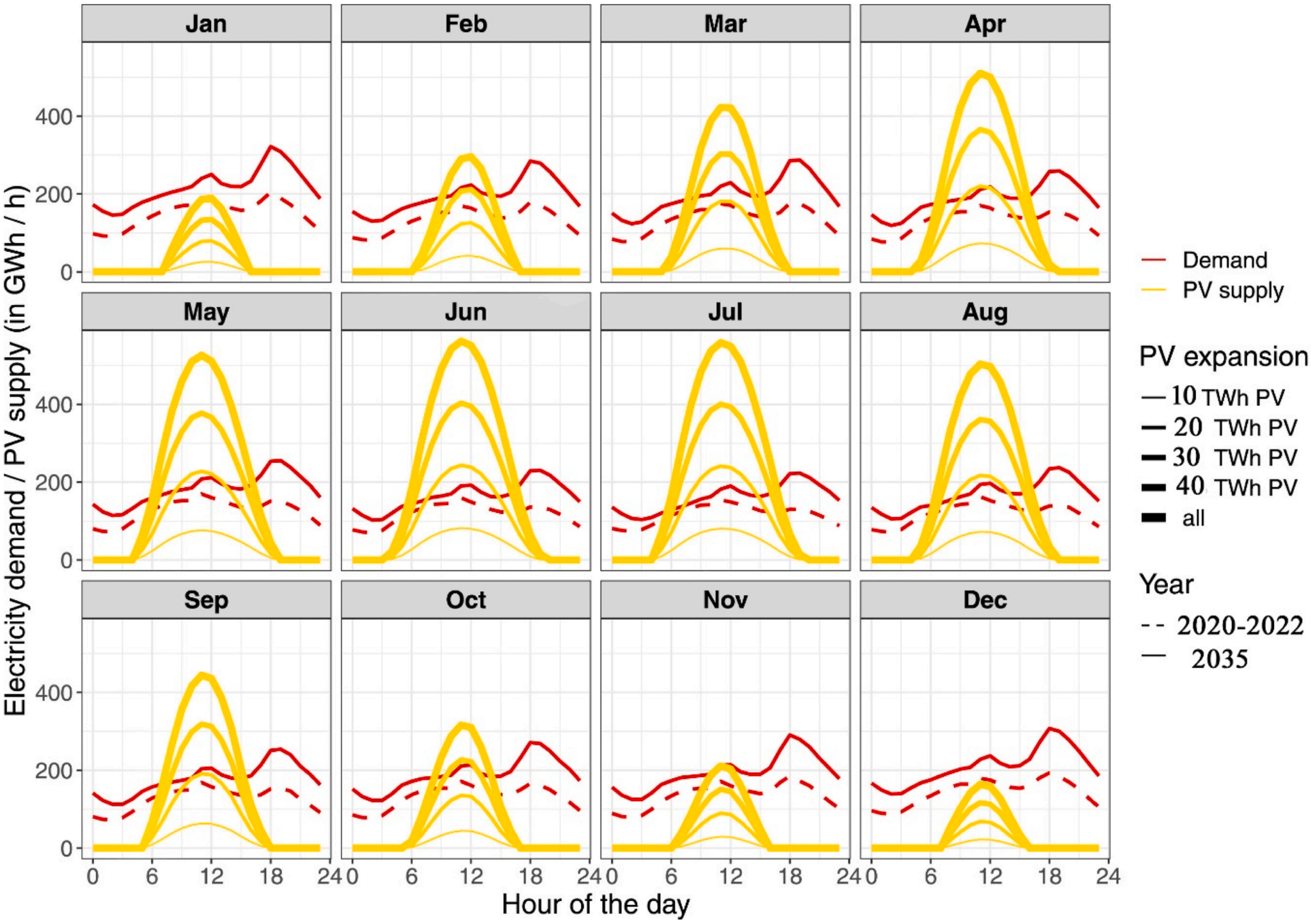

Fig. 12. The overview of the projected solar roof PV system in 2035 at several capacities.

the capacities of 10, 20, 30, and 40 TWh, as analyzed through GIS data over the years 2020–2022, paints a promising picture for Iraq energy future. It emphasizes the critical role that solar energy can play in a diversified energy portfolio, meeting the demands of today without compromising the needs of future generations.

Fig. 14 presents a sensitivity analysis conducted to assess the suitability of various regions within Iraq for the installation of solar PV roof systems at different capacity levels: 10 TWh (a), 20 TWh (b), 30 TWh (c), and 40 TWh (d). This analysis integrates applicable partial sensitivity indices, which are critical in determining the extent to which certain variables affect the output of the models used to estimate the potential of solar PV installations. The maps use color coding to delineate areas deemed suitable (in green) and not suitable (in blue) for solar PV roof systems. At the 10 TWh capacity (a), we observe a modest proportion of areas classified as suitable, indicating a conservative estimate of the regions' potential. As the capacity increases to 20 TWh (b) and 30 TWh (c), the suitable areas expand, suggesting a positive correlation between increased capacity and the number of areas that could feasibly support solar PV installations.

1. Current challenges and opportunities in solar PV deployment

Challenges and opportunities in solar PV deployment present a comprehensive picture of the factors influencing the widespread adoption of solar energy in Iraq.

1. **Technical challenges:** one of the primary technical obstacles hindering solar PV deployment in Iraq is grid integration. As solar energy is intermittent and depends on weather conditions, integrating it seamlessly into the existing electricity grid can be challenging. Effective grid management, energy storage solutions, and grid balancing technologies are essential to ensure a stable and reliable power supply. Additionally, developing local manufacturing capabilities for solar PV components can reduce dependency on imports and make solar energy more cost-effective [41].
2. **Economic and financial challenges:** solar PV faces several financial barriers compared to conventional energy sources in Iraq. The initial upfront costs of installing solar panels and associated equipment can be significant, deterring some potential investors and consumers [42]. Although solar PV has become more cost-effective over the years, further advancements are needed to reach grid parity with conventional energy sources. Access to financing, incentives, and long-term investment security are crucial factors in overcoming these financial challenges.
3. **Social and cultural factors:** social acceptance and cultural aspects play a role in influencing solar PV adoption in Iraq. Public awareness and education about the benefits of solar energy are essential to overcome skepticism and misconceptions about renewable energy sources [43]. Building trust in solar PV technology, showcasing successful case studies, and engaging with local communities are key strategies to foster social acceptance. Moreover, considering cultural preferences in solar PV design and implementation, such as aesthetics and architectural considerations, can enhance its integration into communities [44].
4. **Policy and regulatory issues:** Iraq must address policy gaps and regulatory barriers to promote solar PV development. Clear and consistent renewable energy policies and supportive regulations are necessary to attract investments and foster market growth [45].

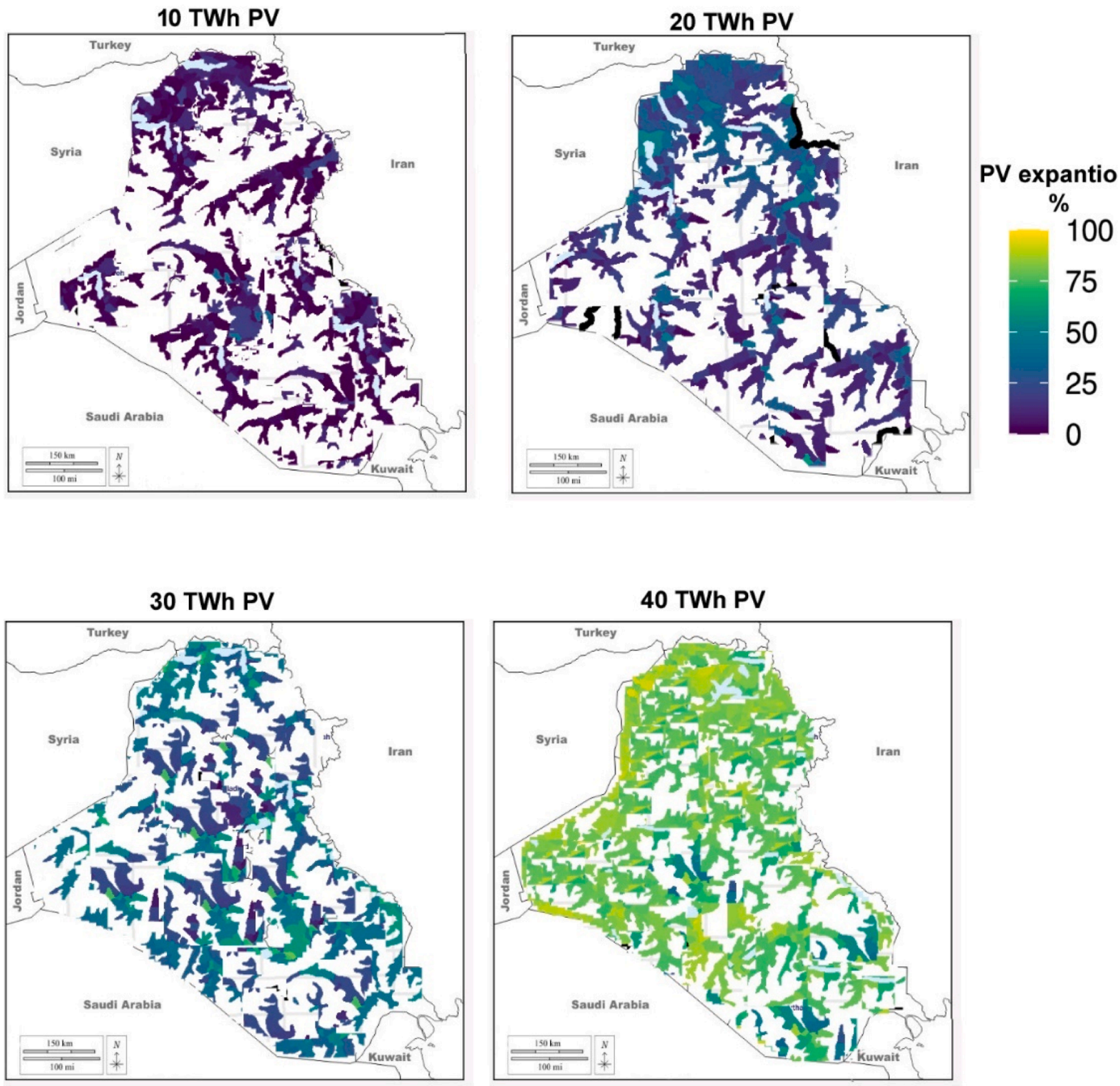

Fig. 13. Solar PV roof systems across different capacities over Iraqi territories using GIS.

Streamlining permitting processes, ensuring fair market access for solar projects, and providing stable incentives are critical for building investor confidence [46]. Policymakers should also consider incorporating renewable energy targets, renewable portfolio standards, and feed-in tariffs to create a conducive environment for solar PV expansion.

While challenges exist, there are also promising opportunities in Iraq solar PV sector. The country abundant solar irradiance offers immense potential for solar energy generation, making it a sustainable and viable option for meeting growing energy demands. By strategically addressing technical challenges, enhancing cost-effectiveness, promoting social acceptance, and enacting supportive policies, Iraq can unlock the vast opportunities in solar PV deployment.

1. Policies of renewable energy adoption in Iraq

Policies of renewable energy adoption in Iraq play a crucial role in shaping the country transition towards a more sustainable and diversified energy future. As a country rich in oil and gas resources, Iraq faces both opportunities and challenges in promoting renewable energy, especially given the pressing need to address climate change, increase energy security, and diversify its economy. Over the years, the Iraqi government has taken significant steps to develop a policy framework that encourages the adoption of renewable energy sources, including solar, wind, and hydropower. This essay will explore the key policies and initiatives driving renewable energy adoption in Iraq, their impact on the energy landscape, and the challenges that still need to be addressed.

One of the primary policy instruments promoting renewable energy in Iraq is the National Renewable Energy Policy and Strategy (NREPS) [47]. Launched in 2018, NREPS sets ambitious targets for renewable energy deployment, aiming to achieve 10 % renewable energy in the total energy mix by 2028 [48]. The strategy emphasizes the development of solar and wind energy projects, as well as promoting investment in research and development to enhance the efficiency and cost-effectiveness of renewable technologies. NREPS provides a clear roadmap for renewable energy development, outlining the necessary policy measures, incentives, and regulations to achieve its targets [49].

To attract private investments and foster renewable energy projects, the Iraqi government has implemented supportive financial incentives. These include feed-in tariffs, which guarantee a fixed price for renewable energy generated and injected into the grid. Feed-in tariffs provide long-term price stability, making renewable energy projects more

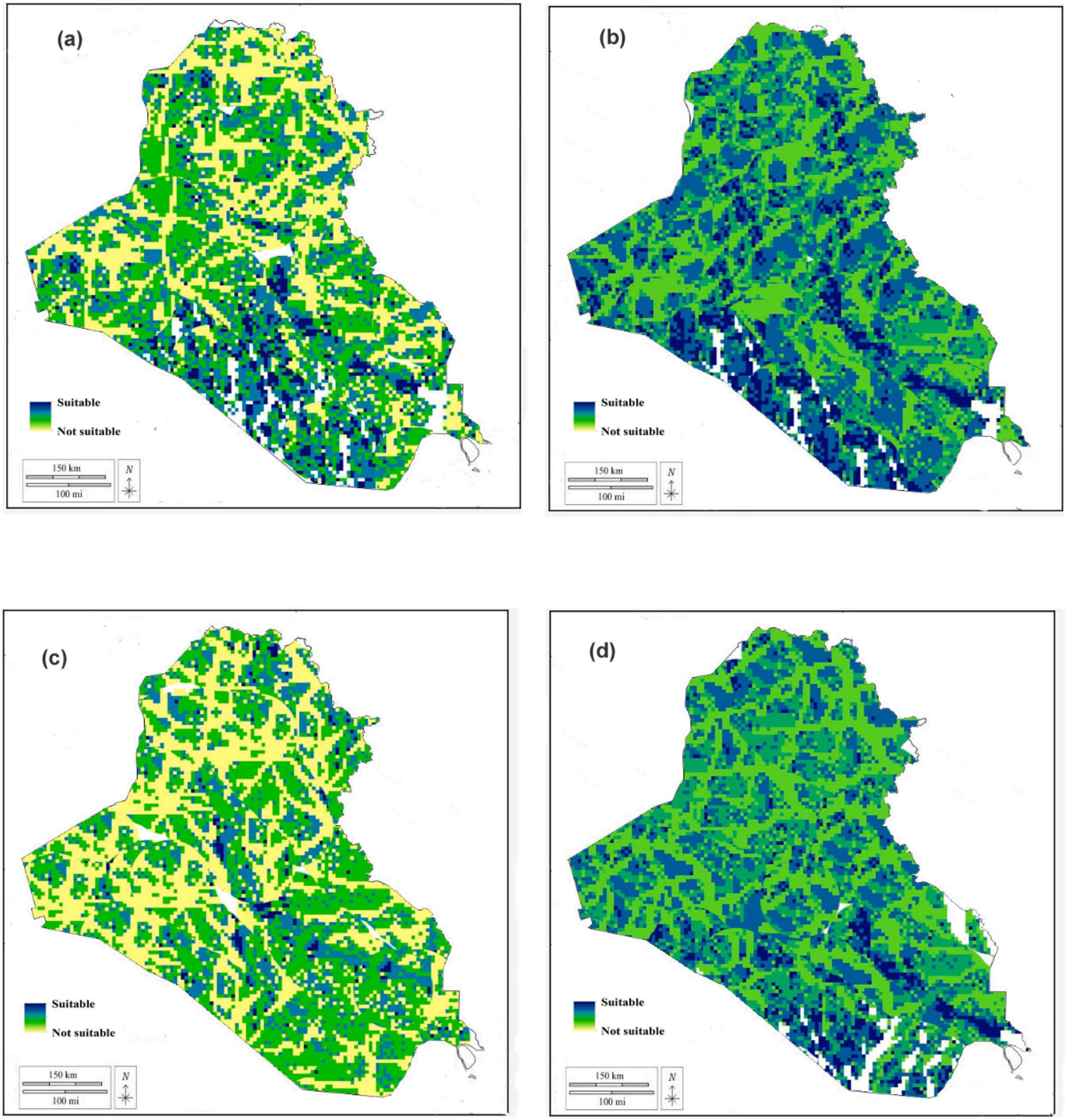

Fig. 14. Sensitivity analysis incorporating applicable partial sensitivity indices criteria for solar PV roof systems across different capacities (a) 10 TWh, (b) 20 TWh, (c) 30 TWh, (d) 40 TWh.

attractive to investors. Additionally, the government has offered tax incentives, customs duty exemptions, and other financial benefits to companies engaged in renewable energy development [50]. Such financial incentives aim to reduce the risk for investors and facilitate the implementation of large-scale renewable energy projects. Another significant policy instrument is the Power Purchase Agreement (PPA) framework, which defines the terms and conditions for purchasing renewable energy from private developers [51]. The PPAs provide a legal and financial framework for developers to sell their generated energy to the national grid, ensuring a stable revenue stream. By guaranteeing a reliable market for renewable energy, PPAs encourage private investments and support the growth of renewable energy projects in Iraq. In addition to these policies, Iraq has embraced international collaborations to accelerate renewable energy adoption. The country is a member of the International Renewable Energy Agency (IRENA), which provides technical expertise, knowledge sharing, and capacity building in the field of renewable energy [52]. Collaborations with international organizations and countries enable Iraq to access funding opportunities, best practices, and cutting-edge technologies to bolster its renewable energy sector [53]. Despite these policy initiatives, Iraq still faces significant challenges in fully realizing its renewable energy potential. One of the primary obstacles is the dominance of conventional energy sources, primarily oil and gas, in the country energy mix. As a major oil exporter, Iraq relies heavily on oil revenues to support its economy, making it challenging to swiftly transition to renewable energy without impacting the economy.

Table 3 show a comparing Iraq renewable energy policy with those of Germany, Denmark, Sweden, China, Costa Rica, and Norway [54–61]. We notice significant differences in ambition, scope, and diversity. Germany comprehensive guidelines include Tradable REC and Investment Tax Credits, Denmark policies cover Electric Utility Quota Obligations, and Sweden has implemented Tradable Renewable Energy Certificates. Costa Rica emphasizes Net Metering and Billing Regulations, and China integrates public investments, grants, and a variety of renewable energy sources in its planning. Norway focuses on full decarbonization by 2050, emphasizing public investment and a diverse renewable energy portfolio.

Iraq could look to these countries to enhance its renewable energy policy framework. By embracing a broader range of incentives, adopting more aggressive targets, and implementing more diverse tendering processes, Iraq can develop a more comprehensive renewable energy strategy. The experiences of these countries could guide Iraq in integrating various renewable sources, promoting public and private investments, and creating a regulatory environment conducive to sustainable energy development.

Iraq renewable energy policies are relatively nascent compared to the more established and ambitious frameworks seen in Germany, Denmark, Sweden, China, Costa Rica, and Norway. Iraq target of 10 % renewable energy by 2030 pales in comparison to the goals of other countries, such as Costa Rica 100 % target by 2030 or Sweden aim for 100 % by 2040. The prevalent national policies and tender structures in Iraq mainly focus on feed-in tariffs and solar tendering procedures, lacking the comprehensive approach seen in other countries that encompass electric utility quotas, net metering regulations, and a broader spectrum of renewable energy sources. Opportunities for improvement in Iraq renewable energy policy might include adopting practices from the compared countries such as establishing clear long-term renewable energy targets, developing diversified renewable energy sources, implementing public investments, grants, and subsidies, and introducing robust regulatory measures for net metering and billing. Collaboration with these countries could also facilitate knowledge transfer and the development of an integrated approach that suits Iraq unique energy landscape, resources, and needs.

1. Involvement in the net metering program for small-scale solar PV systems

Involvement in the net metering program for small-scale solar PV systems is an intricate process that requires various steps and adherence to specific requirements as presented in Fig. 15. Consumers wishing to participate must have an active account with their local electricity distribution service provider (DSP), and must obtain necessary permissions, as well as meet property ownership criteria. Connection to the distribution network is also mandatory [61,63]. Once engaged, consumers must fulfill various requirements, such as completing an application, paying related fees, and complying with applicable standards for PV modules and materials. Certified contractors must carry out the design and installation. Participants in the program must follow guidelines concerning capacity, location, safety, and compliance with distribution codes. The program provides compensation for surplus renewable energy fed into the grid, with specific metering arrangements to measure and credit this energy. Two meters are installed to monitor consumption and production, with costs shared between the DSP and the consumer. Overall, participation in the net metering program encourages the generation and use of renewable energy, aiding in sustainable energy practices.

Participation in the net metering program for small-scale solar PV systems is governed by a set of stringent requirements and procedures. It facilitates the integration of renewable energy into the grid, providing benefits to the consumers and supporting the broader goal of sustainable energy adoption.

5. Conclusions

The study indicates that with strategic PV installations, Iraq could significantly boost its renewable energy share in the national energy

Table 3
Comparing Iraq renewable energy policies with those of Germany, Denmark, Sweden, China, Costa Rica, and Norway.

Country	Prevalent national policies and tender structures	Established subnational policies and tender frameworks	Countrywide tender process	Regional tender procedures	Emerging regulatory measures
Germany	– Renewable Energy Targets: 65 % by 2030 – General Renewable Energy Guidelines – Feed-in Tariff Policies – Tradable REC, Investment Tax Credits	– Feed-in Tariff at the state level	– Regular tendering for solar & wind	– Varies by region	– New CO_2 pricing system
Denmark	– Renewable Energy Targets: 100 % by 2050 – Feed-in Premium Payment Policies – Electric Utility Quota Obligations	– Regional Renewable Energy Guidelines	– Regular tendering for offshore wind	– Varies by region	– New technology support
Sweden	– Renewable Energy Targets: 100 % by 2040 – Tradable Renewable Energy Certificates (REC)	– Regional Renewable Portfolio Standards (RPS)	– Tendering for wind energy	– Varies by region	– Emerging net metering
China	– Renewable Energy Targets: 65 % by 2060 – Electric Utility Quota Obligations – Public Investment, Grants, and Subsidies	– Subnational Renewable Energy Planning	– Regular solar and wind tendering	– Varies by province	– EV charging incentives
Costa Rica	– Renewable Energy Targets: 100 % by 2030 – Net Metering and Billing Regulations – Public Investment, Renewable Energy Subsidies	– Regional Renewable Portfolio Standards (RPS)	– Tendering for various RE sources	– Varies by region	– Emerging biofuel support
Norway	– Renewable Energy Targets: Full decarbonization by 2050 – Tradable Renewable Energy Certificates (REC) – Public Investment, Grants, and Capital	– Regional Renewable Energy Guidelines	– Regular offshore wind tendering	– Varies by region	– Emerging hydrogen strategy
Iraq	– Renewable Energy Targets: 10 % by 2030 – Feed-in Tariff or Premium Payment Policies – Investment or Production Tax Credits	– Subnational Renewable Energy Planning	– Solar tendering procedures	– Varies by region	– Emerging regulatory reform

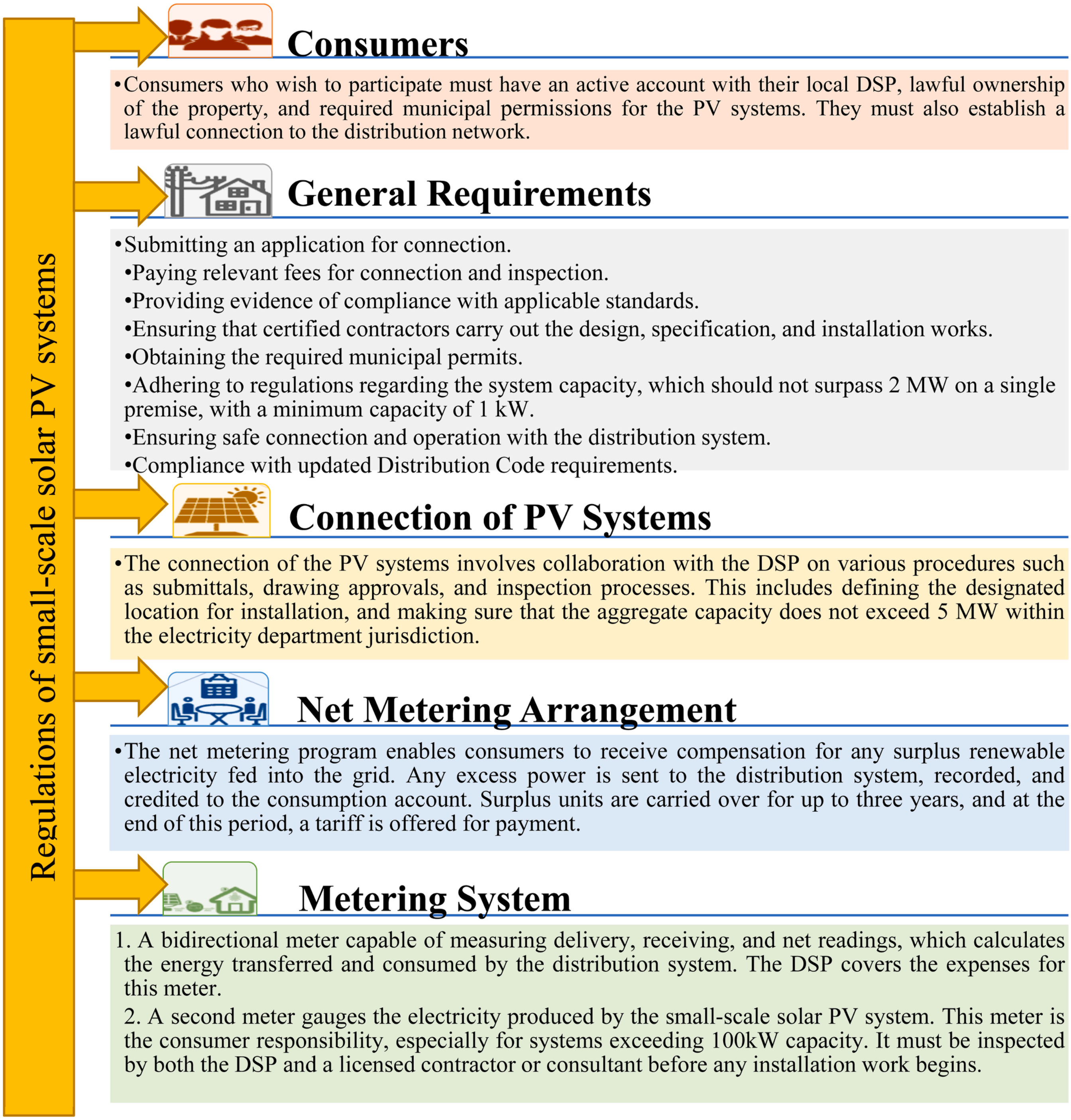

Fig. 15. Roadmap for net metering program for small-scale solar PV systems.

mix. The GIS results point towards a vast potential for solar energy generation. Across the Iraqi territories, the projections for the solar roof PV system capacities ranging from 10 TWh to 40 TWh by 2035 show promising outcomes. It clear that as the capacity increases, the percentage of energy generation also rises, indicating a linear relationship between capacity and energy generation. Furthermore, the involvement in the net metering program for small-scale solar PV systems offers a practical approach to incentivizing solar energy use among individual consumers and businesses. This program, which credits consumers for surplus renewable energy fed back into the grid, creates a sustainable, cost-effective solution for managing energy consumption. It encourages solar PV adoption by offsetting costs and making renewable energy a more economically viable option. Additionally, the study also highlights the significance of a rooftop solar PV system. This relatively simple and cost-effective method of harnessing solar energy can contribute significantly to the country renewable energy portfolio. By adopting a rooftop solar system, households, businesses, and industries can reduce their carbon footprints, promote energy independence, and enjoy economic benefits from reduced electricity bills.

The progression towards a sustainable future in Iraq hinges on the efficient implementation and scaling up of solar PV energy. While the potential is vast, harnessing it effectively requires concerted efforts from government agencies, private sectors, and consumers. The renewable energy policy frameworks need to be robust and should encourage the adoption of solar PV systems, creating a conducive environment for renewable energy investments. The net metering program and the implementation of solar rooftop systems across the Iraqi territories are steps in the right direction, serving as catalysts for change in this crucial journey towards sustainability. As Iraq moves towards 2035, these initiatives could fundamentally alter its energy landscape, providing a model for other countries in the region with similar solar potential. In this light, the path to sustainable energy in Iraq is not just a possibility but an achievable reality.

6. Future prospects and recommendations

Potential for growth: Iraq possesses immense potential for solar PV energy growth due to its abundant solar irradiance. The country geographical location allows for year-round exposure to sunlight, making solar PV a reliable and sustainable energy source. With strategic planning and investment, solar PV has the potential to become a major contributor to Iraq energy mix. By leveraging its solar resources, Iraq can significantly reduce its dependence on fossil fuels, enhance energy security, and mitigate greenhouse gas emissions.

Recommendations:

- **Enhance policy and regulatory framework:** policymakers should develop a comprehensive and stable policy framework that provides clear guidelines, incentives, and long-term security for solar PV projects [63]. This includes setting ambitious renewable energy targets, offering attractive feed-in tariffs, implementing renewable portfolio standards, and streamlining permitting processes.
- **Invest in infrastructure and grid integration:** the government should prioritize investments in grid infrastructure and modernization to accommodate large-scale solar PV projects. Integrating energy storage solutions and smart grid technologies will enhance grid stability and enable effective management of intermittent solar power [64,65].
- **Facilitate financing and investment:** policymakers should work to attract private investments in solar PV projects by offering financial incentives, tax breaks, and access to low-cost financing. Public-private partnerships can be encouraged to leverage expertise and resources from both sectors [66].
- **Support research and development:** investing in R&D for solar PV technology can drive innovation, improve efficiency, and reduce costs [67]. Collaboration with research institutions and international partners can accelerate technological advancements in the sector.
- **Promote local manufacturing and job creation:** encouraging local manufacturing of solar PV components can create jobs and reduce dependency on imports [68]. The government can provide incentives for domestic manufacturing and support skill development in the renewable energy sector [69].

Community engagement: community involvement is essential to promote solar PV awareness and acceptance in Iraq. Engaging local communities through educational programs, public forums, and participatory planning will build trust and understanding of the benefits of solar energy. Incentivizing community-based solar projects can empower citizens and foster a sense of ownership in the transition to clean energy [70,71].

Long-term vision: Iraq long-term vision for a sustainable energy future should prioritize renewable energy, with solar PV playing a pivotal role. By 2030, Iraq should aim to have a substantial share of its energy mix sourced from solar PV, gradually increasing this share over time. By 2050, the country can envision a predominantly renewable energy-based economy, with solar PV as a major contributor to meet the energy needs of industries, residential areas, and infrastructure [72,73].

The vision should include strategies to achieve energy efficiency, energy storage advancements, and the integration of other renewable sources such as wind and hydro. Iraq sustainable energy future should also focus on energy equity, ensuring access to clean and affordable energy for all its citizens. By embracing solar PV as a key component of it is energy transition, Iraq can pave the way towards a greener, more resilient, and prosperous future for its people and the planet.

CRediT authorship contribution statement

Qusay Hassan: Conceptualization, Methodology, Software, Supervision, Project administration. **Sameer Algburi:** Formal analysis, Investigation, Data curation. **Marek Jaszczur:** Software, Data curation, Writing – review & editing. **Maha Barakat:** Writing – original draft, Writing – review & editing. **Aws Zuhair Sameen:** Investigation, Visualization. **Bashar Mahmood Ali:** Validation, Investigation, Visualization. **Dunya Jameel Kassid:** Methodology, Writing – original draft.

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

No data was used for the research described in the article.

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Qusay Hassan: is a Prof. Dr. in energy engineering from University of Stuttgart-Germany, and Postdoc in energy from University of Calgary-Canada. Currently is an esteemed researcher and academic affiliated with the Department of Mechanical Engineering at the University of Diyala in Diyala, Iraq. With a profound interest in energy systems and sustainable technologies, Dr. Hassan work focuses on bridging innovative solutions with practical applications to address pressing energy challenges. His-contributions have been recognized for their potential to shape the future of energy transitions in Iraq and beyond.

Sameer Algburi: is a Prof. Dr. dedicated scholar and educator within the College of Engineering at Al-Kitab University, located in Kirkuk, Iraq. Sameer expertise lies in engineering principles and advancements, particularly in the context of energy management

and conservation. Through his research endeavors, he strives to establish a foundation for holistic approaches to energy utilization, catering to the needs of both present and future generations.

Marek Jaszczur: is a Prof. Dr. a prominent academic within the Faculty of Energy and Fuels at AGH University of Science and Technology in Krakow, Poland. With a global perspective, Marek work extends beyond national borders, aiming to foster international collaboration for sustainable energy advancements. His-research contributions have a far-reaching impact, resonating with the pursuit of cleaner and more efficient energy solutions worldwide.

Dr. Maha Barakat: based at the Business Administration Department, Al-Turath University College, Baghdad, Iraq, holds a Ph.D. in Business Administration. Her research interests lie in organizational behavior, strategic management, and entrepreneurship. Dr. Barakat is known for her innovative teaching methodologies and her contributions to the understanding of business dynamics in emerging markets.

Dr. Aws Zuhair Sameen: As a faculty member at the College of Medical Techniques, Al-Farahidi University, Baghdad, Iraq, Dr. Aws Zuhair Sameen brings a Ph.D. in Health Sciences to his role. His-research primarily focuses on medical technologies, healthcare management, and public health policies. Dr. Sameen's work aims to bridge the gap between medical research and clinical practice, enhancing healthcare outcomes.

Dr. Bashar Mahmood Ali: is a prominent figure in the Department of Construction Engineering and Project Management at Al-Noor University College, Nineveh, Iraq. With a Ph.D. in Construction Management, his research encompasses sustainable construction practices, project management strategies, and the integration of technology in the construction industry. Dr. Ali is an advocate for sustainable development and innovation in construction.

Dr. Dunya Jameel Kassid: is affiliated with Mazaya University College, Iraq, where she contributes her expertise in the field of Environmental Science, holding a Ph.D. in the subject. Her research is centered on environmental pollution control, waste management, and the development of sustainable environmental practices. Dr. Kassid is dedicated to promoting environmental awareness and sustainable practices through her academic and community engagements.