International Journal of Engineering & Applied Sciences (IJEAS)
Vol.16, Issue 4 (2024) 179-194
http://dx.doi.org/10.24107/ijeas.1564584
Int J Eng Appl Sci 16(4) (2024) 179-194

Investigating Solar Energy Potential in Afghanistan under Certain Climatic and Geometrical Parameters of Cities and Buildings

Edris Naseri [a], Burcin Deda Altan [b], Afsin Gungor [c]*

[a] *Department of Mechanical Engineering, Institute of Natural and Applied Sciences, Akdeniz University, Antalya, Turkey*
[b,c] *Department of Mechanical Engineering, Faculty of Engineering, Akdeniz University, Antalya, Turkey*

: naseri6341@gmail.com [a*], bdeda@akdeniz.edu.tr [b], afsingungor@akdeniz.edu.tr [c], *: 0009-0001-4121-3665[a*], 0000-0001-6834-9215[b], 0000-0002-4245-7741 [c]*

Received: 10.10.2024, Revised: 3.12.2024, Accepted: 6.12.2024

Abstract

Afghanistan faces significant challenges in meeting its growing energy demands, with the building sector consuming a substantial portion of its energy supply. The country increasingly turns to solar energy as a clean and sustainable alternative to address these challenges. While previous studies have explored solar energy potential in Afghanistan, there is a lack of comprehensive research focusing on building sector applications and the interplay of climatic and geometrical factors. This study aims to assess the potential of solar energy for the building sector in Afghanistan by examining the influence of climatic and geometrical factors. A systematic literature review was conducted to identify existing research and data on solar energy resources, building characteristics, and energy consumption patterns. The findings reveal that Afghanistan possesses substantial solar energy potential, particularly in the southwest and west regions. Building orientation, insulation, and shading are identified as crucial factors influencing solar energy performance. By exploring the suitability of various solar technologies, including solar photovoltaic, solar thermal, and solar lighting systems, this research contributes to the knowledge base on solar energy in Afghanistan. It provides insights for policymakers and practitioners seeking to promote sustainable building practices.

Keywords: Afghanistan, solar asset, building energy, solar energy, geometrical parameters.

1. Introduction

Afghanistan (AFG) is facing a profound energy crisis, characterized by a persistent energy deficit, unreliable electricity supply, and a rapidly increasing demand for energy, particularly in the building sector. The country's heavy reliance on imported electricity and fossil fuels, coupled with a rapidly expanding population, has exacerbated these challenges. The lack of access to reliable electricity hinders economic growth, social development, and quality of life. Solar energy (SE), with its abundant availability and minimal environmental impact, offers a sustainable and viable solution to Afghanistan's energy challenges. Harnessing solar power has the potential to reduce the country's reliance on fossil fuels, mitigate greenhouse gas emissions, and enhance energy security. However, the full potential of solar energy in Afghanistan has yet to be realized, particularly in the building sector.

Access to power energy is the top priority for Afghan homes and businesses after security. During 2005–2012, energy consumption grew at more than double the pace of economic growth. Conversely, Afghanistan has one of the lowest per capita energy consumption rates in the world and is a net energy importer. More than 80% of the country's overall power supply comes from neighboring nations, with the balance coming from hydroelectric and thermal power plants. Afghanistan's energy security is still hampered by a lack of local power generation. Afghanistan is a geography that has hot summers and chilly winters, the country's climate is marked by intense solar radiation and long hours of sunlight [1].

Solar energy is extensively considered to be a sustainable and easily available energy source in the building sector. According to a United Nations report, 55% of the world's population resides in downtowns, as they consume a large amount of energy and generate enormous global carbon emissions simultaneously. In particular, urbanization shifts gradually in the residence of the human population from rural to urban areas, and that is expected to increase to 68% by 2050 [2]. Air pollution in the building sector is a significant worldwide concern in developed and developing countries. The swelling of the urban population density in cities, pollution emissions increase, and air pollution aggravates that effect on the environment and human health[3]. Hence, air quality in cities should be considered urgently, and factors that can exacerbate air pollution sources should be controlled to improve national health levels. This leads to the need to use solar energy to reduce the effects of fossil fuel consumption and improve the quality of life of society [4].

Buildings are the main component in the fabric of cities. Also, the building and construction sector is one of the most significant areas of intervention, providing opportunities to limit environmental impacts and help achieve sustainable development goals. It has been estimated that the building sector comprises one-third of energy-related greenhouse gas (GHG) emissions [5] and these factors combine to make the building sector one of the largest energy consumers in the world [6]. Moreover, solar energy brings several benefits both economically and environmentally because it preserves the ecosystem [7]. As a result, solar energy might be considered a viable alternative source of sustainable energy in the construction industry. The number of solar concentrating systems for building integration has expanded dramatically in recent years, as these systems are more efficient in terms of space consumption than typical flat modules [8]. Significant growth can be expected in building energy consumption, which includes electrical power, heating, and cooling, etc.

Afghanistan's energy sector has notable obstacles, such as a major dependence on imports, a rapid increase in energy consumption, and a significant demand for energy in the building sector [9]. Although the country possesses vast solar resources [10], it has not fully used this potential to meet its energy requirements [11]. This study aims to examine the feasibility of incorporating solar energy into the building sector in Afghanistan by studying how climatic and geometric elements interact.

Although previous research investigated Afghanistan's overall capacity for solar energy, there is a lack of thorough knowledge regarding its specific use in the construction industry. This review aims to fill this gap by analyzing the current collection of information on solar energy resources, building attributes, and energy usage patterns in Afghanistan. This research enhances the development of sustainable and resilient building practices in the country by identifying the most appropriate solar technologies and investigating their integration into the building structure. This study concentrates on the application of solar energy in the building sector of Afghanistan, going beyond earlier research that has only investigated the general possibilities of solar energy. This review seeks to comprehensively examine the viability of various solar technologies for different building typologies in Afghanistan by examining climatic and geometrical parameters.

This paper is structured as follows: Section 3 provides a comprehensive overview of AFG's climatic and geographical conditions, and essential factors influencing SE potential. Section 4 explores global energy trends to provide a broader context for AFG's energy challenges. Section 5 delves into the country's energy demand, with a particular focus on the building sector.

Building characteristics and the potential integration of SE systems are analyzed in Section 6. Section 7 provides a forum for discussion, analyzing critically how well SE works to address the issues of AFG's energy challenges. Finally, Section 8 summarizes the findings, and outlines potential avenues for future research.

2. Methodology

This review employed a systematic literature review approach to investigate the potential of SE in AFG's building sector. The following steps were undertaken:

Literature Search
A comprehensive literature search was conducted using Google Scholar, Scopus, and Web of Science. Keywords such as "Afghanistan," "solar energy," "building," "climatic factors," and "geometrical parameters" were used to identify relevant studies. The search was limited to peer-reviewed articles published in English and the local language.

Inclusion and Exclusion Criteria
Studies were included if they:

- Focused on SE in AFG.
- Addressed the building sector and its energy needs.
- Provided quantitative or qualitative data on SE potential, climatic conditions, or building characteristics.

Studies were excluded if they:

- Lacked sufficient methodological rigor or data.
- Were primarily opinion-based or anecdotal.

Data Extraction
Relevant data, including author(s), publication year, journal, study design, methodology, key findings, and conclusions, were extracted from the selected studies using a standardized data extraction form.

Data Analysis
A qualitative thematic analysis was conducted to identify key themes and patterns in the literature. Quantitative data, where available, was analyzed using descriptive statistics and statistical software.

Limitations
The limitations of this review must be acknowledged. This may have affected the depth of study because there is a dearth of detailed data on SE in AFG. Also, it's possible that pertinent studies written in other languages were overlooked due to the concentration on English and regional publishing. Taking into account the impact of geometrical and climatic factors, this review attempts to offer a thorough and perceptive summary of the SE potential in AFG's building industry by employing a methodical methodology.

3. The Geography and Climate of Afghanistan

AFG is located in Central Asia [12], and it is a landlocked and mountainous country [1, 13]. The geography of AFG includes irrigation areas, small but fertile river valleys, deep gorges, deserts, highlands, and snow-capped mountains. The eastern part of the country is divided by the towering Hindu Kush and Pamir mountains which rise to around 7500 meters [14]. The land of AFG is very different and by crossing the lower central mountains, to the high mountains in the northeast, it is going from the deserts of the Kandahar region in the West to the Turkestan plains in the North [13]. About 73% of AFG is savannah, shrubbery and meadow, while 15% is snow and ice alongside sparse or barren vegetation [15].

The performance of solar systems depends on local climatic conditions. The climate in AFG, however, varies significantly across provinces. Most parts of the country have an arid or semiarid continental climate and the variance in terrain and elevation results in different climatic types [1]. AFG with hot summers and cold winters has although high air turbidity. In the summertime, the high temperature frequently exceeds 38°C in the Southwest region, while wintertime lows can reach below -25°C [16]. Elevations and air turbidity suggest high renewable resources [17].

4. Global Energy Scenarios

The global energy landscape is undergoing significant transformation, driven by factors such as population growth, economic development, and climate change. While renewable energy (RE) sources, particularly solar and wind, are gaining prominence, fossil fuels continue to dominate the global energy mix. The latest reports in the energy sector mark a major change in the energy sector in the coming decades. For instance, the Government of India reports that more than 99 % of the population has access to electricity, and useful and operative policies are being implemented in some countries in Africa. Also, the assessments show that about 2.6 billion people did not have access to clean cooking and 770 million people did not have connected to electricity in 2019 [18].

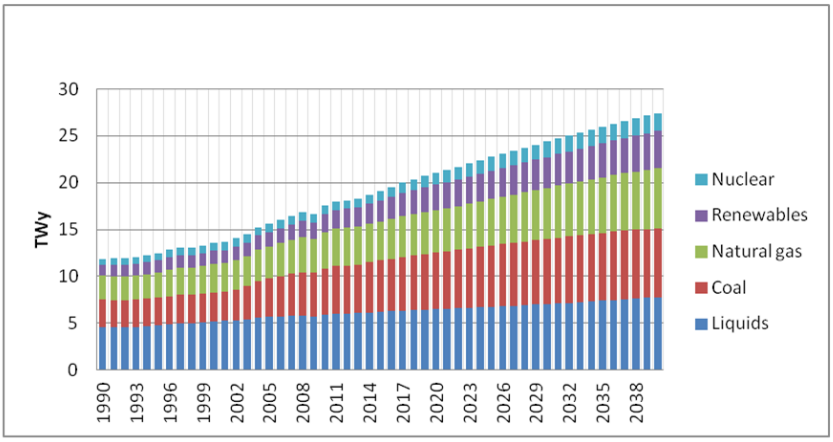

Fig. 1. EIA World energy consumption projection by fuel type

The increase in energy demand is proportional to population growth [19] as a result the global primary energy consumption increased from 270.5 EJ in 1978 to 580 EJ in 2018, more than doubled. In the past 40 years, fossil fuels mostly covered the total world energy consumption and the contribution of fossil fuels was 7 % less in 2018 than in 1978 [20]. Globally, as indicated in Fig. 1, by 2040 renewables still provide less than 5 % of the global energy demand. Fossil fuels (coal, oil, and natural gas) continue to dominate [21].

The global energy transition offers both challenges and opportunities in AFG. The country's energy demand is rapidly increasing, driven by population growth and economic development. However, AFG faces significant challenges in meeting this growing demand, including a lack of infrastructure, political instability, and a reliance on imported electricity and fossil fuels.

By leveraging its abundant solar resources, AFG can reduce its dependence on fossil fuels, improve energy security, and contribute to global efforts to mitigate climate change. Integrating SE into the country's energy mix can provide a sustainable and cost-effective solution to its energy challenges.

5. Energy Demand in Afghanistan

Access to safe energy resources in AFG has been virtually disrupted due to three decades of wars [2]. Most of the electricity generation, transmission, and distribution infrastructure was destroyed and the remaining facilities were very, very small [22]. In 2001, less than 5 % of the country's population had access to electricity, while in 2015 the figure rose to 30 % [23]. AFG has one of the lowest electricity consumption in the world, consuming 119.8 kWh per capita [12].

Recently, the development of electricity capacity in AFG has depended on imports of energy from neighboring countries. In 2011, about 80 % of the country's total electricity was imported from Uzbekistan [22]. In 2015, the capacity of electricity generation inside AFG was about 1000 gigawatts/hour (GWh), which was 22 percent of the total electricity consumption[23]. Hence, in the Power Sector Master Plan of the government, electricity consumption is considered to grow at the rate of 8.7 % per year through 2032 [24].

There are enough fossil fuels and RE in AFG. About 80 million barrels of oil reserves, 75 billion cubic meters of natural gas, 440 billion cubic meters of unspecified natural gas, and 73 million tons of coal reserves have been identified [23]. However, energy production from renewable sources is estimated at 318 GW [25], which is why the largest share of AFG's energy generation is expected to come from RE sources. The enormous wind power potential in AFG can help the South Asian region take a big step forward in meeting its energy needs [12].

Mohammad, Shrestha [26] calculated the urban residential energy use in Kandahar, AFG. This study is based on a survey conducted in the third quarter of 2011 in 10 districts of Kandahar city. Analysis shows that around 72 % of total residential energy is used for cooking, and firewood is still the main form of energy, with a share of around 58 %. The amount of energy consumed in the housing sector has a major share in the total energy consumed in the cities of AFG.

6. Buildings & Solar Energy Systems

The buildings and buildings construction sectors combined are considered as the main driver of energy consumption and GHG emissions in the world. Buildings consume about 40 % of global energy, and the world's total energy demand in residential areas reached 86.8 EJ in 2010 [27]. The share of energy consumption by residential sectors in AFG accounts for 54 % of total consumption [26], and the consumption varies significantly across provinces. Electric grid accessibility and residential facilities affect annual consumption and it ranges from a low value of 178 kWh/household in Ghor and 551 kWh/household in Laghman, to a higher value in urban centers such as Kabul 3,000 kWh/ household and Herat 2,600 kWh per household [28]. Hence, in the Power Sector Master Plan of the government, annual electricity consumption is considered to be 1500 KWh/household through 2032 [28].

Solar radiation is considered to be a primary source of energy for many human activities [29]. The application of SE in buildings discusses the successful utilization of the Sun’s energy in the building industry and related fields [30]. In AFG, the main uses of SE in buildings are solar water heaters, solar cookers, solar pumps, and photovoltaic PV systems. Interestingly, with the inadequacy of local electricity grids and rapidly rising electricity prices, the utilization of SE in the building industry is accelerating. This is due to its potential availability and safe use for small and large scales by residential and commercial buildings (Fig. 2.).

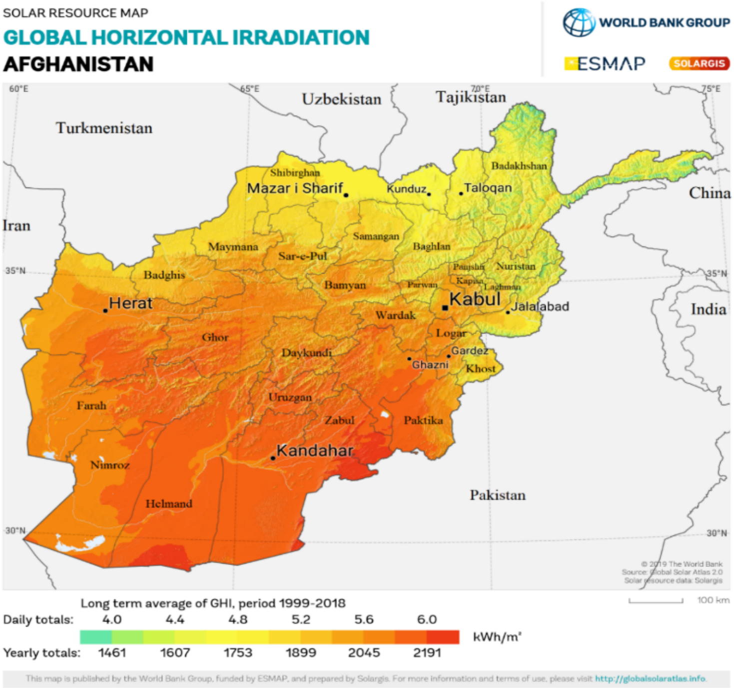

Fig. 2. Horizontal Irradiation, AFG [47]

6.1. Solar Assets

The intensity of SE is approximately 1370 W/m^{2}outside of the earth's atmosphere. The amount of incoming solar radiation or insolation that AFG receives is primarily a function of its latitude and most of AFG lies between a latitude of 29 and 38 degrees north [16]. AFG occurs in the subtropical and arid regions of southwest Asia [1]. In summer the northern hemisphere is tilted towards the sun and the periods of daylight are longer. This leads to high temperatures across the country where the maximum daily temperature is above 38°C. Differences in temperatures occur in winter when the sun sinks to the horizon and the length of the day shortens. As a result, the country acquires a relatively high degree of solar radiation in summer and a low degree of solar radiation in winter [16].

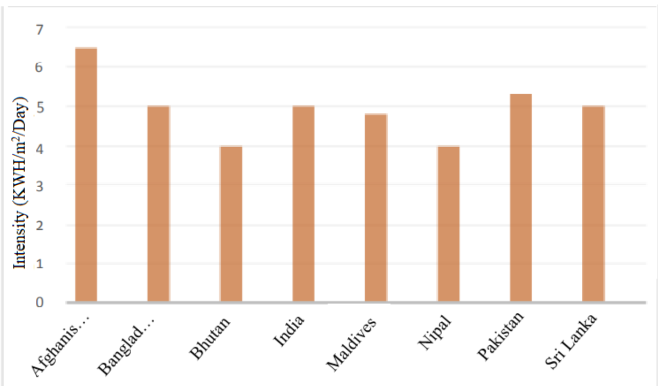

Fig. 3. Average Solar Power Potential of South Asian Countries [31]

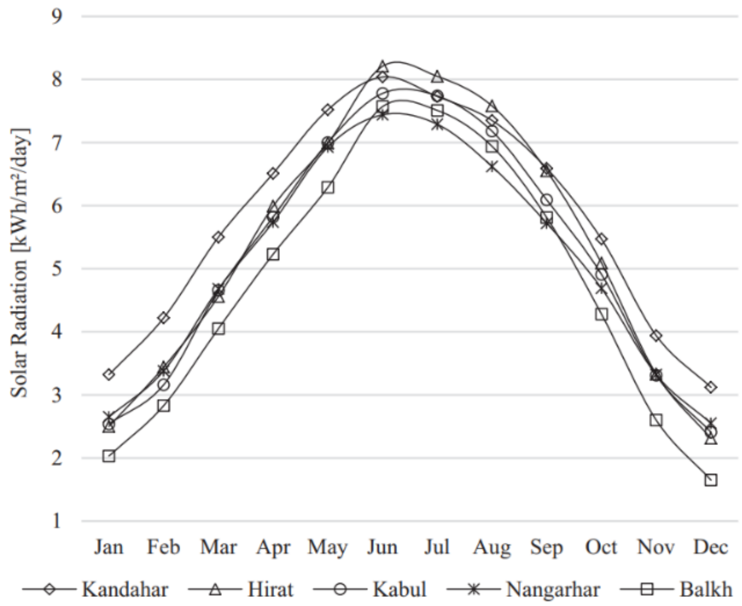

Fig. 4. Monthly GHI of major cities in AFG [34]

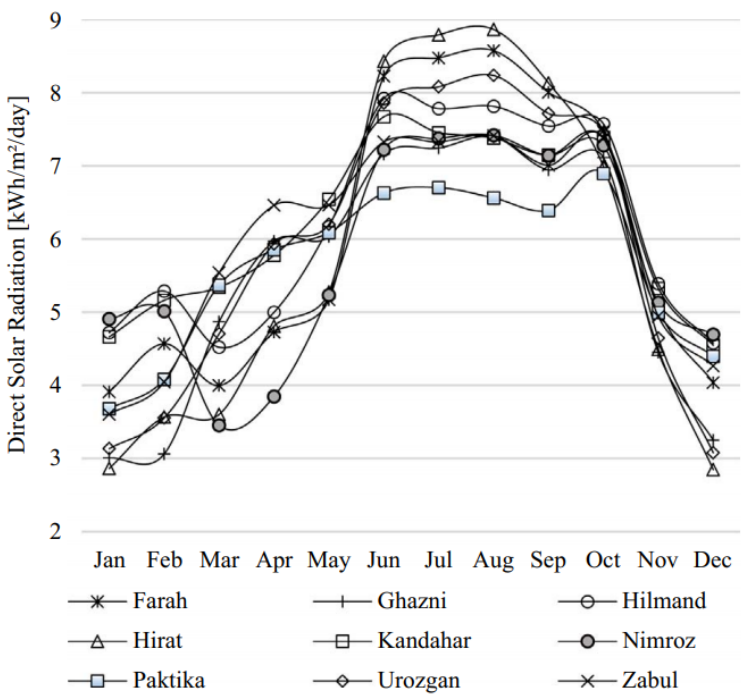

Fig. 5. DNI of CSP areas in AFG [34]

AFG with hot summers and cold winters has although high air turbidity and the climate of the country is characterized by strong solar radiation and huge sunshine hours (more than 3000 hours annually) [1] and more than 300 sunny days per year. Fig. 3 shows the average solar power potential of South Asian Countries [31]. As result, the average solar potential Global Horizontal Irradiance (GHI) is estimated at 6.5 kWh per m^2 per day [12]. Hence, the energy production from SE is 220 gigawatts [23] and the government aims to produce 5,000 megawatts of RE by 2032, which corresponds to 95 % of the country's electricity demand [32].

The U.S. National Renewable Energy Laboratory (NREL) has recently produced high-resolution satellite-derived SE resource maps and related data products for AFG, and the data was included in a geospatial toolkit. Users can manipulate the resource information along with country-specific geospatial information and then transfer resource data for specific locations [33]. NREL produced datasets in a gridded format and with a ground resolution of 0.1° latitude and 0.1° longitude (8.5 km × 10 km). Irradiance datasets include monthly averages over three years from 2002 to 2005 [24]. NREL provided data for different provinces of AFG that have been analyzed and compared with meteorological measurements at each site as shown in Fig. 4 & Fig. 5.

6.2. Solar Potential in the Building

The life of the people of AFG, in terms of important geographical location, has been influenced by the cultures and arts of different ethnic groups, and this impact has been accompanied by observation and understanding of aesthetics, including the art of architecture. This is seen in the architecture of cities, mosques, houses, and other buildings.

The estimation of surface solar irradiation is very important for many different solar applications. Thousands of domed houses and monuments are located in the cities and villages of AFG, each of which has its value and importance, and archaeologists consider it a valuable treasure of antiquities and historical monuments. Faghih and Bahadori [35] analyzed the solar radiation on domed roofs. Four domed roofs received and absorbed solar radiation at the same rate as a flat roof, and the roofs all had the same base area. As a result, domed roofs received far more solar radiation than flat roofs.

Urban morphology is the analysis of the abstract form of the existing reality [36]. Taking into account the optimal combination of morphological parameters, the solar radiation of ceilings and facades can increase by 9 % and 45 % respectively [37]. Poon, Kämpf [38] performed a parametric study of URBAN morphology on building SE potential in the Singapore context. The researchers discovered a link between urban morphology and yearly average irradiance on rooftops and façades. They considered two multilinear regression predictive models for rooftop and façade and 10 morphology in parameters to compare the correlation performance of building irradiance with the two definitions of the Sky View Factor (SVF). The analysis shows that the correlation performance of the two SVF definitions is the strongest ($r = 0.94$ to 1), while R2 for the rooftop irradiance model (R2 = 0.61) and other individual parameters (R2 = 0 to 0.36).

Li, Ding [39] estimated the SE potential on building roofs. This study considers several flat-roofed buildings in the town planning of Xiuyuan eco-city as a study area for measuring solar potential on the roofs of buildings. This study was conducted with a pixel-based methodology. The solar radiation in a given cell is mathematically formulated in pixels, and its yields over a given period are immediately calculated by taking into account a few solar irradiances and presented by visual image processing. Analysis shows that the maximum and minimum annual radiation yields are 4717.72 MJ/m^2 and 342.58 MJ/m^2 respectively. Hence, 20 % of the roof areas of each building can obtain 4500 MJ/m^2/year or more solar radiation.

Kanters and Horvat [40] demonstrated the exploration of geometric shapes of urban blocks and the potential of SE for local energy production. They performed the Simulations with the Ecotect program for the city of Lund, in southern Sweden. This study showed that the impact of the geometric shape on the SE potential can be up to twice and some shapes are less sensitive to different orientations. In dense cities, when buildings are surrounded by another geometry, the share of SE decreases by 10 to 75 %.

6.3. Utilization of Solar Energy in Buildings

The concept of harnessing the power of the sun was common practice even thousands of years before the era of solar panels. Although SE plays a dynamic and fundamental role in today's power potential, the use of SE for water heating, light fires, sunrooms, and drying crops has had a tradition in the past, so there is a long history behind PV that embodies the concept of SE. Solar panels provide clean energy [4]. There are no harmful GHG emissions in the process of PV energy production, therefore solar PV energy is environmentally friendly [7].

There are many applications of SE such as light-gathering, SE photo-thermal, and PV utilization which is cost-effective, particularly for the AFG building industry. Yang, He [41] analyzed the application of solar technologies in building energy efficiency. Meanwhile, they showed that photo-thermal technology is suitable for solar-powered residential buildings in comparison with the light-gathering utilization, and PV utilization in terms of technology and current economy.

6.3.1 Solar thermal utilization

Concentrating solar thermal technologies collect and concentrate solar radiation to convert it into thermal energy at high temperatures as shown in Fig. 7. [42]. This thermal energy is then transmitted via a transport medium or moving fluid for domestic use. In AFG, the building sector uses local coal, fuel wood, and liquefied petroleum gas (LPG) as part of its energy mix. AFG's energy production and supply are highly volatile, as is the country's reliance on imported petroleum products. Therefore, concentrating solar thermal technologies can be efficient for a wide variety of AFG building sector applications, including heating and cooling, process heating, and power generation.

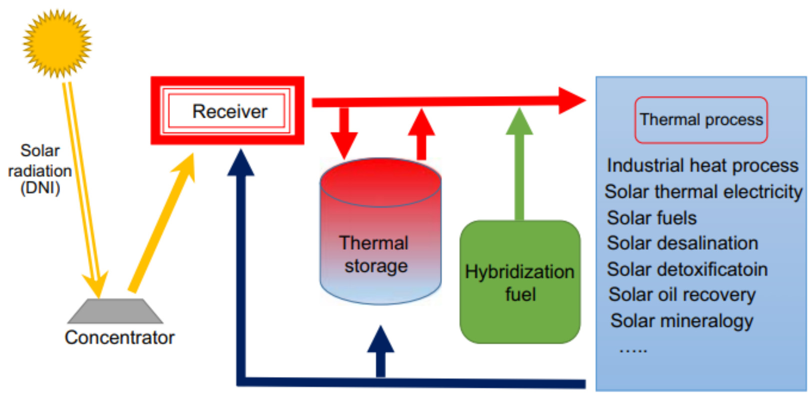

Fig. 6. General scheme of a concentrating solar thermal system [42]

With a payback period of 7-11 years on average, solar thermal panels appear to be less costly than solar PV systems. Hakimi et al. [43] carried out a thermo-economic analysis to compare the performance of a PV, Central Tower Receiver (CTR) plant, and a Parabolic Trough Collector (PTC) plant with and without storage for the Herat, AFG. Through the Typical Meteorological Year (TMY) data generated by Meteonorm software, this analysis shows that the PTC plant with energy storage has the highest efficiency of about 43 % which is approximately 50 % more than the PV plant but the PV plant has more uniform power production profile. PTC with energy storage displays 25 % more power output than PTC without energy storage. The Leveled Cost of Electricity is 0.146 $/kWh for the CTR plant, 0.063 $/kWh for the PV plant, 0.1076 $/kWh for the PTC plant with energy storage, and 0.104 $/kWh for the PTC plant without storage.

6.3.2 Solar light- gathering

The most basic method of SE utilization is light-gathering. The solar radiation is converged by a mirrored surface with high specular reflection to provide concentrated light from the sun into the receiving surface. A solar cooker is a device that uses solar radiation to cook and heat food, which is a good example of light-gathering utilization [44]. The rural population of AFG is almost entirely reliant on biomass fuels for cooking and heating, resulting in air pollution. More than two-thirds of the population lives in rural areas, where traditional fuels are used and power is scarce. As a result, light-gathering can be used effectively in a wide range of building applications in AFG's rural areas.

6.3.3 Solar photovoltaic

Photovoltaic is the most convenient way to use SE by converting it directly into electricity. Solar power is typically produced in a building using concentrating photovoltaic (CPV) systems and conventional flat-panel devices. CPV systems have many advantages over traditional flat-panel devices in buildings [8]. These systems, in comparison to conventional flat modules, allow for a more compact use of space, with facades and roofs in buildings, which are the program's target areas [45]. Furthermore, CPV aims to reduce the cost of PV by using less expensive concentrator materials rather than expensive solar cell materials [46]. In AFG, the energy sector is one of the least developed, with nearly 70 % of the country's population lacking access to electricity [32]. Energy has always been one of the most basic human needs, and now it is one of the Afghan people's most pressing and fundamental issues. Even in large cities of AFG, the government has not been able to take sufficient steps to address or reduce the issue of electricity. Therefore, CPV systems are a viable option for addressing AFG's electricity shortage.

7. Discussion

There is a big chance for SE integration in AFG's building sector. The country's abundant solar resources and rapidly increasing energy consumption strengthen the argument for utilizing SE to address the country's energy issues. Despite the immense potential, successful implementation requires careful consideration of a few factors.

The Table 1. provides an overview of the critical points discussed regarding SE utilization in Afghan buildings, highlighting energy consumption patterns, solar potential, and the effectiveness of different solar technologies. A building's attributes largely determine its SE potential. The analysis of urban morphology and building orientation highlights the importance of optimizing building design for SE capture. The domed roofs of traditional Afghan architecture make for an intriguing case study when examining the possibilities of atypical building forms for SE collection. More investigation is necessary to calculate the energy savings from such architectural features.

Table 1. Energy consumption patterns, solar potential, and the effectiveness of solar technologies

Parameter	Value/Insight
Energy Consumption in Buildings (AFG Residential)	54 % of total energy consumption in AFG; annual consumption ranges from 178 kWh/household (Ghor) to 3,000 kWh/household (Kabul)
Average Solar Potential (GHI)	6.5 kWh/m²/day
Solar Radiation Hours	Over 3,000 hours of sunshine annually; more than 300 sunny days per year
Estimated SE Production	220 gigawatts
Government Target for RE	5,000 MW by 2032 (95 % of national electricity demand)
Solar Assets (Global Solar Intensity)	1370 W/m² outside of Earth's atmosphere; high solar radiation with an average of 6.5 kWh/m²/day
Urban Morphology's Impact on SE	Ceilings and facades can increase solar radiation capture by 9 % to 45 % based on optimal morphology; reductions in SE due to dense urban environments
Solar Radiation on Domed Roofs	Domed roofs receive more solar radiation compared to flat roofs.
Flat Roof Solar Potential	Maximum annual radiation: 4717.72 MJ/m²; Minimum annual radiation: 342.58 MJ/m²
Solar Thermal Technologies in Buildings	Efficient for heating, cooling, and power generation; PTC plants with energy storage have 43 % efficiency and a leveled cost of $0.1076/kWh
Solar Light-Gathering in Rural Areas	Effective for rural cooking/heating needs, especially in areas lacking access to electricity
CPV Systems for Electricity in Buildings	Suitable for addressing AFG's electricity shortage; compact for urban rooftops and facades; cost-effective alternative to traditional PV systems

AFG's diverse climate presents both challenges and opportunities for SE utilization. While the country experiences high solar radiation during the summer months, the winter months can be characterized by lower solar irradiance and increased cloud cover. To mitigate these seasonal variations, it is important to optimize the design and operation of SE systems. For instance, high-efficiency solar panels and advanced inverter technologies can help maximize energy output during periods of low solar radiation. Additionally, incorporating energy storage solutions, such as batteries or thermal storage, can help ensure a reliable and consistent power supply. Selecting the right SE technology is essential for maximizing production and lowering expenses. Although solar thermal systems are more economical, concentrated solar power (CSP) technologies have the potential to produce energy with greater yields. PV systems can offer a hybrid solution to satisfy various energy needs, especially when combined with CSP. Technical improvements and economic factors will influence the best technology option for various building types and locations in AFG.

To fully realize the potential of SE in AFG's building sector, a supportive policy and regulatory framework is important. Implementing feed-in tariffs, tax incentives, and accelerated depreciation can encourage private investment and reduce upfront costs for solar installations. Streamlining permitting procedures and providing technical assistance can facilitate the integration of SE into buildings. Additionally, long-term support for research and development is essential to improve the efficiency and reduce the cost of solar technologies. By adopting these policy measures, AFG can create a conducive environment for SE adoption and accelerate the transition to a sustainable energy future.

Even though this study offers insightful information about the potential of SE in AFG's building industry, more investigation is required to fully address certain opportunities and challenges. It is imperative to do a thorough examination of the financial viability of various SE solutions, taking into account variables like installation charges, ongoing maintenance costs, and energy conservation. Investigating the integration of energy storage devices to overcome the intermittent nature of solar power would also enhance the dependability and value proposition of SE solutions.

8. Conclusion

AFG's abundant solar resources offer a significant opportunity to alleviate the country's chronic energy shortages, particularly in the building sector. However, the energy sector faces considerable challenges due to security concerns, infrastructure limitations, and a lack of widespread adoption of RE technologies.

The evaluation of solar radiation across various cities in AFG, as shown in Table 2, identifies Herat as the most promising location for SE exploitation. Herat exhibits the highest summer peak radiation at 8.7 kWh/m²/day and stable winter levels at 4 kWh/m²/day, ensuring consistent year-round energy generation. Kandahar, Farah, and Hilmand also show strong potential, with summer peaks of 8.5 kWh/m²/day and winter levels around 4.0 kWh/m²/day, making them suitable for sustainable energy projects. Nangarhar and Zabul demonstrate good solar potential, with summer peaks of 8.0 kWh/m²/day and steady winter values of 4.0 kWh/m²/day. In contrast, Balkh, Kabul, Ghazni, Urozgan, and Nimroz exhibit moderate suitability due to slightly lower radiation values, with winter radiation levels ranging between 3.0 and 3.5 kWh/m²/day. Paktika, with the lowest radiation levels (6.5 kWh/m²/day in summer and 3.1 kWh/m²/day in winter), is the least favorable location for SE development. These findings highlight the need to prioritize southwestern and western regions with higher solar radiation levels to maximize the efficiency and sustainability of SE systems in AFG. Additionally, climatic and geometrical factors play a crucial role in optimizing SE capture for buildings. By leveraging solar energy, AFG can move toward a more sustainable and energy-independent future.

Integrating SE into building energy systems is essential for AFG's sustainable development. This study emphasizes three forms of SE utilization in buildings, focusing on their functionalities and cost-effectiveness:

- Solar concentrators with thermal performance can reach higher temperatures and are therefore suitable for use in building heating.
- CPV can generate electric energy for buildings while saving PV materials and costs.
- For AFG's rural areas, solar light-gathering can provide more convenient and clean cooking and heating systems.

The findings of this study are relevant to other countries in Central Asia and the Middle East, such as Uzbekistan, Tajikistan, Kazakhstan, Iran, Iraq, Egypt, and Morocco, which share similar geographical, climatic, and socioeconomic conditions. For instance, Uzbekistan, with its arid climate and high solar radiation, faces similar challenges in grid infrastructure and energy security as AFG. By learning from AFG's experiences in SE deployment, Uzbekistan can accelerate its transition to a sustainable energy future. Similarly, countries like Egypt and Morocco, with their ambitious RE targets, can benefit from AFG's insights into policy frameworks and regulatory incentives.

Table 2. Comparative Solar Radiation Evaluation for Cities

City	Summer Peak Radiation (kWh/m²/day)	Winter Radiation (kWh/m²/day)	Year-Round Suitability
Herat	8.7	4	Excellent
Kandahar	8.5	4.3	Excellent
Farah	8.5	4.1	Excellent
Hilmand	8.5	4.2	Excellent
Nangarhar	8	4	Very Good
Zabul	8	4	Very Good
Balkh	7.5	3.5	Good
Kabul	7.5	3	Good
Ghazni	7	3	Moderate
Urozgan	7	3	Moderate
Nimroz	8	3.5	Moderate
Paktika	6.5	3.1	Low

Abbreviations

AFG	Afghanistan
CPV	Concentrating Photovoltaic
CSP	Concentrating Solar Power
CTR	Central Tower Receiver
DNI	Direct Normal Irradiance
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GWh	Giga Watt Hour
kWh	Kilowatt-hour
LPG	liquefied petroleum gas
NREL	National Renewable Energy Laboratory of the US
PTC	Parabolic Trough Collector
PV	Photovoltaic
R	Pearson correlation coefficient
R^2	Squared Pearson Correlation Coefficient
RE	Renewable Energy
SE	Solar Energy
SVF	Sky View Factor
TMY	Typical Meteorological Year

Author Contribution

Edris Naseri: Conceptualization, Methodology, Investigation, Writing and Editing
Burcin Deda Altan: Methodology, Review & Editing
Afsin Gungor: Conceptualization, Review & Editing

References

[1] Shroder, J.F., Natural resources in Afghanistan: geographic and geologic perspectives on centuries of conflict. Elsevier, 2014.

[2] Nations, U., Department of economic and social affairs population dynamics. World Urbanization Prospects, 2018.

[3] Organization, W.H., WHO guidelines for indoor air quality: household fuel combustion. World Health Organization, 2014.

[4] Pearce, J.M., Photovoltaics—a path to sustainable futures. *Futures*, 34(7), 663-674, 2002.

[5] Zhong, X., et al., The evolution and future perspectives of energy intensity in the global building sector 1971-2060. *Journal of Cleaner Production*, 305, 127098, 2021.

[6] Cao, X., X. Dai, and J. Liu, Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and buildings*, 128, 198-213, 2016.

[7] Ouria, M. and H. Sevinc, Evaluation of the potential of solar energy utilization in Famagusta, Cyprus. *Sustainable cities and society*, 37, 189-202, 2018.

[8] Aldegheri, F., et al., Building integrated low concentration solar system for a self-sustainable Mediterranean villa: The Astonyshine house. *Energy and buildings*, 77, 355-363, 2014.

[9] Ludin, G.A., et al., Technical and economic analysis of an HVDC transmission system for renewable energy connection in Afghanistan. *Sustainability*, 14(3), 1468, 2022.

[10] Amarkhail, S., Potential and utilization of renewable energy sources in Afghanistan. *Journal of Engineering Research and Applied Science*, 11(1), 2032-2038, 2022.

[11] Jahangiri, M., et al., Investigating the current state of solar energy use in countries with strong radiation potential in asia using GIS software, a review. *Journal of Solar Energy Research*, 5(3), 477-497, 2020.

[12] Shukla, A.K., K. Sudhakar, and P. Baredar, Renewable energy resources in South Asian countries: Challenges, policy and recommendations. *Resource-Efficient Technologies*, 3(3), 342-346, 2017.

[13] Milbrandt, A. and R. Overend, Assessment of biomass resources in Afghanistan. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2011.

[14] Pulsipher, L.M., et al., World regional geography: global patterns, local lives, New York, NY: W.H. Freeman and Company; 7th edition 2017.

[15] Shroder, J.F. and S.J. Ahmadzai, Transboundary water resources in Afghanistan: Climate change and land-use implications, Elsevier 2016.

[16] Palka, E.J., Afghanistan: A Regional Geography. 2001.

[17] Burns, R.K., Afghanistan: Solar assets, electricity production, and rural energy factors. *Renewable and Sustainable Energy Reviews*, 15(4), 2144-2148, 2011.

[18] Cozzi, L., et al. World Energy Outlook. IEA Paris, 2020.

[19] Bose, B.K. Energy, environment, and advances in power electronics. in ISIE'2000. Proceedings of the 2000 *IEEE International Symposium on Industrial Electronics*. IEEE, 2000.

[20] Kober, T., et al., Global energy perspectives to 2060–WEC's World Energy Scenarios 2019. *Energy Strategy Reviews*, 31, 100523, 2020.

[21] Conti, J.J., et al., Annual energy outlook 2014. US Energy Information Administration, 2014.

[22] Bank, W., Energy Security Trade-Offs Under High Uncertainty: Resolving Afghanistan's Power Sector Development Dilemma. World Bank, 2016.

[23] Aminjonov, F., Afghanistan's energy security. *Tracing Central Asian countries' contribution*, 1-30, 2016.

[24] Ershad, A.M., R.J. Brecha, and K. Hallinan, Analysis of solar photovoltaic and wind power potential in Afghanistan. *Renewable Energy*, 85, 445-453, 2016.

[25] Ahmadzai, S. and A. McKinna, Afghanistan electrical energy and trans-boundary water systems analyses: Challenges and opportunities. *Energy Reports*, 4, 435-469, 2018.

[26] Mohammad, A., P. Shrestha, and S. Kumar, Urban residential energy use in Kandahar, Afghanistan. *Cities*, 32, 135-142, 2013.

[27] Nejat, P., et al., A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). *Renewable and sustainable energy reviews*, 43, 843-862, 2015.

[28] Korkovelos, A., et al., A GIS approach to planning electrification in Afghanistan, 2017.

[29] Martins, F.R., et al., Data generated by evaluating the seasonal variability and trend analysis of the solar energy resource in the Northeastern Brazilian region. *Data in brief*, 26, 104529, 2019.

[30] Sayigh, A., Solar energy application in buildings. *Elsevier*, 2012.

[31] Mohmand, R. and A. Mohan, Potential of Solar Energy in Afghanistan. *Journal of Critical Reviews*, 7(12), 2644-2652, 2020.

[32] Safi, R. and M. Sharma, Energy Scenario of Afghanistan. *Energy*, 9(4), 2019.

[33] Renné, D.S., et al. Solar and wind resource assessments for Afghanistan and Pakistan. *Proceedings of ISES World Congress 2007* (Vol. I–Vol. V). Springer, 2008.

[34] Anwarzai, M.A. and K. Nagasaka, Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. *Renewable and Sustainable Energy Reviews*, 71, 150-160, 2017.

[35] Faghih, A.K. and M.N. Bahadori, Solar radiation on domed roofs. *Energy and Buildings*, 41(11), 1238-1245, 2009.

[36] Çalışkan, O. and S. Marshall, Urban Morphology and Design Introduction, 2011.

[37] Sarralde, J.J., et al., Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London. *Renewable Energy*, 73, 10-17, 2015.

[38] Poon, K.H., et al., Parametric study of URBAN morphology on building solar energy potential in Singapore context. *Urban Climate*, 33, 100624, 2020.

[39] Li, Y., et al., A pixel-based approach to estimation of solar energy potential on building roofs. *Energy and Buildings*, 129, 563-573, 2016.

[40] Kanters, J. and M. Horvat, Solar energy as a design parameter in urban planning. *Energy Procedia*, 30, 1143-1152, 2012.

[41] Yang, L., B.-j. He, and M. Ye, The application of solar technologies in building energy efficiency: BISE design in solar-powered residential buildings. *Technology in Society*, 38, 111-118, 2014.

[42] Blanco, M. and L.R. Santigosa, Advances in concentrating solar thermal research and technology. Woodhead Publishing, 1st edition, 2016.

[43] Hakimi, M., E. Baniasadi, and E. Afshari, Thermo-economic analysis of photovoltaic, central tower receiver and parabolic trough power plants for Herat city in Afghanistan. *Renewable Energy*, 150, 840-853, 2020.

[44] Ahmed, S.M., et al., Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240, 2020.

[45] Marín-Sáez, J., et al., Outdoor performance evaluation of a holographic solar concentrator optimized for building integration. *Applied Energy*, 250, 1073-1084, 2019.

[46] Sellami, N. and T.K. Mallick., Design of nonimaging static solar concentrator for window integrated photovoltaic. *AIP Conference Proceedings*. American Institute of Physics, 2012.

[47] Global Solar Atlas. https://globalsolaratlas.info/global-pv-potential-study.
Accessed 15 April 2024.