energies

Article

Rooftop Solar Photovoltaic in Saudi Arabia to Supply Electricity Demand in Localised Urban Areas: A Study of the City of Abha

Abdullah Shaher [1,2,*], Saad Alqahtani [1,3], Ali Garada [1,4] and Liana Cipcigan [1]

1 School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
2 Electrical Engineering Department, Faculty of Engineering, Najran University, Najran 66241, Saudi Arabia
3 Electrical Engineering Department, Faculty of Engineering, King Khalid University, Abha 61411, Saudi Arabia
4 Centre for Integrated Renewable Energy Generation and Supply, Wales CF10 3AT, UK
* Correspondence: shahera@cardiff.ac.uk; Tel.: +44-7490931159

Abstract: This paper explores the potential of rooftop solar PV to meet the electricity demand in the urban areas of Abha city, Saudi Arabia (KSA), minimising imports from the grid. A localised energy system for Abha is proposed that considers two types of loads: (i) residential loads with a monthly aggregated energy consumption of 172,440 MWh and an electric demand of 239.5 MW, and (ii) commercial loads with a monthly aggregated energy consumption of 179,280 MWh and an electric demand of 249 MW. The grid currently supplies this load. This paper proposes a PV development planning tool for residential and commercial areas to calculate the total PV production for each type of load to achieve a balanced energy area, considering (i) the number of buildings, (ii) the type of load, (iii) the peak load, and (iv) the total PV array area in m^2 per building. The results of the modelling study using real data demonstrate that the anticipated total PV production in residential and commercial areas is sufficient to meet local peak demand, and there is an excess of power that can either be stored locally or exported to the grid.

Keywords: solar energy (PV); rooftop PV; buildings; planning tool; KSA; residential and commercial communities

check for updates

Citation: Shaher, A.; Alqahtani, S.; Garada, A.; Cipcigan, L. Rooftop Solar Photovoltaic in Saudi Arabia to Supply Electricity Demand in Localised Urban Areas: A Study of the City of Abha. *Energies* **2023**, *16*, 4310. https://doi.org/10.3390/en16114310

Academic Editor: Syed Abdul Moiz

Received: 26 January 2023
Revised: 5 May 2023
Accepted: 20 May 2023
Published: 24 May 2023

1. Introduction

1.1. Background

Over the last decade, the Kingdom of Saudi Arabia's (KSA's) electricity consumption has increased by about 7 to 8% per year. The maximum demand for electricity in summer rose significantly by 93% from 2004 to 2013, increasing from 28 GW to 54 GW. In addition, the annual growth of electricity consumption in the KSA was over 6% between 2013 and 2020. According to the King Abdullah Center for Atomic and Renewable Energy [1], the increased demand will necessitate a capacity increase to 120 GW by 2032. This increase in demand in KSA is due to high cooling and heating demand. There are five distinct climate regions in KSA, all with considerable cooling requirements, as illustrated in Figure 1 [2]. The typical energy consumption of a villa in these regions ranges from 40% to 71% for cooling purposes. The cooling loads in KSA are comparatively high, as depicted in Figure 1, underscoring the pressing need for prompt action to enhance energy efficiency. Studies have highlighted notable difficulties faced by buildings in KSA, which include substantial electricity consumption due to air conditioning (AC) units, accounting for as much as 70% of electricity usage in residential buildings, and insufficient insulation in building envelopes, with up to 70% of residential buildings lacking proper thermal insulation [2]. The government conducted a survey, which revealed that during the summer, approximately 60% of the total electricity consumption is attributed to AC systems. The Saudi Ministry of Water and Electricity has reported a 35% increase in electricity consumption in the country over the past two decades, primarily driven by the extensive use of air conditioning during the summer. Therefore, it is imperative for Saudi Arabia to improve the energy consumption patterns in residential buildings and transition towards more energy-efficient constructions.

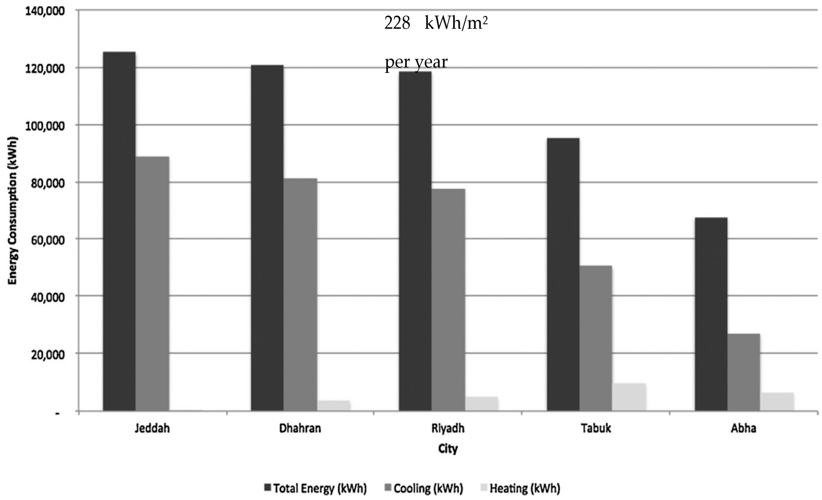

Figure 1. Total annual energy consumption, space cooling and space heating for a villa located in five cities [2].

KSA has three major demand sectors: residential, commercial, and government buildings according to the King Abdullah Petroleum Studies and Research Center (KAPSARC) [3]. Domestic residents' electricity consumption accounts for approximately 49% of the total annual electricity usage across various sectors. In comparison, the industry consumes about 19%, followed by the commercial and government sectors with 16% and 11%, respectively. Conversely, agriculture only utilises 2% of the total electricity usage, as shown in Figure 2 [4]. Several studies conducted by the King Abdullah Petroleum Studies and Research Center (KAPSARC) in the Kingdom of Saudi Arabia (KSA) have affirmed that residential buildings contribute to approximately 50% of the total electricity consumption in the country [5,6]. The yearly average growth rate in total electricity consumption is estimated to be around 5% to 8%. This indicates that, by the year 2035, the production and consumption of oil would be at an equal level [7].

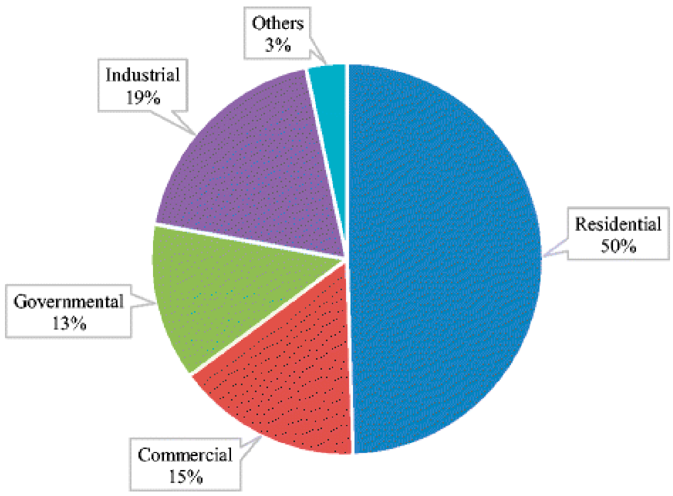

Figure 2. Electrical energy consumption by sectors [4].

KSA's current demands are met by conventional crude oil, heavy crude oil, and gas extraction. In particular, KSA's electricity consumption exceeds one-third of the country's daily oil production. According to Statista's Research Department [8], KSA's oil production in 2020 was 11.04 million barrels per day, which represents a decrease from 11.83 million barrels per day in the previous year. Recently, the Kingdom of Saudi Arabia has seen major economic growth, fast population increase, and quick urban development, all supported by crude oil earnings. This has led to a much higher demand for electricity. A report on Saudi Arabia's power market in 2016 showed that the main sources of electricity were 40% oil, 50% natural gas, and the rest from renewable energy sources [9].

In the Middle East, the integration of photovoltaic (PV) technology into the building sector presents a promising opportunity to foster sustainable development and decrease dependency on fossil fuels. However, several limitations need to be overcome in order to encourage the widespread adoption of PV systems in the region's building sector [10]. Among these challenges is the substantial initial investment necessary for PV systems, which can deter building owners and developers from embracing this technology. Furthermore, the Middle East experiences frequent dust storms and high levels of airborne particles that can lead to the accumulation of dust on PV modules, subsequently reducing energy production and increasing maintenance costs [11]. In addition, the region's harsh weather conditions, including high ambient temperatures, can negatively impact the efficiency and performance of PV systems [12], while sandstorms and dust buildup can contribute to abrasion and premature degradation of PV modules [13]. Another concern is the lack of skilled labour in the Middle East's emerging PV industry, which is needed for designing, installing, and maintaining these systems [14]. Finally, the inadequate or nonexistent regulatory frameworks and policies for renewable energy in many Middle Eastern countries act as a barrier to the growth and adoption of PV technology in the building sector [15]. To address these challenges, efforts should be directed towards implementing government incentives and subsidies, promoting local manufacturing of PV components, investing in research and development to enhance PV efficiency under extreme conditions, and strengthening policies and regulatory frameworks that support the integration of PV systems in buildings.

Many countries are investing in renewable energy sources (RESs) to work towards a cleaner and more sustainable future. Renewable energy sources will help to meet KSA's energy demand and provide a wider range of energy sources in the future, which will reduce the use of fossil fuels [16]. The use of renewable energy (RE) is increasingly being considered to be a viable solution for addressing both the world's energy and environmental challenges. Solar energy, wind power, hydropower, and biomass are examples of RESs that are not only abundant but also supply environmentally friendly forms of energy. Of these, solar photovoltaic (PV) technology is one of the most promising RESs. The solar PV sector has experienced record annual growth since 2012 and global installed capacity exceeded 303 GW by the end of 2016 [17]. Solar PV has a wide range of scale applications, ranging from a few watts (W) to hundreds of megawatts (MW). However, buildings have been one of the most successful applications of solar PV [18,19]. Solar PV panels can be installed in a building in several different ways, such as on the roof, the walls, the floors, or even as a coating on the windows. Rooftop installations account for the majority of PV generation in buildings.

On 25 April 2016, the government of the KSA implemented a new long-term strategy for Vision 2030, which emphasises the challenges of meeting the growing demand for electricity [16]. Since the announcement of Vision 2030 in 2016, several major actions have been made to improve climate action and environmental protection. For example, the government's focus shifted to clean energy in 2019. In 2018, the total installed renewable energy generation was 87 MW, which significantly increased to 397 MW in 2019. On 23 October 2021, KSA launched the Saudi Green Initiative (SGI), which is a new strategy and action plan to reach net-zero emissions by 2060 [20]. The main goal of SGI is to improve the quality of life and secure future generations by increasing reliance on clean energy and offsetting the impact of fossil fuels. Furthermore, to achieve this goal, SGI collaborates on environmental protection, energy transformation, and sustainability programmes.

Vision 2030 emphasises urban development and eco-friendly sustainability. A key step in reaching sustainable growth objectives is incorporating local renewable energy sources (RESs). This can be done by constructing new net-zero energy buildings (NZEB) that generate power for local consumption through photovoltaic (PV) technology. The Kingdom of Saudi Arabia holds great potential for harnessing solar energy to fulfil demand, particularly in urban regions. Solar power is the country's most plentiful renewable resource, and it is anticipated to play the largest role in achieving the 2030 targets. As a result, the KSA has pledged to set up 27.3 GW of renewable power by 2023, with solar PV making up the bulk of it (20 GW). Additionally, the KSA has declared plans to establish a 40 GW photovoltaic power system by 2030, positioning it as the world's largest PV power project [21].

The transition to a more sustainable and renewable energy future presents a significant challenge, especially in countries with centralised electricity grids and a small proportion of renewable energy sources. In Saudi Arabia, for instance, the existing grid is largely centralised, and the proportion of renewable energy sources in the energy mix is relatively small. This study examines the potential for rooftop PV systems to support the grid by generating electricity locally and increasing the proportion of renewable energy in the community to address this issue. This paper aims to demonstrate the potential of implementing rooftop PV systems on buildings across various sectors, exploring the advantages of potential electricity sharing between structures, and addressing the challenges associated with dependency on fossil fuels.

1.2. Related Work

Rooftop solar panels in cities can help meet energy demand during peak times. The KSA's strong solar resources are great for making photovoltaic and concentrated solar power technologies work well. In the western region of the KSA, average solar irradiation amounts to 2400 kWh/m^2/year, while in the eastern region, it is around 2000 kWh/m^2/year [22]. However, the implementation of photovoltaic panels on residential and commercial building rooftops in the KSA, along with the potential for power generation and its effect on electricity consumption, has not been extensively explored or emphasised yet.

The evolution of solar PV worldwide has been considerably supported by small-scale and building-related applications [23]. In this context, assessing the potential of solar energy through the installation of PV systems on rooftops has been of interest to researchers, with examples of research from several countries [24–26]. For example, ref. [27] discovered that rooftop PV panels can generate 39% of total national electric-sector sales in the United States (US). Furthermore, it has been shown that installing PV on all available residential rooftops could supply 79% of all residential energy demands in Andalusia [28]. However, there is limited research on the subject throughout the Gulf Cooperation Council (GCC) region, including KSA. Two recent studies have assessed the use of PV at the urban scale in KSA [23,29]. However, these studies have some limitations. The first study investigated the feasibility of constructing rooftop PV on a university campus, while the second study investigated the feasibility of rooftop PV applications in 13 major cities in KSA. Both studies used simple methods to determine how much roof space is available. They also made general assumptions about obstacles on the roof and shading.

Several studies have demonstrated the viability of installing PV panels on rooftops to generate electricity [30–32]. These evaluations mainly focus on the building's structure, shading zones, and estimated electricity output from solar panels, often overlooking power demand and utilisation. Multiple studies have pointed out the significant potential of rooftop solar PV installations in the KSA [33–36]. These studies also discuss the drawbacks of installing rooftop solar panels, including the requirement for a more robust roof structure to bear the additional weight, challenges in accessing the roof for cleaning and upkeep, and potential heat buildup between the roof and the panels. The majority of homes in the KSA feature flat roofs and walls with a thickness of four feet. Nevertheless, to avoid shading and heat trapping, solar panels ought to be positioned above the walls.

Research in [34] investigated the behaviour of male and female residents in Khobar, Saudi Arabia, with a focus on their comprehension of domestic energy consumption and knowledge of renewable energy alternatives. The study found that the number of adults in a household and their education level significantly influence energy usage. Moreover, the geographical location of a renewable energy project plays a critical role in its success. A recent study in the context of Saudi Arabia addressed this issue by developing a Geographical Information System (GIS) Analytical Hierarchy Process (AHP) method for optimal site selection [35]. The research identified Yanbu Industrial City as one of the top locations in Saudi Arabia for solar or renewable energy initiatives. The study also considered factors such as sunlight intensity, temperature, tilt, and orientation angles across various Saudi Arabian cities to identify the most suitable locations [36].

A team of researchers in the eastern region of KSA assessed the feasibility of placing solar PV panels on university housing unit rooftops [36]. They estimated that such installations could potentially supply around 30% of residential electricity demand. To achieve the ambitious goals for rooftop PV installations, however, the relevant stakeholders must implement legal changes and increase public awareness. Several research papers have investigated the potential sustainability and future possibilities of solar technology in the Middle East. For example, it has been shown that significant increases in energy demand and favourable solar conditions are the most important factors driving solar technology adoption in the region, particularly in KSA and Egypt [37]. Furthermore, the large increase in energy demand in GCC countries provides an opportunity for the deployment of renewable technology [38]. The viability of solar and wind power technologies in KSA has been studied and it was shown that a renewable portfolio standard policy may be a suitable method for introducing these technologies [39]. In addition, solar energy could be a strong alternative to fossil fuel power generators in KSA when indirect costs are taken into account [40]. Meanwhile, the use of hybrid PV to help bring electricity to rural areas in KSA has been studied and it was found that hybrid PV could help bring electricity to rural areas [41]. The maximum potential rooftop solar deployment across 13 cities in the KSA has been evaluated and it was found that these cities have the capacity to generate 51 TWh of electricity annually, which is comparable to 30% of the Kingdom's annual domestic power demand [29]. The feasibility of installing solar panels on rooftops in Seoul, South Korea has been analysed and it was found that roughly 11 GW could be installed in the city based on an evaluation of the number of roofs suitable for PV panel installation [42]. A similar study for Hong Kong concluded that the amount of PV-suitable rooftop space available could support the installation of 6 GW of solar panels [43]. It was also found that the PV system needs help from the government to be able to compete with electricity from the grid. Other research has looked at utility-scale solar deployment in the Middle East from a broader perspective. For example, the use of PV technology has been found to have a beneficial impact on the Saudi economy [44]. The financial burden that solar energy places on the Saudi electrical grid has been studied and it was concluded that utility-scale PV solar deployment has the potential to reduce system costs [44]. Finally, it has been shown that deregulation of fossil fuels or a change in how prices are set will encourage the use of PV solar technology in KSA [45].

The previous studies in this field have primarily concentrated on small-scale applications of rooftop photovoltaic (PV) systems. In contrast, this study focuses on larger city areas with large and diverse number of buildings, which represents a significant advancement over the existing literature. Additionally, to the best of authors' knowledge, no prior research in Saudi Arabia has explored the potential of rooftop PV systems in urban communities and the benefits of these communities in supporting the grid. Hence, this study fills an important gap in the literature and provides valuable insights into the potential of community energy systems.

1.3. Renewable Energy in KSA

KSA's unique location and climate make RESs commercially viable, which helps KSA's efforts to diversify its energy mix. To address global climate issues and create a clean, healthy environment based on clean energy, the KSA has paid a great deal of attention to RESs by establishing renewable energy projects around the Kingdom. This interest is generated by solar energy initiatives in urban and industrial areas that are designed to reduce carbon dioxide emissions. According to the Saudi Arabia Energy Report [46], KSA has increased its use of renewable energy in recent years, with a focus on solar and wind power. At the end of 2018, KSA had an installed capacity of 142 MW for RESs, which included 3 MW of wind power and 139 MW of solar power, including 89 MW of photovoltaic systems and 50 MW of concentrated solar power. In contrast, in 2018 the total renewable capacity of the GCC was approximately 867 MW. In 2018, total global generation of renewable energy was approximately 2468 TWh, with KSA accounting for roughly 0.01% of global production of renewable energy at 0.4 TWh. However, renewable energy generation in the country more than doubled between 2017 and 2018 [46].

1.4. PV Initiative in Saudi Arabia

The geographical position of the KSA is ideal for harnessing solar energy, boasting an average daily solar radiation intensity of 6 kWh/m^2 and 80–90% clear sky days over the year [47]. The yearly solar radiation level surpasses 2100 kWh/m^2 [48], as illustrated in Figure 3. The KSA possesses significant solar energy potential, and a large portion of its energy needs could be met through solar power. Factors such as abundant solar irradiation, expansive arid regions, and extended daylight hours make the country exceptionally well-suited for large-scale utilisation and implementation of solar energy resources [49]. The KSA also enjoys long average daily sunshine hours (8.53 h), extensive areas of unoccupied land, and cloud-free skies. These elements contribute to a highly favourable setting for adopting solar photovoltaic technologies.

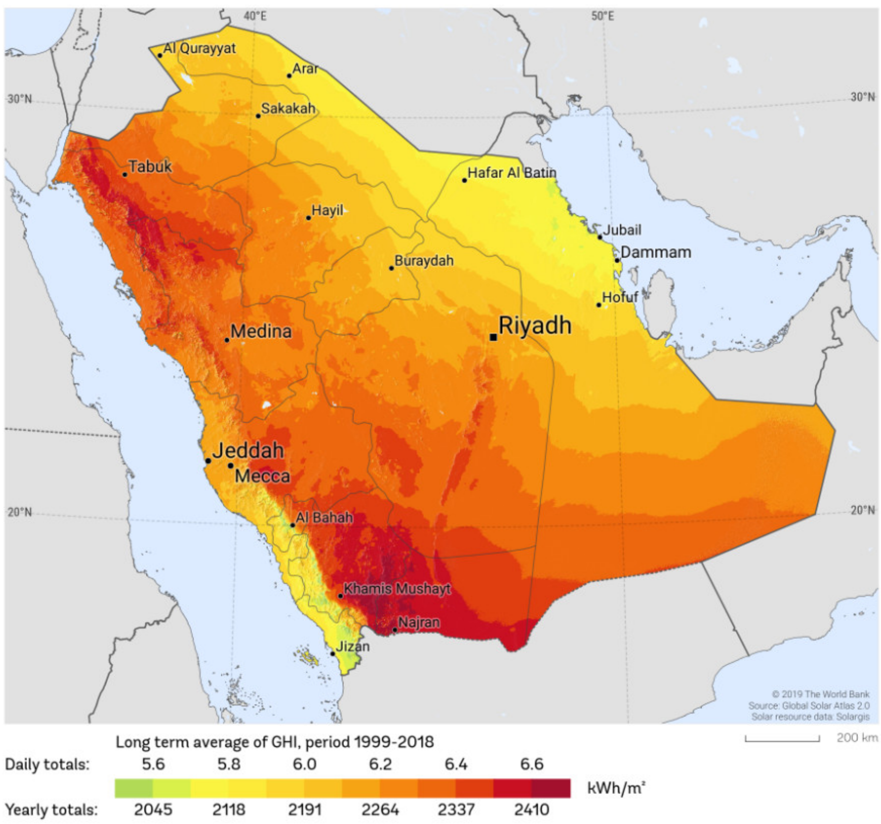

Figure 3. Global horizontal irradiation map of KSA [48].

1.5. Aims and Contributions

This study is conducted in collaboration with a Saudi Arabian electricity company that provided actual data, making it a case study. This study demonstrates the benefits of local generation and provides data at a granular level. These are very extensive and real data.

The main aim of this study is to develop a methodology for estimating the power generation potential of distributed PV systems installed on residential and commercial rooftops in Abha, Saudi Arabia. The method relies on real data from the local electricity company's database. The focus of this research is on buildings typical of the Middle East, characterised by their flat roofs (see Figure 4). The main contribution lies in utilising real data from a wide variety of buildings in Abha, including 8067 commercial, 10,788 residential, and 1508 service buildings, demonstrating the proposed methodology's feasibility and applicability to other contexts or regions. Specifically, this research explores the ability of rooftop solar panels in Saudi Arabia to satisfy local urban electricity demand and reduce reliance on the grid. The electricity generated is used locally. A planning tool was created to estimate the total solar panel production on residential and commercial rooftops in Abha, which can help the local electricity company evaluate the feasibility of rooftop solar installations. This case study encompasses over 20,363 buildings with a combined floor area exceeding 6 million square metres in both residential and commercial communities.

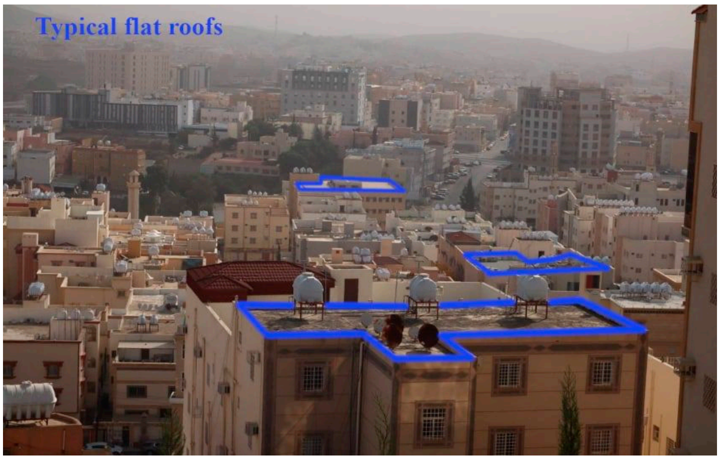

Figure 4. Typical flat roofs in the area under study.

The study covers a significant number of buildings in Abha city, including commercial, residential, and service buildings, providing extensive and real data. Additionally, this paper demonstrated the potential of rooftop PV in KSA to meet localised urban electricity demand and minimise the electricity import from the grid. The emphasis of this study is placed on buildings that are typical of the Middle East, which are dominated by their flat roofs.

1.6. Structure of This Paper

The rest of this paper is structured as follows. Section 2 discusses the study framework, the location of the case study, the input data, and the planning tools. Section 3 presents the results and the main discussions of the study. Finally, the conclusion is presented in Section 4.

2. Methodology

There are two fundamental methods for calculating rooftop solar photovoltaic (PV) potential: the constant-value approach and the GIS-based approach [42,50,51]. The choice of method depends on data availability and the scope of the study.

The constant-value methodology utilises existing building data, including the total number of buildings, floors, and floor space [42,51]. These data are combined with general assumptions, such as roof angle, rooftop direction, and shading, in a matrix model to estimate the overall rooftop area and solar PV potential for the target area [42,50,52,53].

The GIS-based method utilises GIS software to identify optimal locations for rooftop solar installations by evaluating crucial rooftop properties within the base-map data layers [50]. Although this method provides a detailed analysis, it demands significant time and resources, which renders it less practical for large-scale assessments such as national or city-wide evaluations. Moreover, the reliability and accuracy of GIS data tend to diminish over vast regions [53]. Consequently, current research primarily applies this methodology to smaller-scale regions, such as county-level areas [54].

The constant-value method was used in this study to develop a tool to estimate the technical PV potential across large geographic areas with high accuracy. The constant-value method was selected because it has the ability to provide an accurate estimate of the PV potential while also being computationally efficient. As a result, this method is well-suited for the analysis of large land areas.

2.1. Case Study of Abha City

The initial stage in the suggested methodology involves choosing a suitable case study for analysis. This study focuses on Abha, which is the capital of Aseer Province and is located in the southwest of the country near the Red Sea (see Figure 5). Abha is located between 18°130′ north and 42°30′ east latitudes. The city has a pleasant climate throughout the year. Figure 6 displays two lines: the red line illustrates the average monthly temperature throughout the summer months, and the blue line depicts the average monthly temperature during the winter season.

The weather in Abha throughout the summer is moderate, with a slight increase in temperature in June, which leads to an increase in air conditioning demand during the peak time. Energy consumption from December to February is relatively high due to the use of heaters. During this time of year, the temperature can drop by as much as 11 °C.

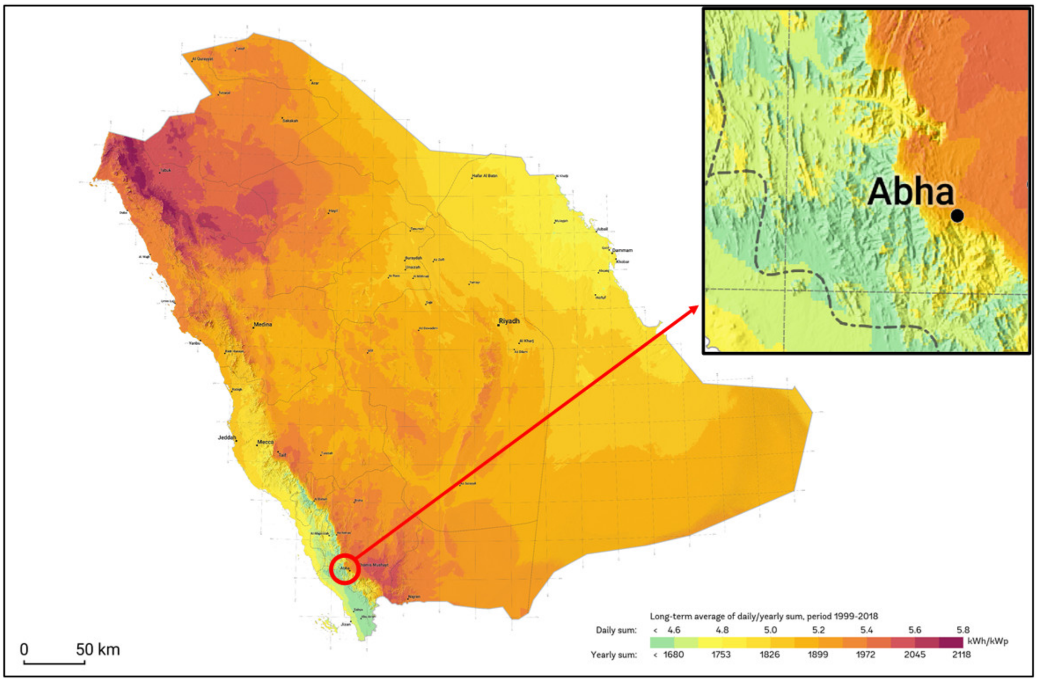

Figure 5. The location of Abha city [55].

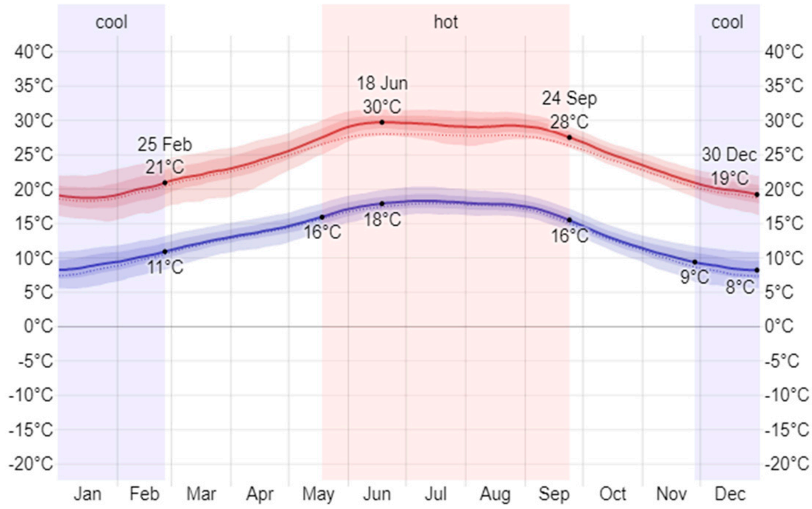

Figure 6. The daily average temperature of Abha city [56].

2.1.1. System Description

The Abha city schematic network is presented in Figure 7. This network supplies the main grid with 380 kV Abha power plant. The total load power demand for residential and commercial areas is 239.5 MW and 249 MW, respectively. Based on the aggregated load, the urban area is divided into two communities: commercial only and residential only. The analysis is based on real data obtained from the local electricity company.

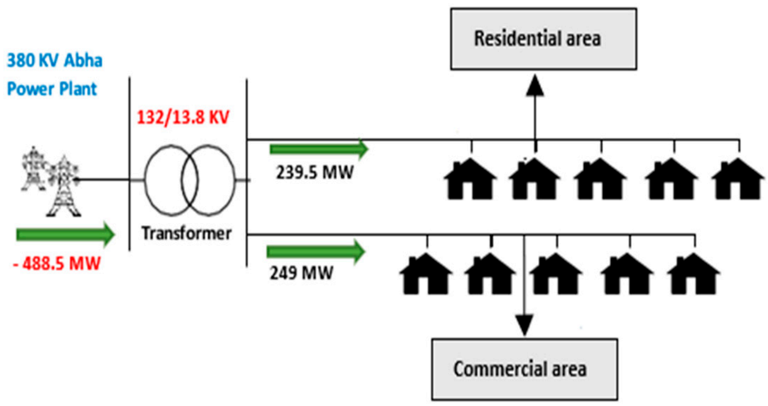

Figure 7. Abha case study network.

2.1.2. Residential Community

Residential communities (see Figure 8) are further divided according to dwelling type, which includes traditional houses, villas, and apartments. Traditional residences and villas are largely inhabited by Saudi nationals. Each family can have a large house with an area suitable for rooftop PV installation. As shown in Table 1, each residential community typically has a full range of commercial services, including local shops, supermarkets, mosques, schools, and health care centres. According to actual electricity bills, Table 2 shows the total monthly electricity consumption of these residential communities for the year 2021.

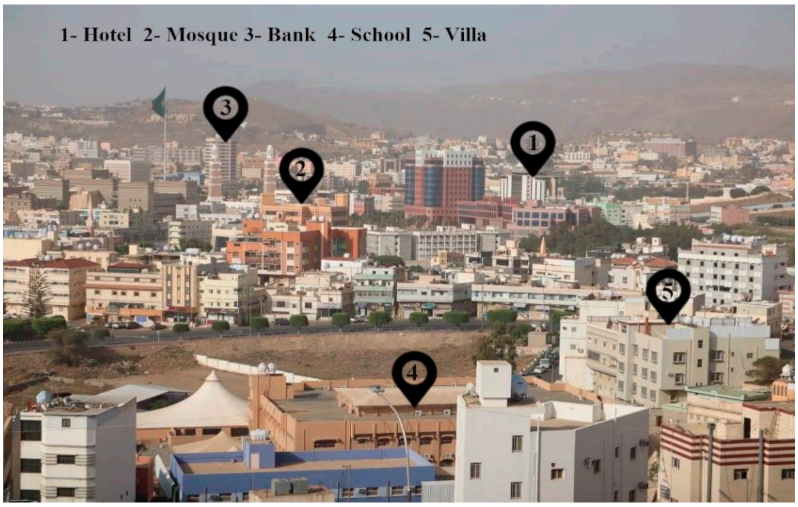

Figure 8. Residential community in the study area.

Table 1. Residential community buildings [57].

Category of Buildings	Roof Area (m^2)	Number of Buildings
Hospitals (01)	24,382	62
Hotels (02)	59,603	251
Supermarkets (03)	37,428	136
Petrol Stations (04)	15,003	31
Street Lighting (05)	29,906	48
University (06)	12,930	29
Restaurants (07)	20,203	48
Commercial Shops (08)	96,478	337
Mosques (09)	51,012	114
Pharmacy (10)	15,527	36
Clinics (11)	15,575	47
Workshops (12)	21,102	58
Communication Building (13)	11,900	27
Schools (14)	27,016	37
Furnished Apartment (15)	15,351	70
Water Pumping (16)	5902	10
Abha Municipality Buildings (17)	12,080	22
Banks (18)	10,602	32
Farms (19)	12,300	42
Government Buildings (20)	6400	21
Amusement Parks (21)	4950	12
Telephone Exchange (22)	3175	8
Stadium (23)	4400	11
Picnic Spots (24)	4625	19
Total	517,850	1508

Table 2. Total monthly residential consumption in 2021 [57].

Month	TOTAL Monthly Residential + Building Service Consumed Load (MW)
January	20.9
February	25.2
March	21.2
April	17.7
May	17.5
June	18.3
July	22.0
August	20.0
September	19.6
October	20.5
November	17.9
December	18.8

2.1.3. Commercial Community

As shown in Figure 9, the commercial community in Abha includes malls and supermarkets, as well as restaurants and pharmacies. Table 3 gives the number of commercial buildings that are used in this study, while Table 4 shows monthly electricity consumption data. As can be seen from the data profile, the demand from July to August increased due to the high number of customers attending these commercial buildings, along with tourists. During the summer, all shops are open 24 h a day.

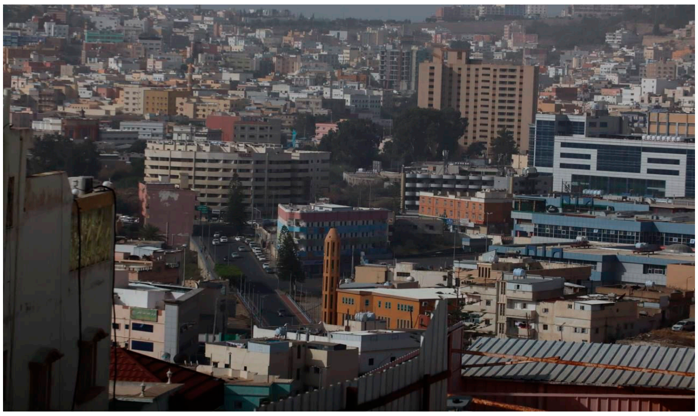

Figure 9. Commercial community in the study area.

Table 3. Commercial area buildings [57].

Category of Buildings	Roof Area (m^2)	Number of Buildings
Restaurant (01)	100,404	387
Supermarket (02)	159,798	425
Banks (03)	36,531	126
Clinics (04)	56,741	213
Hospital (05)	44,907	98
Communication Building (06)	5451	14
Hotel (07)	284,324	1085

Table 3. *Cont.*

Category of Buildings	Roof Area (m^2)	Number of Buildings
Petrol Station (08)	91,514	329
Pharmacy (09)	75,901	354
School (10)	97,397	206
Workshop (11)	112,906	437
Shopping Mall (12)	509,917	1938
Warehouse (13)	54,295	74
Commercial (14)	465,988	2381
Total	2,096,074	8067

Table 4. Total monthly commercial consumption in 2021 [57].

Month	TOTAL Monthly Consumed Load (MW)
January	18.98
February	20.79
March	18.43
April	18.87
May	19.12
June	21.48
July	24.24
August	24.37
September	22.58
October	21.90
November	19.74
December	18.30

2.2. PV Production Calculations

The approach for estimating solar energy potential on flat residential and commercial rooftops is shown in Figure 10. The first step involves finding the total available space for solar panel installation. The angle and direction of the roof, structural stability, building obstructions, and shading can all affect the available space for solar panels. This study focuses on using the flat rooftops of homes and commercial buildings for solar energy installations. For context, studies on rooftop solar panel market penetration provide values for the access factor [58]. Abha city, situated in a warm climate zone, has a 60% access factor for its rooftops [58]. This value is determined based on three factors: (i) 75% shading factor, (ii) 80% structural adequacy factor, and (iii) 100% orientation factor. The access factor is calculated by multiplying these three parameters together.

The pitched roof access factor is 24.3%. On flat-roof buildings, solar panels are usually arranged in parallel rows. Nonetheless, this setup requires attention to shading between panels, a common issue in multi-row PV installations. By carefully designing an optimal array layout, this shading loss can be reduced [59].

The setback ratio (SBR) is calculated by dividing the horizontal distance between rows by the vertical distance between the highest edge of the panel and the ground. In areas with abundant sunlight and lower latitudes, the SBR is at least 2:1. Conversely, in regions with greater cloud cover and higher latitudes, the SBR is at least 3:1 [59]. In this study, based on Abha city's location and climate, an SBR of 3:1 was assumed for all buildings due to its higher cloud cover and latitude. The ground cover ratio (GCR) factor is used to account for the influence of shading between rows on solar PV systems.

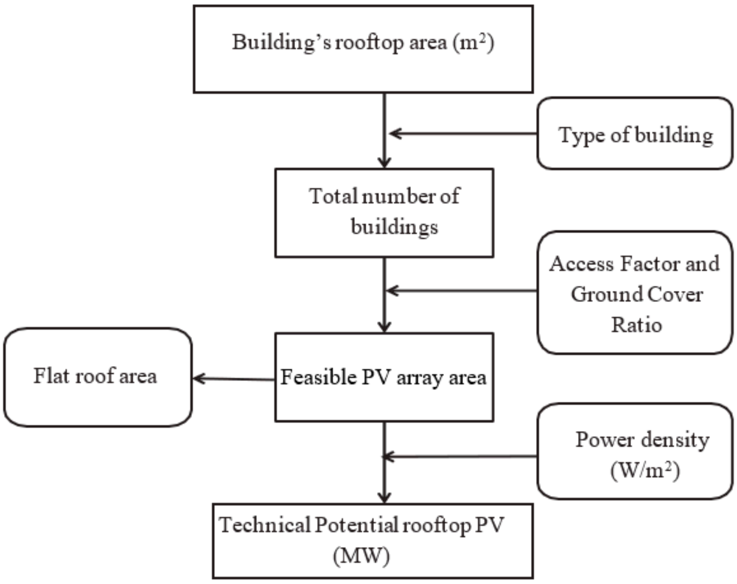

Figure 10. A methodology for determining the technical potential of rooftop solar PV installations in residential and commercial areas.

The GCR evaluates panel-to-panel shading effects on PV array areas by dividing the array area by the ground area. Tilt angle, SBR, and GCR are interrelated in multi-row systems, as demonstrated in Equation (1):

$$GCR = (\cos(\beta) + SBR \times \sin(\beta))\,\hat{}\,{-1}) \quad (1)$$

In reality, PV arrays are set at the ideal angle β, obtained from Equation (1), to minimise shading between panels. Increased tilts require more roof space, lowering the GCR. To maximise the financial efficiency of flat commercial building rooftops, solar panel tilt angles are often set between 5° and 10° [60]. The majority of commercially available racking systems offer tilt angles of 5°, 10°, 15°, and 20° [61]. In this study, a 20° tilt angle was applied to flat roofs. Based on these assumptions, the GCR was determined to be 50.87% using Equation (1). Table 5 presents the parameters utilised for estimating PV potential.

Table 5. Parameters used in determining the PV potential.

PV Calculation Data	Values	Ref
Optimal Tilt Abha (β)	20°	[61]
Setback Ratio (SBR)	3:1	[59]
Ground Cover Ratio (GCR)	50.87%	[59]
Access Factor of Flat Roofs (Warmer Climate)	60%	[58]
Efficiency of the Solar Panel	22%	[62]
Power Density (W/m^2)	1000	[59]

To calculate the technical power potential, the estimated total area of the PV array is multiplied by the assumed power density of the solar system (W/m^2). The estimation method is represented in Equations (2) and (3). The efficiency of the chosen solar panels determines the solar power density. Based on current market conditions, a conservative average panel efficiency of 22% was considered. According to the National Renewable Energy

Laboratory's (NREL) most recent Tracking the Sun Report, the market median efficiency of PV modules has increased at a steady rate from 16% to 22% between 2015 and 2020 [62].

$$\text{Power Density (W/m}^2\text{) under Standard Test Condition} = 1000\ \text{W/m}^2 \times \text{Panel Efficiency.} \quad (2)$$

$$\text{Technical PV potential (MW)} = \text{Total PV Array Area} * \text{Power Density} \div 10\hat{}6 \text{ to get MW generation.} \quad (3)$$

The buildings' information from each type of community was gathered. The full representation of the buildings, including floor area, number of floors, and roof area, is based on real data collected from the electricity company supplying Abha city. One-year peak load calculations are considered when analysing the data for every building type. As shown in Figure 11, data for PV monthly power generation are obtained from the Photovoltaic Geographical Information System (PVGIS) [63] based on the weather and location of Abha. Microsoft Excel was used to create a PV Planning Tool for Residential and Commercial Buildings (PVPT). This is used to determine the PV production available for residential and commercial buildings. Figure 12 illustrates the tool's basic features. The tool's inputs include the type of building, the peak load for each building, the number of buildings, and the total roof area in m^2. The model created for this specialised application is adaptable, user-configurable, and applicable to a variety of applications.

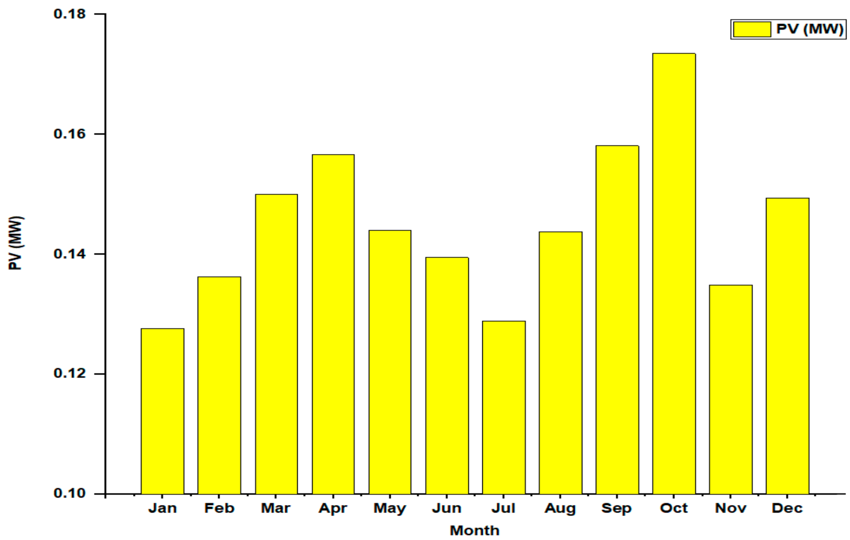

Figure 11. Monthly generated power from solar PV in Abha [63].

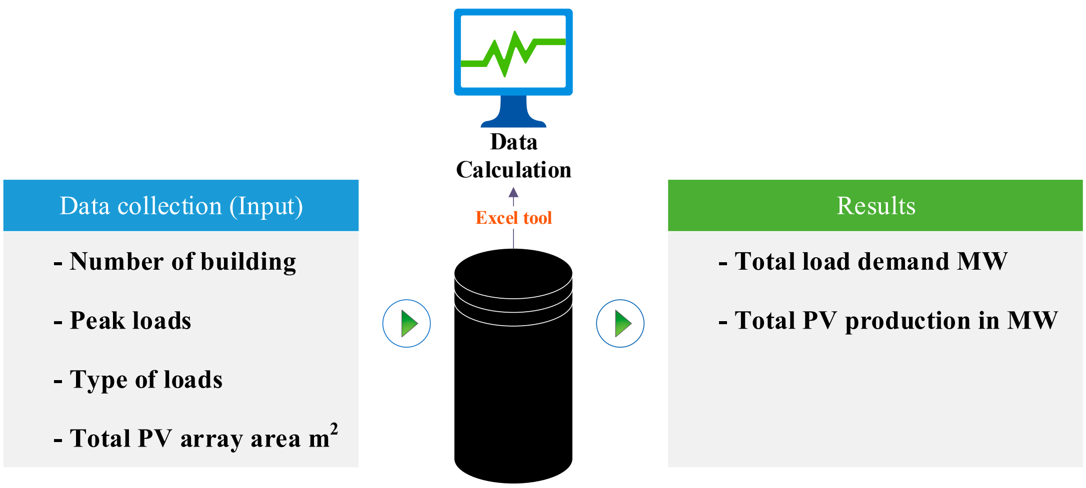

Figure 12. Structure of the PV Planning Tool for Residential and Commercial Buildings model.

3. Results

The potential PV array area on Abha city's residential building rooftops is shown in Table 6. Using Equations (2) and (3), the technical PV potential for residential areas was calculated, with results depicted in Figure 13. Table 7 provides a summary of the potential PV array area for commercial building rooftops in Abha city. Employing Equations (2) and (3), the technical PV potential for commercial sites was determined, and the outcomes are displayed in Figure 14.

The total power consumption in the commercial area amounts to 248.84 MW, with residential areas consuming 168.1 MW and service buildings consuming 71.45 MW. Table 8 illustrates the PV potential for each area and their respective yearly electricity consumption.

According to the data presented in Table 8, PV panels installed on rooftops have the potential to supply a significant percentage of the demand for electricity in selected areas. In residential buildings, the amount of power that can be generated from PV is exceeding the required power, providing opportunities to send the extra power back to the grid. For commercial buildings, PV generated power meets more than half of the electricity demand.

Table 6. Feasible PV array area in residential and service buildings.

Category of Buildings	Roof Area (m^2)	Feasible PV Array Area (m^2)
Residential Area	3,398,668	1,037,341.45
Hospital (1)	24,382	7441.87
Hotel (2)	59,603	18,192.03
Supermarket (3)	37,428	11,423.77
Petrol Station (4)	15,003	4579.22
Street Lighting (5)	29,906	9127.91
University (6)	12,930	3946.49
Restaurant (7)	20,203	6166.36
Commercial Shops (8)	96,478	29,447.02
Mosque (9)	51,012	15,569.88
Pharmacy (10)	15,527	4739.15
Clinic (11)	15,575	4753.80
Workshop (12)	21,102	6440.75
Communication Building (13)	11,900	3632.12
Schools (14)	27,016	8245.82
Furnished Apartment (15)	15,351	4685.43
Water Pumping (16)	5902	1801.41
Abha Municipality Buildings (17)	12,080	3687.06
Banks (18)	10,602	3235.94
Farms (19)	12,300	3754.21
Government Buildings (20)	6400	1953.41
Amusement Parks (21)	4950	1510.84
Telephone Exchange (22)	3175	969.07
Stadium (23)	4400	1342.97
Picnic Spots (24)	4625	1411.64
Total	517,850	158,058.18

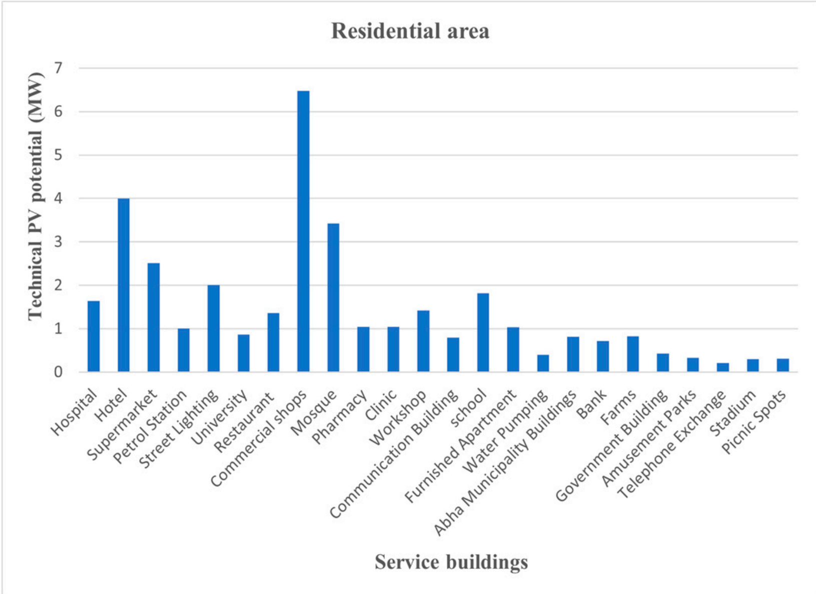

Figure 13. Rooftop PV potential for service buildings.

Table 7. PV array area in commercial area.

Category of Buildings	Roof Area (m^2)	PV Array Area (m^2)
Restaurant (1)	100,404	30,645.31
Supermarket (2)	159,798	48,773.55
Banks (3)	36,531	11,149.99
Clinics (4)	56,741	17,318.49
Hospitals (5)	44,907	13,706.51
Communication Buildings (6)	5451	1663.75
Hotels (7)	284,324	86,781.37
Petrol Stations (8)	91,514	27,931.90
Pharmacy (9)	75,901	23,166.50
Schools (10)	97,397	29,727.51
Workshops (11)	112,906	34,461.17
Shopping Malls (12)	509,917	155,636.87
Warehouse (13)	54,295	16,571.92
Commercial buildings (14)	465,988	142,228.86
Total	2,096,074	639,763.7

Commercial buildings generate a total of 140.75 MW through photovoltaic production, meeting up to 50% of the buildings' energy demand. Residential buildings produce 228.22 MW of PV power, fulfilling their entire energy demand. Consequently, this study highlights the substantial rooftop PV potential in these areas.

Based on the PV array area and technical PV potential of each building, the PV production in each community is calculated. The effect of rooftop solar systems on the monthly profile of peak demand was explored using the proposed planning tool. The total PV production at each community based on the weather of the city, load demand, and the technical PV potential at each building was calculated. This analysis is for the modelling of PV systems on the rooftops of 20,363 buildings (12,296 residential and residential service buildings and 8067 commercial buildings). It was found in this modelling study that installing PV systems on the rooftops of buildings is the most effective way to reduce the required power from the grid since the monthly peak load corresponds to the monthly peak solar production.

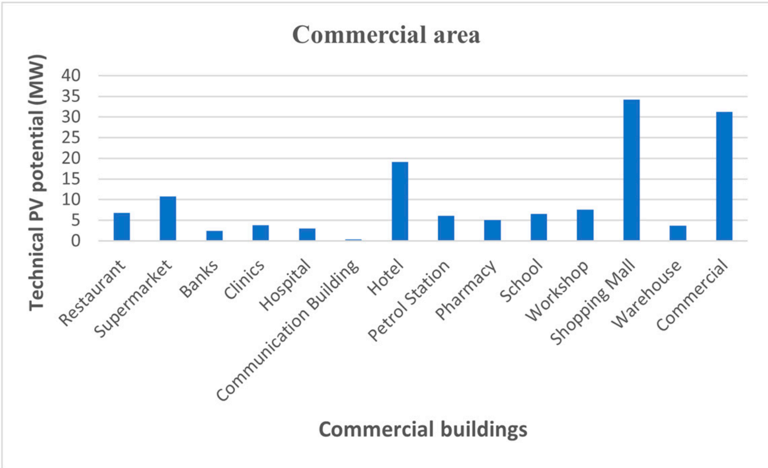

Figure 14. Technical rooftop PV potential for commercial buildings.

Table 8. PV potential and total annual electricity consumption for residential and commercial buildings.

Type of Buildings	Total Electricity Consumption (MW)	Technical PV Potential (MW)
Commercial buildings	248.84	140.75
Residential buildings	168.1	228.22
Service buildings	71.45	34.77

3.1. Residential Area

The residential demand profiles and PV generation is different from one building to another and from one month to another. Figure 14 compares the monthly PV production of the proposed PV system and the typical residential demand. Based on the calculated results, it was observed that the proposed PV system is sufficient to meet the energy demands of the residential buildings. October has the highest PV generation in the residential area (approximately 39.59 MW), as shown in Figure 15. In contrast, due to the use of heaters in the winter, the peak demand occurs in February, when it reaches 18.9 MW.

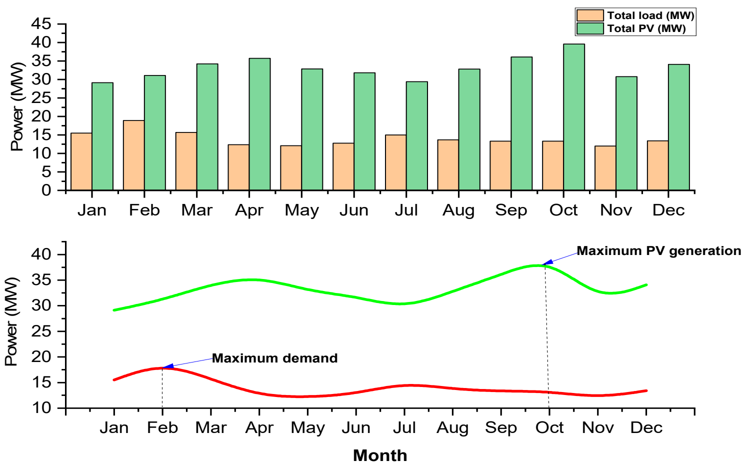

Figure 15. Residential load profile and PV production.

The residential area includes facilities such as schools, hospitals, and stores. Figure 15 illustrates the actual consumption in the service buildings and the amount of solar PV production resulting from the proposed installation of PV panels on the service buildings. According to the data from the PV planning tool, the total PV production from residential service buildings is not high enough to meet the electricity demand during the summer (i.e., July to September). Figure 16 also shows the peak demand during the summer and the peak PV production throughout the year, while the maximum PV production and electricity demand both occur in October.

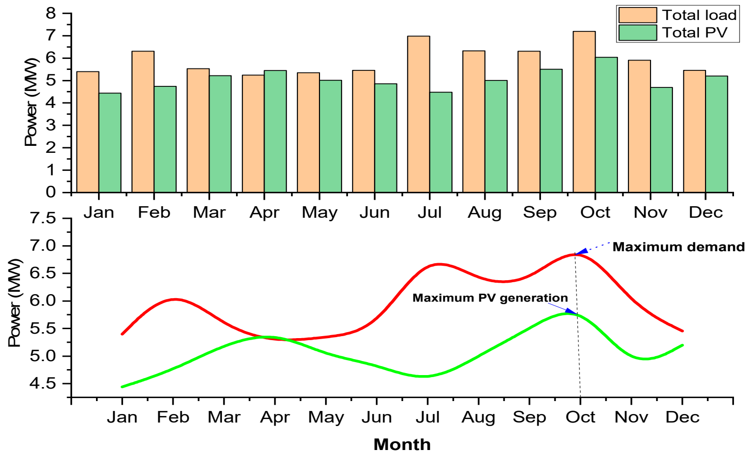

Figure 16. Service buildings load profiles and PV production.

3.2. Commercial Area

As seen in Figure 17, the consumption of commercial buildings increases in June and reaches a peak in July. The peak consumption happens in July, while the peak PV production occurs in December. Consequently, PV production can meet the commercial area's electricity demand.

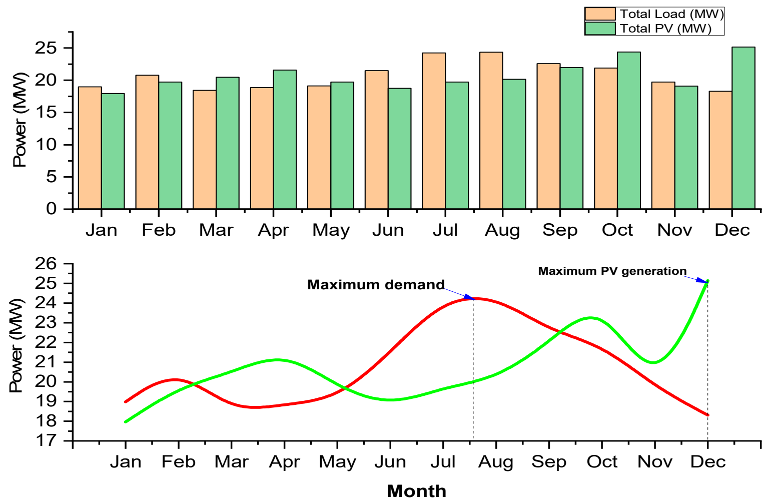

Figure 17. Commercial area demand and PV production.

4. Analysis of the Results

Based on the results of this study, solar energy is an effective solution for powering buildings locally and can contribute to the energy sector's efforts to become more environmentally friendly. This study estimates the rooftop PV energy generation potential of Abha's residential and commercial buildings (see Figure 18).

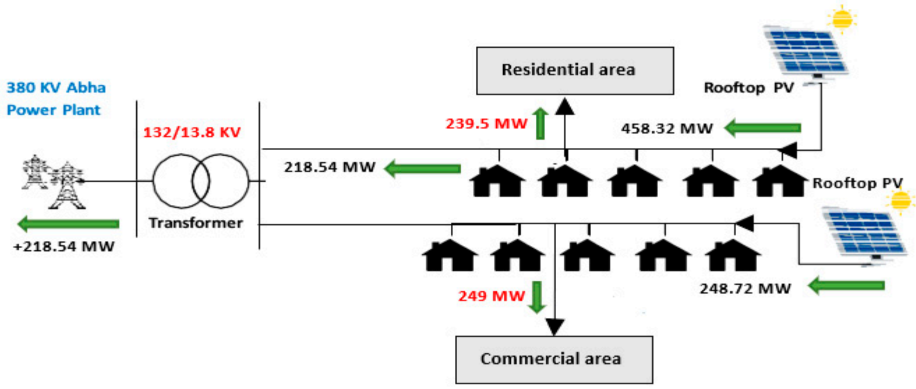

Figure 18. Abha case study network after connecting rooftop PV.

In the base scenario, the total consumption of residential and commercial sectors that are powered by the grid is 488.5 MW. The purpose of this study was to demonstrate the potential of rooftop PV to meet the demand for power in residential and commercial communities, hence reducing the amount of electricity that is imported from the grid. Figure 15 shows that the residential area produces 458.32 MW of PV power but only requires 239.5 MW. This means that PV generation can meet the total residential electricity demand, while also producing surplus power to export back the grid. In contrast, the PV generation installed in the commercial area can meet 99.88% of the total electricity demand of these buildings.

In aggregation, both residential and commercial areas can support the demand of community's buildings using PV generation with a 44.73% (218.54 MW) surplus of power that can be exported to the grid.

It is crucial for achieving efficient and sustainable energy systems to address concerns about excess electricity generation from rooftop systems [64]. A surplus of electricity production can present challenges to the management and stability of the grid, and it can also bring attention to the necessity of developing efficient energy storage and compensation mechanisms [65]. It is important to investigate the appropriate sizing of energy storage solutions, such as batteries, and develop control systems for managing the import and export of electricity to and from the grid to optimise the integration of PV systems into the grid. This will allow the optimal integration of PV systems [66]. By considering the aforementioned factors, researchers, energy companies, and policymakers can develop a more comprehensive understanding of the management and utilisation of excess electricity generation. This will ultimately improve the overall performance and sustainability of rooftop PV systems [67]. As a future step in this research, this work intends to concentrate on these crucial aspects in order to provide a comprehensive understanding of the difficulties and potential solutions associated with excess electricity generation from rooftop PV systems.

5. Economic Analysis

This study examined the economic feasibility of residential and commercial rooftop solar photovoltaic (PV) systems in Abha, Saudi Arabia. The System Advisor Model (SAM) software was used to conduct an economic analysis based on the total demand for each region and the total PV generation from rooftop systems. The parameters used to calculate the economic analysis of residential and commercial areas are summarised in Tables 9 and 10. The sizes of the PV systems were determined based on meeting each region's total electricity demand. The annual PV generation was estimated using solar radiation data provided by the National Renewable Energy Laboratory (NREL) for Abha, Saudi Arabia. The following results of PV generation for every area were provided:

Table 9. Residential parameters.

Parameter	Value	Reference
Annual PV generation (MW)	239.5	Calculated
Annual solar insolation (kWh/m^2)	1950	[68]
Performance ratio	0.824	[69]
PV system size (kW)	162,260	Calculated
Electricity price for residential ($/kWh)	0.048	[70,71]
Annual energy cost savings ($)	11,496,000	Calculated

Table 10. Commercial parameters.

Parameter	Value	Reference
Annual PV generation (MW)	249	Calculated
Annual solar insolation (kWh/m^2)	1950	[68]
Performance ratio	0.824	[69]
PV system size (kW)	169,200	Calculated
Electricity price for residential ($/kWh)	0.048	[70,71]
Annual energy cost savings ($)	11,952,000	Calculated

In the residential area, 162,260 kW of PV capacity was installed, whereas the commercial area had 169,200 kW of PV capacity. Based on [69] study, we utilised a performance ratio (PR) of 0.824%. The National Renewable Energy Laboratory (NREL) provided data on solar radiation [70], estimating that Abha, Saudi Arabia, receives 2184 h of sunlight annually [68]. According to the Saudi Electricity Company [71], the average residential electricity rate in 2021 will be about 0.18 SAR/kWh, which is equivalent to about $0.048/kWh. The results of the economic analysis are summarised in Tables 11 and 12. In addition, Table 13 compares important parameters between residential and commercial areas.

Table 11. Economic analysis for residential area.

Parameter	Value
PV System Size (kW)	162,260
System Cost	$243,390,000
Performance Ratio	0.824
Hours of sunlight per year	2184 h
Annual PV Generation (MWh)	292,517
Electricity Price ($/MWh)	$40
Annual Savings	$11,700,680

Table 12. Economic analysis for commercial area.

Parameter	Value
PV System Size (kW)	169,200
System Cost	$253,800,000
Performance Ratio	0.824
Hours of sunlight per year	2184 h
Annual PV Generation (MWh)	303,674
Electricity Price ($/MWh)	$40
Annual Savings	$12,146,960

Table 13. Economic analysis summary.

Parameter	Residential	Commercial
PV System Size (kW)	162,260	169,200
System Cost	$243,390,000	$253,800,000
Annual PV Generation (MWh)	292,517	303,674
Annual Savings	$11,700,680	$12,146,960

The analysis indicates that both residential and commercial rooftop PV systems in Saudi Arabia can provide substantial economic benefits. The larger installed capacity of the PV system in the commercial area led to greater annual energy cost savings ($12,146,960) than in the residential area ($11,700,680). Consequently, the estimated system cost for the commercial area was higher than for the residential area ($253,800,000 vs. $243,390,000). These findings suggest that rooftop PV systems can be a viable and attractive option for reducing energy costs and promoting the adoption of renewable energy in Saudi Arabia.

6. Conclusions

The aim of this study was to develop an automated planning tool to calculate the total PV generation that may be produced from PV installation on flat roofs, which are the dominant type of buildings in this area. The tool was developed using a methodical approach and demonstrated through a case study in Abha, KSA. By gathering real data from commercial and residential buildings, the study found that solar rooftop PV systems enable these structures in Abha city to reduce their dependence on grid-imported electricity. The PV planning tools that were developed for residential and commercial buildings are adaptable for use in further applications and locations.

The case study analysed electricity consumption data from two distinct community areas and compared them to the power output from PV arrays installed on the rooftops of these buildings. Results from both residential and commercial areas reveal considerable technical potential for further expansion of rooftop PV installations. The findings also imply that rooftop PV panels in KSA can significantly contribute to the power grid, especially in addressing daytime demand. As demonstrated by the Abha city case study, PV systems can satisfy the entire residential demand, with a surplus of power available during certain months that can be stored locally or exported to the grid. Additionally, PV systems on commercial building rooftops can fulfil 99.88% of consumer demand.

Based on these results, it is feasible to install solar PV panels on a larger scale in KSA's residential and commercial buildings. PV panels installed on buildings can eliminate the need to use land to develop PV farms on a larger scale and serve a number of objectives, including weather protection, energy production, and light management. Solar PV installation reduces the power imported from the grid and powers the buildings with PV power produced locally. Installing PV systems in buildings fosters innovation and provides opportunities for training and employment. Currently, KSA's power system is centralised, and future regional policies could include integrating PV technology. This analysis will be essential for the electricity company if they choose to make this decision, helping to expedite the growth of renewable energy systems, especially solar power, while reducing emissions.

Author Contributions: Conceptualization, A.S. and L.C.; methodology, A.S.; software, A.S.; validation, A.S., S.A. and A.G.; formal analysis, A.S.; investigation, A.S. and L.C.; resources, A.S.; data curation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, L.C., S.A. and A.G.; visualisation, A.S.; supervision, L.C.; project administration, L.C. All authors have read and agreed to the published version of the manuscript.

Funding: The Open Access (OA) charges for this work have been funded by Cardiff University Institutional OA Fund: 2023-OA-0371.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful for support from the Decarbonising Transport through Electrification (DTE) Network+ funded by the Engineering and Physical Sciences Research Council (EPSRC), grant reference EP/S032053/1. The corresponding author would like to thank Najran University, Saudi Arabia, for sponsoring his postgraduate study at Cardiff University, UK. The authors would like to thank the electricity company in Saudi Arabia for providing the data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Autoridad Nacional del Servicio Civil. *Annual Report 2020*; Angewandte Chemie International Edition; Autoridad Nacional del Servicio Civil: Khobar, Saudi Arabia, 2021; Volume 6, pp. 951–952.
2. Felimban, A.; Prieto, A.; Knaack, U.T.K.; Qaffas, Y. Residential Buildings in Jeddah, Saudi Arabia. *Buildings* **2019**, *13*, 1–19.
3. Asif, M. Growth and sustainability trends in the buildings sector in the GCC region with particular reference to the KSA and UAE. *Renew. Sustain. Energy Rev.* **2016**, *55*, 1267–1273. [CrossRef]
4. Balabel, A.; Alwetaishi, M.; Abdelhafiz, A.; Issa, U.; Sharaky, I.; Shamseldin, A.; Al-Surf, M.; Al-Harthi, M. Potential of Solatube technology as passive daylight systems for sustainable buildings in Saudi Arabia. *Alex. Eng. J.* **2022**, *61*, 339–353. [CrossRef]
5. Alrashed, F.; Asif, M. Trends in Residential Energy Consumption in Saudi Arabia with Particular Reference to the Eastern Province. *J. Sustain. Dev. Energy Water Environ. Syst.* **2014**, *2*, 376–387. [CrossRef]
6. Aldossary, N.A.; Rezgui, Y.; Kwan, A. Establishing domestic low energy consumption reference levels for Saudi Arabia and the Wider Middle Eastern Region. *Sustain. Cities Soc.* **2017**, *28*, 265–276. [CrossRef]
7. Almoallem, A.D. Electricity consumption analysis and management for different residential buildings in jeddah, saudi arabia. *Int. J. Energy Prod. Manag.* **2021**, *6*, 245–262. [CrossRef]
8. BP. Saudi Arabia: Oil Production 2020. Statista. 2021. Available online: https://www.statista.com/statistics/265190/oil-production-in-saudi-arabia-in-barrels-per-day/ (accessed on 30 November 2021).
9. Tazay, A. Techno-Economic Feasibility Analysis of a Hybrid Renewable Energy Supply Options for University Buildings in Saudi Arabia. *Open Eng.* **2020**, *11*, 39–55. [CrossRef]
10. Makrides, G.; Zinsser, B.; Norton, M.; Georghiou, G.E.; Schubert, M.; Werner, J.H. Potential of photovoltaic systems in countries with high solar irradiation. *Renew. Sustain. Energy Rev.* **2020**, *14*, 754–762. [CrossRef]
11. Sayyah, A.; Horenstein, M.N.; Mazumder, M.K. Energy yield loss caused by dust deposition on photovoltaic panels. *Sol. Energy* **2014**, *107*, 576–604. [CrossRef]
12. Mesloub, A.; Ghosh, A.; Touahmia, M.; Albaqawy, G.A.; Noaime, E.; Alsolami, B.M. Performance Analysis of Photovoltaic Integrated Shading Devices (PVSDs) and Semi-Transparent Photovoltaic (STPV) Devices Retrofitted to a Prototype Office Building in a Hot Desert Climate. *Sustainability* **2020**, *12*, 10145. [CrossRef]
13. Rezvani, M.; Gholami, A.; Gavagsaz-Ghoachani, R.; Zandi, M. A Review on the Effect of Dust Properties on Photovoltaic Solar Panels' Performance. *J. Renew. New Energy* **2023**, *10*, 198–211. [CrossRef]
14. Elrahmani, A.; Hannun, J.; Eljack, F.; Kazi, M.-K. Status of renewable energy in the GCC region and future opportunities. *Curr. Opin. Chem. Eng.* **2020**, *31*, 100664. [CrossRef]
15. Sgouridis, S.; Griffiths, S.; Kennedy, S.; Khalid, A.; Zurita, N. A sustainable energy transition strategy for the United Arab Emirates: Evaluation of options using an Integrated Energy Model. *Energy Strat. Rev.* **2013**, *2*, 8–18. [CrossRef]
16. Ko, W.; Al-Ammar, E.; Almahmeed, M. Development of Feed-in Tariff for PV in the Kingdom of Saudi Arabia. *Energies* **2019**, *12*, 2898. [CrossRef]
17. International Renewable Energy Agency. Renewables 2017 Global Status Report. 2017. Available online: http://www.irena.org/publications/2017/Jun/Renewables-2017-Global-Status-Report (accessed on 30 November 2021).
18. Emziane, M.; Al Ali, M. Performance assessment of rooftop PV systems in Abu Dhabi. *Energy Build.* **2015**, *108*, 101–105. [CrossRef]
19. Ordenes, M.; Marinoski, D.L.; Braun, P.; Rüther, R. The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil. *Energy Build.* **2007**, *39*, 629–642. [CrossRef]
20. SAUDI GREEN INITIATIVE. About—Saudi Green Initiative. 2021. Available online: https://www.saudigreeninitiative.org/about-saudi-green-initiative/ (accessed on 31 December 2021).
21. Al Otaibi, Z.S.; Khonkar, H.I.; Al Amoudi, A.O.; Alqahtani, S.H. Current status and future perspectives for localizing the solar photovoltaic industry in the Kingdom of Saudi Arabia. *Energy Transit.* **2020**, *4*, 1–9. [CrossRef]
22. Alghamdi, A.S. Potential for Rooftop-Mounted PV Power Generation to Meet Domestic Electrical Demand in Saudi Arabia: Case Study of a Villa in Jeddah. *Energies* **2019**, *12*, 4411. [CrossRef]
23. Asif, M. Urban Scale Application of Solar PV to Improve Sustainability in the Building and the Energy Sectors of KSA. *Sustainability* **2016**, *8*, 1127. [CrossRef]
24. Gautam, B.R.; Li, F.; Ru, G. Assessment of urban roof top solar photovoltaic potential to solve power shortage problem in Nepal. *Energy Build.* **2015**, *86*, 735–744. [CrossRef]
25. Hong, T.; Koo, C.; Park, J.; Park, H.S. A GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system. *Energy* **2014**, *65*, 190–199. [CrossRef]

26. Khan, J.; Arsalan, M.H. Estimation of rooftop solar photovoltaic potential using geo-spatial techniques: A perspective from planned neighborhood of Karachi—Pakistan. *Renew. Energy* **2016**, *90*, 188–203. [CrossRef]
27. Gagnon, P.; Margolis, R.; Melius, J.; Phillips, C.; Elmore, R. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*; National Renewable Energy Lab.: Golden, CO, USA, 2016.
28. Ordóñez, J.; Jadraque, E.; Alegre, J.; Martínez, G. Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). *Renew. Sustain. Energy Rev.* **2020**, *14*, 2122–2130. [CrossRef]
29. Khan, M.M.A.; Asif, M.; Stach, E. Rooftop PV Potential in the Residential Sector of the Kingdom of Saudi Arabia. *Buildings* **2017**, *7*, 46. [CrossRef]
30. Dehwah, A.H.; Asif, M.; Rahman, M.T. Prospects of PV application in unregulated building rooftops in developing countries: A perspective from Saudi Arabia. *Energy Build.* **2018**, *171*, 76–87. [CrossRef]
31. Asif, M.; Hassanain, M.A.; Nahiduzzaman, K.M.; Sawalha, H. Techno-economic assessment of application of solar PV in building sector. *Smart Sustain. Built Environ.* **2019**, *8*, 34–52. [CrossRef]
32. Alyahya, S.; Irfan, M.A. Role of Saudi universities in achieving the solar potential 2030 target. *Energy Policy* **2016**, *91*, 325–328. [CrossRef]
33. Griffiths, S. Renewable energy policy trends and recommendations for GCC countries. *Energy Transit.* **2017**, *1*, 3. [CrossRef]
34. Nahiduzzaman, K.; Aldosary, A.S.; Abdallah, A.S.; Asif, M.; Kua, H.W.; Alqadhib, A.M. Households energy conservation in Saudi Arabia: Lessons learnt from change-agents driven interventions program. *J. Clean. Prod.* **2018**, *185*, 998–1014. [CrossRef]
35. Al Garni, H.Z.; Awasthi, A. Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. *Appl. Energy* **2017**, *206*, 1225–1240. [CrossRef]
36. Al Garni, H.Z.; Awasthi, A.; Wright, D. Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia. *Renew. Energy* **2019**, *133*, 538–550. [CrossRef]
37. Nematollahi, O.; Hoghooghi, H.; Rasti, M.; Sedaghat, A. Energy demands and renewable energy resources in the Middle East. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1172–1181. [CrossRef]
38. Abdmouleh, Z.; Alammari, R.A.; Gastli, A. Recommendations on renewable energy policies for the GCC countries. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1181–1191. [CrossRef]
39. Ramli, M.A.; Twaha, S.; Al-Hamouz, Z. Analyzing the potential and progress of distributed generation applications in Saudi Arabia: The case of solar and wind resources. *Renew. Sustain. Energy Rev.* **2017**, *70*, 287–297. [CrossRef]
40. Almasoud, A.; Gandayh, H.M. Future of solar energy in Saudi Arabia. *J. King Saud Univ.-Eng. Sci.* **2015**, *27*, 153–157. [CrossRef]
41. Shaahid, S.; El-Amin, I. Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development. *Renew. Sustain. Energy Rev.* **2009**, *13*, 625–633. [CrossRef]
42. Byrne, J.; Taminiau, J.; Kurdgelashvili, L.; Kim, K.N. A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. *Renew. Sustain. Energy Rev.* **2015**, *41*, 830–844. [CrossRef]
43. Peng, J.; Lu, L. Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits. *Renew. Sustain. Energy Rev.* **2013**, *27*, 149–162. [CrossRef]
44. Matar, W.; Anwer, M. Jointly reforming the prices of industrial fuels and residential electricity in Saudi Arabia. *Energy Policy* **2017**, *109*, 747–756. [CrossRef]
45. Matar, W.; Murphy, F.; Pierru, A.; Rioux, B. Lowering Saudi Arabia's fuel consumption and energy system costs without increasing end consumer prices. *Energy Econ.* **2015**, *49*, 558–569. [CrossRef]
46. Alghamdi, A. Saudi Arabia Energy Report. *King Abdullah Pet. Stud. Res. Cent.* **2020**, *19*, 1–28. [CrossRef]
47. Alnaser, W.; Alnaser, N. The status of renewable energy in the GCC countries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3074–3098. [CrossRef]
48. Global Solar Atlas. Available online: https://globalsolaratlas.info/download/saudi-arabia (accessed on 16 June 2020).
49. Imam, A.A.; Al-Turki, Y.A.; Kumar, R.S. Techno-Economic Feasibility Assessment of Grid-Connected PV Systems for Residential Buildings in Saudi Arabia—A Case Study. *Sustainability* **2019**, *12*, 262. [CrossRef]
50. Melius, J.; Margolis, R.; Ong, S. *Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques*; NREL Technical Report; USDOE Office of Energy Efficiency and Renewable Energy: Golden, CO, USA, 2013; p. 35.
51. Schallenberg-Rodríguez, J. Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal. *Renew. Sustain. Energy Rev.* **2013**, *20*, 219–239. [CrossRef]
52. Wiginton, L.K.; Nguyen, H.T.; Pearce, J.M. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Comput. Environ. Urban Syst.* **2010**, *34*, 345–357. [CrossRef]
53. Vardimon, R. Assessment of the potential for distributed photovoltaic electricity production in Israel. *Renew. Energy* **2011**, *36*, 591–594. [CrossRef]
54. Ko, L.; Wang, J.-C.; Chen, C.-Y.; Tsai, H.-Y. Evaluation of the development potential of rooftop solar photovoltaic in Taiwan. *Renew. Energy* **2015**, *76*, 582–595. [CrossRef]
55. File: Abha, Saudi Arabia Locator Map.Png—Wikimedia Commons. Available online: https://commons.wikimedia.org/wiki/File:Abha,_Saudi_Arabia_locator_map.png (accessed on 27 April 2023).
56. Abha climate: Temperature Abha & Weather by Month—Climate-Data.org. Available online: https://en.climate-data.org/asia/saudi-arabia/asir-region/abha-3634/ (accessed on 27 April 2023).

57. Shaher, A.; Alqahtani, S.; Garada, A.; Cipcigan, L. Technical potential for rooftop solar photovoltaic in Commercial and Residential Areas in Saudi Arabia. In Proceedings of the 2022 57th International Universities Power Engineering Conference (UPEC), Istanbul, Turkey, 30 August–2 September 2022; pp. 1–6. [CrossRef]
58. Paidipati, J.; Frantzis, L.; Sawyer, H.; Kurrasch, A. Rooftop photovoltaics market penetration scenarios. In *Renewable Energy Grid Interaction: The Business of Photovoltaics*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2009; pp. 1–26.
59. Kurdgelashvili, L.; Li, J.; Shih, C.H.; Attia, B. Estimating technical potential for rooftop photovoltaics in California, Arizona and New Jersey. *Renew. Energy* **2016**, *95*, 286–302. [CrossRef]
60. Culligan, J.B.M. Impact of Tilt Angle on System Economics for Area Constrained Rooftops. Semantic Scholar. 2007. Available online: https://www.semanticscholar.org/paper/Impact-of-Tilt-Angle-on-System-Economics-for-Area-Culligan-Botkin/eb9907610e42f0945bc83751005cb6f383815fd6 (accessed on 17 May 2022).
61. Mayfield, R. Flat Roof Mounting Systems-Solutions for the Wide-Open Commercial Landscape—Google Search. 2009. Available online: https://www.solaracks.com/flat-roof-mounting-systems-issue-solutions-for-the-wide-open-commercial-landscape/ (accessed on 17 May 2022).
62. Barbose, G.; Darghouth, N.; Shaughnessy, E.O.; Forrester, S. *Tracking the Sun Systems in the United States 2021 Edition*; Berkeley Lab.: Berkeley, CA, USA, 2021.
63. European Commission, Photovoltaic Geographical Information System (PVGIS), Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology. Available online: https://capacity4dev.europa.eu/groups/afretep/info/pvgis-photovoltaic-geographical-information-system (accessed on 7 July 2022).
64. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. [CrossRef]
65. Albadi, M.; El-Saadany, E. A summary of demand response in electricity markets. *Electr. Power Syst. Res.* **2008**, *78*, 1989–1996. [CrossRef]
66. Oudalov, A.; Chartouni, D.; Ohler, C. Optimizing a Battery Energy Storage System for Primary Frequency Control. *IEEE Trans. Power Syst.* **2007**, *22*, 1259–1266. [CrossRef]
67. Borenstein, S. The Private and Public Economics of Renewable Electricity Generation. *J. Econ. Perspect.* **2012**, *26*, 67–92. [CrossRef]
68. PVGIS Online Tool. Available online: https://joint-research-centre.ec.europa.eu/pvgis-online-tool_en (accessed on 3 May 2023).
69. Akpolat, A.N.; Dursun, E.; Kuzucuoğlu, A.E.; Yang, Y.; Blaabjerg, F.; Baba, A.F. Performance Analysis of a Grid-Connected Rooftop Solar Photovoltaic System. *Electronics* **2019**, *8*, 905. [CrossRef]
70. Sengupta, M.; Xie, Y.; Lopez, A.; Habte, A.; Maclaurin, G.; Shelby, J. The National Solar Radiation Data Base (NSRDB). *Renew. Sustain. Energy Rev.* **2018**, *89*, 51–60. [CrossRef]
71. Saudi Electricity Company. 2022. Available online: https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx (accessed on 23 January 2022).