Department of Mechanical and Aerospace Engineering

Coverage of the Electricity Demand of Irbid City, Jordan, through Renewable Energy Integration

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Abstract

Jordan, a country with limited internal natural resources, imports 94% of its energy from neighbouring countries, consequently being extremely reliant on external sources. The importance of renewable energy adoption has been emphasised by the nation's pursuit of energy sustainability and security. This study focuses on Irbid, Jordan's third-largest city, as an optimal starting place for addressing this challenge. The research evaluates the potential and effectiveness of powering Irbid's electricity demands with Photovoltaic (PV) technology. The study's objectives include a varied analysis, given the country's concentration on renewable energy adoption to offset its high reliance on energy imports. First, an assessment of the city's energy demand and consumption trends over the last decade attempts to provide insights into the city's evolving energy situation. Second, an assessment of Irbid's solar energy potential will be conducted, considering its climatic circumstances, and will be compared to the current energy requirements. The research aims to assess the potential power generation achieved by incorporating Photovoltaics (PV) into Irbid's energy framework. Furthermore, evaluating optimal PV storage, and conducting a cost-benefit analysis of PV alone and PV + Battery scenarios for Irbid's energy needs is a significant aspect of the research.

The System Advisor Model (SAM) software simulation results demonstrate that the PV + Battery scenario exceeds the PV-alone scenario, delivering greater power contributions to the grid. While both scenarios have a positive Net Present Value (NPV), the net capital cost of PV alone is less costly at USD 695,034,432 than the PV + Battery scenario at USD 1,477,598,372. PV has an NPV of USD 647,748,955, whereas PV + Battery has an NPV of USD 536,576,708. Furthermore, the Payback Period (PBP) for the PV-alone is shorter (7 years) than for the PV + Battery scenario (10 years), indicating a quicker initial investment recovery. Despite the positive financial indications for the PV scenario, the decision to favour PV + Battery integration is impacted by additional critical factors. These include the ability of the PV + Battery to generate more power, contribute to grid stability, and increase income production. The PV+ Battery effectively meets 90% of Irbid's power needs, saving USD 151,063,131. This system draws 10% from the grid during demand fluctuation, costing USD 16,784,792, unlike the PV-only option covering 60%, saving USD 100,708,745 but relying 40% on the grid at a cost of USD 67,139,183. Given the concerning trend of escalating electricity import prices, a strategic shift towards greater energy self-reliance becomes imperative. This paper offers a review of renewable energy solutions, offering critical insights for informed decisions in advancing Irbid's sustainable energy transition.

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Thank you for being the guiding lights on this remarkable journey.

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Nomenclature

Symbol	Description
PV	Photovoltaics
CSP	Concentrated Solar Power
AC	Alternative Current
DC	Direct Current
GDP	Gross Domestic Product
NEPCO	National Electric and Power Company
t.o.e	Tonne of Oil Equivalent
W	Watts
KW	Kilo Watt
KWH	Kilo Watt Hours
GWH	Giga Watt Hours
MWH	Mega Watt Hours
NDC	National Determined Contribution
KM	Kilometres
˚C	Degree Celsius
IDECO	Irbid District Electricity Company
EDCO	Electricity Distribution Company
MENA	Middle East and North Africa
Si	Silicon
ESS	Energy Storage System
CAES	Compressed Air Energy Storage
PHS	Pumped Hydro Storage
SAM	System Advisor Model
NPV	Net Present Value
PBP	Payback Period

1.0 Introduction

The global trend towards achieving greater sustainability and heightened environmental consciousness has prompted municipalities and nations around the world to reassess their energy consumption behaviours and investigate the feasibility of renewable energy sources as viable alternatives. Within this context, the city of Irbid, situated in the northern region of Jordan, has undergone a notable transformation in recent decades, evolving from a modest agricultural township into a thriving urban hub. This rapid urban development, accompanied by substantial population expansion and industrial advancement, has exerted unprecedented strain on Irbid's energy infrastructure. As the demand for electrical power continues to surge, the dependence on conventional fossil fuel-derived energy supplies has grown progressively unsustainable, giving rise to environmental challenges and apprehensions related to energy security.

Through utilising the sunlight that covers this area, Irbid city may become a role model for sustainable urban development by incorporating Photovoltaic (PV) technology into its energy infrastructure. This study investigates the viability of addressing this challenge by implementing photovoltaic (PV) technology in two distinct scenarios: PV alone and PV combined with battery storage. The first scenario explores direct solar energy conversion through PV panels, mitigating reliance on conventional sources and fostering grid integration. The second scenario delves into PV+ Battery integration, aiming to overcome intermittency issues by storing excess solar energy for later use. Each scenario presents opportunities and complexities that will shape Irbid's path toward a more resilient and environmentally conscious energy future.

The study is centred on addressing electricity demand coverage in Irbid, Jordan, through the integration of photovoltaics technology. This research follows a comprehensive methodology that transitions from a scoping study, employing scenarios with fixed assumptions to demonstrate the method and initial results, to a parametric study that explores system sizing options, cost ranges, and energy demands to capture uncertainties. The methodology concludes with the identification of an optimal configuration that accounts future demands and energy prices. The study intends to contribute to sustainable urban energy planning by examining renewable energy scenarios adapted to the environment of Irbid.

1.1 Research Background

Electricity is the lifeblood of economic activity, infrastructural development, and quality of life improvements in modern civilization, and its importance cannot be emphasised. According to various research, energy consumption is growing through time, demonstrating a link between the availability of energy resources and global growth. However, as Irbid grows at an exponential rate, traditional fossil-fuel-based energy sources are becoming more insufficient and harmful to the environment. Jordan, on the other hand, is actively pursuing renewable energy sources. Investors have demonstrated a strong interest in investing in Jordan to build projects geared at producing power, consequently improving the country's financial situation.

The global shift towards sustainable and environmentally conscious energy sources has prompted significant interest and research in the field of renewable energy. As conventional fossil fuels continue to contribute to climate change, resource depletion, and geopolitical tensions, the imperative to transition to cleaner and more sustainable energy alternatives has become evident. The concept of transitioning entire regions or even countries to 100% renewable energy has gained traction, necessitating comprehensive studies that address technical, economic, and social dimensions.

Renewable energy encompasses a diverse range of sources, including solar, wind, hydroelectric, geothermal, and biomass. The research landscape in renewable energy encompasses a range of disciplines, from engineering and technology development to policy and economics. Technological advancements in energy conversion, storage, and distribution have facilitated the integration of renewable sources into existing energy grids, paving the way for a decentralized and resilient energy infrastructure. Research efforts have also focused on optimizing the efficiency, reliability, and cost-effectiveness of renewable energy technologies, ensuring their competitiveness in the global energy market.

1.2 Research Questions

One of the study’s aims is to identify answers to the following questions on using renewable energy in Jordan, focusing on Irbid city as a case study. By addressing these questions, the research aims to provide comprehensive insights into the technical and economic aspects of electrifying Irbid through solar energy solutions, facilitating informed decision-making for sustainable urban development.

- What is the current energy demand and consumption pattern in Irbid, Jordan?

- What is the solar energy potential in Irbid, considering its geographical location and climatic conditions?
- What is the current energy mix in Jordan, and how much of the energy supply is reliant on conventional fossil fuel-based sources?
- What are the existing policies, regulations, and incentives related to renewable energy adoption in Jordan?
- How can photovoltaics (PV) technology be effectively integrated into Irbid's energy infrastructure?
- What is the most suitable and efficient battery technology to complement a photovoltaic (PV) system, and how does its selection contribute to enhancing the overall system efficiency, grid integration, and reliability?
- How do the cost-benefit analyses of PV technology differ in the context of Irbid's energy requirements?

1.3 Research Aim & Objective

The aim of this thesis is to assess the potential and effectiveness of powering the Jordanian city of Irbid by incorporating Photovoltaic (PV) technology into existing energy infrastructure. The study aims to investigate the potential of solar energy in Irbid, considering the city's growing population and energy consumption, and to determine the benefits and obstacles connected with the city's extensive adoption of renewable energy sources.

The study’s objectives are:

- Assess the current energy demand and consumption patterns in the city of Irbid, Jordan, and analyse how they have evolved over the past decade.
- Evaluate the solar energy potential of Irbid, considering its geographical location and climatic conditions, and compare it with the city's current and projected energy demand.
- Investigate the power that can be generated by Photovoltaics (PV) technology into Irbid's energy infrastructure.
- Identify the most suitable and efficient energy storage solution that complements the photovoltaic (PV) system.
- Conduct a cost-benefit analysis of a PV scenario alone and PV+ battery scenario technology in the context of Irbid's energy requirements.

1.4 Research Hypothesis

1.4.1 Main Hypothesis

H0: The integration of a Photovoltaic (PV) system into Irbid's grid could have a potential impact on covering the city's electricity demand, reducing dependency on conventional energy sources, and fostering sustainability.

1.4.2 Secondary Hypothesis

H1: Usage of PV system can cover Irbid’s electric demand and its fluctuation patterns.

H2: The PV system's electricity generation will demonstrate a positive correlation with solar irradiance levels in Irbid, resulting in high energy output during peak sunlight hours.

H3: During periods of low solar irradiance, the energy storage capability of the integrated PV system, combined with suitable battery technology, will enable continuous electricity supply, and enhance grid stability.

H4: The economic analysis of the PV system integration will demonstrate a favourable return on investment, indicating that transitioning to renewable energy sources is financially viable for Irbid's grid.

1.5 Approach and Chapter Descriptions

This thesis adopts a structured approach with nine interconnected chapters to comprehensively investigate the feasibility of integrating Photovoltaic (PV) technology for addressing Irbid's electricity demand. Beginning with an introduction highlighting Jordan's energy challenges and Irbid's significance, followed by a literature review encompassing Jordan's renewable energy landscape and Irbid's specific context, the methodology chapter outlines research strategies. The subsequent chapters analyse Irbid's electricity demand trends, present simulation results for PV and PV + Battery scenarios, conduct a cost-benefit analysis, assess associated risks, and conclude with a reflection on findings. The final chapter proposes future research directions. This approach ensures a systematic exploration of renewable energy's potential in Irbid, aiding in the formulation of effective energy strategies for sustainable development.

1.6 Research Scope

This thesis undertakes analysis to assess the potential of Photovoltaic (PV) systems and PV + Battery systems in meeting the electricity demand of Irbid, Jordan. The study aims to shed light on the viability and effectiveness of these renewable energy technologies within the context of the city's energy requirements. The research objectives encompass a thorough evaluation of the following aspects: Firstly, the capability of PV systems to generate electricity and contribute to fulfilling Irbid's electricity demand. Secondly, the exploration of the benefits associated with integrating battery storage alongside PV systems to enhance energy reliability and optimize utilization. Lastly, a critical assessment of the economic feasibility of both standalone PV and PV + Battery scenarios concerning Irbid's unique electricity demand characteristics.

However, this study operates within specific boundaries. Firstly, due to time constraints and limited data, the analysis is limited to a particular timeframe, thus offering a snapshot of Irbid's electricity demand and renewable energy potential rather than a comprehensive long-term view. Moreover, this research narrows its scope to PV systems and PV + Battery systems, excluding the consideration of other solar generation technologies such as Concentrated Solar Power (CSP). Additionally, the exploration of non-electrical load transitions—such as the shift of transport and heating to electricity—is constrained by data availability, specifically city level data. While the study employs data from Jordan as a whole, the details required for a comprehensive analysis of load transitions at the city level is unavailable within the given timeframe.

Nevertheless, the groundwork laid through the methodologies and datasets developed within serves as a steppingstone for future research interests. The framework established holds the potential to be expanded, incorporating other renewable energy technologies like CSP, and investigating deeper into the transition of non-electrical loads to electricity with more localized data. As such, this research contributes to an enriched understanding of Irbid's renewable energy potential while acknowledging its defined scope, limitations, and avenues for future exploration.

2.0 Literature Review

The integration of renewable energy sources has emerged as a crucial strategy to address the growing energy demand and environmental challenges faced by rapidly urbanizing cities worldwide. This literature review section aims to critically analyse and synthesize the existing body of knowledge surrounding the electrification of urban areas through Photovoltaic technologies. By examining a diverse array of scholarly works, research articles, reports, and case studies, this review intends to highlight the current state of research, identify gaps in knowledge, and provide a comprehensive understanding of the potential challenges and opportunities related to implementing Photovoltaic system in Irbid city.

2.1 The Country of Jordan

The state of Jordan, known as the Hashemite Kingdom of Jordan, is an Arab country located in the Middle East. Jordan is named after the Jordan River that runs through its western boundaries. Jordan is regarded as a country that incorporates several Arab cultures and dialects. Jordan is a country rich in history which has hosted some of humanity's first towns and communities [1]. Depicted in Figure 1, Jordan's geographical confines encompass Syria to the north, Iraq to the northeast, Israel and the Palestinian National Authority to the west, and the Kingdom of Saudi Arabia to the east and south. Furthermore, its southwestern edge is characterized by the Gulf of Aqaba, where the city of Aqaba commands a viewpoint over the expanse of the Red Sea [2]. Jordan is around 88,794 km² and is divided into 12 provinces including the capital city Amman and Irbid. Jordan's population is estimated to be around 11,057,000 million in 2021 [6]. Jordan's climatic profile results from the convergence of Mediterranean region climate characteristics and the arid desert landscape; the northern and western sectors are primarily influenced by the Mediterranean basin climate, while the remainder of the country is characterized by a desert climate [4]. Jordan's weather is hot and dry in the summer but warm and wet in the winter. The temperature often fluctuates between 12 and 25 degrees Celsius. Summer temperatures in arid locations might exceed 40 degrees Celsius. The average annual rainfall ranges from 50 mm in the desert to 800 mm in the northern highlands, and it occasionally snows [5].

Figure 1: Jordan Map [3]

2.1.1 Energy Situation in Jordan

Jordan faces major challenges in maintaining its energy demands due to the lack of substantial domestic natural resources. Compared to several of its oil-rich neighbours, Jordan's energy landscape is marked by low indigenous fossil fuel sources, leaving the country significantly reliant on energy imports from other countries. Jordan relies on neighbouring nations for fuel security, namely the Arab Gulf nations, Iraq, and Egypt [12]. This reliance on external fuel sources has not only brought economic issues but has also emphasised the significance of diversifying the country's energy mix to maintain energy security and sustainability. According to the Ministry of Energy and Mineral Resources (MEMR), Jordan imported 94% of its energy needs in 2018, accounting for roughly 10% of the country's gross domestic product (GDP) [7].

Jordan's demand for electricity is rising as the country's economy expands across several industries. The influx of 750,000 Syrian refugees into the nation over the previous seven years has further increased demand [8]. The refugee crisis, along with the disruption of relatively inexpensive natural gas imports from Egypt, forced Jordan to reconsider its energy security, and the energy issue has emerged as one of the country's top political and economic objectives [9].

As illustrated in Figure 2, imports account for most energy supply. Between 2005 and 2017, energy imports accounted for 98.7% of total primary energy supply [7]. Imports fell to 94% of primary energy supply in 2018 because of efforts to diversify energy sources and investment in renewable energy [9]. In Jordan, around 39% of primary energy is utilised for electricity generation, which is mostly derived from natural gas and oil [10]. According to the National Electric and Power Company (NEPCO), imported natural gas accounted for 93% of total electrical output in 2018, with the remainder generated from crude oil, solar, and hydropower [11].

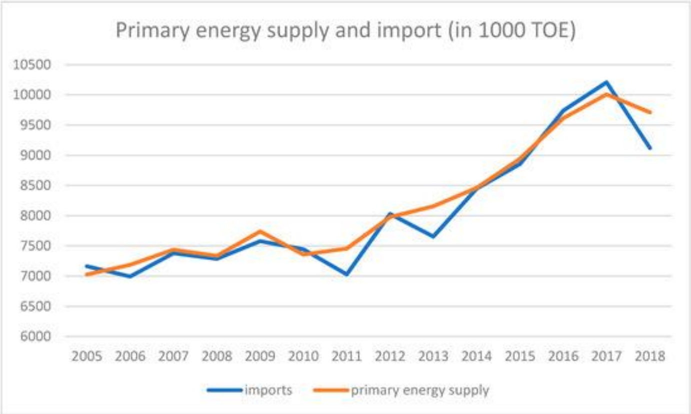


Figure 2: Jordan's energy Supply and Imports [9]

2.1.2 Energy Consumption in Jordan

The State of Jordan relies on various sources of energy, where crude oil and petroleum derivatives are the main source for consumption. Renewable energy resources are increasing year by year. Table 1 presents the consumed primary energy data from the Ministry of Energy and Mineral Resources (MEMR) in Jordan from 2017 up to 2019 [16].

Table 1: Consumed Primary Energy 2017-2019 (thousand t.o.e)

Year	Crude Oil	Natural Gas	Renewable Energy	Coal & Petroleum	Electricity	Total	Percentage Change
2017	5671	3510	515	313	13	10022	4.2
2018	5225	3438	753	297	47	8760	-2.6
2019	5518	3509	756	311	42	10136	3.85

As demonstrated in Table 2, the transport sector ranks first in Jordan in terms of consumption, with the percentage increasing through the years [16]. In 2017, most Jordan's passenger vehicles operated on diesel and petrol fuel. Only a modest number of 0.23%, or 3586 vehicles, were powered by electricity [17]. Jordan has historically relied on other nations for gasoline and is thus vulnerable to rises in fuel prices. Because of its reliance on imported energy, it has the potential to make considerable use of electric vehicles in the coming years.

Its region-leading position as a country actively constructing renewable energy projects provides the availability of a renewable and clean transportation system that will enable the transition to electric Vehicles [17].

Table 2: Sectorial Distribution & Percentage Consumption of Energy (thousand t.o.e)

Year	**Transportation**		**Industry**		**Household**		**Others**		**Total**	**Perc. Change**
	Quant	**%**	**Quant**	**%**	**Quant**	**%**	**Quant**	**%**		
2017	3431	50	938	14	1549	23	950	13	6868	7.0
2018	3363	49	954	14	1463	21.5	981	15.5	6761	-1.6
2019	3401	50	942	14	1452	21	973	14.5	6768	0.1

Jordan provides access to electricity to its people, with access to power available to both rural and urban inhabitants. As shown in Figure 3, electricity usage has been gradually growing, with homes accounting for most of it. In 2018, residentials utilised 46% of the power, industry 22%, water pumping 16%, commercial 14%, and street lighting 2% [9].

Jordan's electrical system's peak demand in 2019 hit 3380 MW in January, up from 3205 MW in 2018, representing a 5.5% increase [12]. Jordan's energy consumption is expanding at a rapid pace. The rate of demand will continue to accelerate. Using the forecasting approach, the predicted energy load in Jordan until 2040 has a demand increase rate of roughly 3% [12].

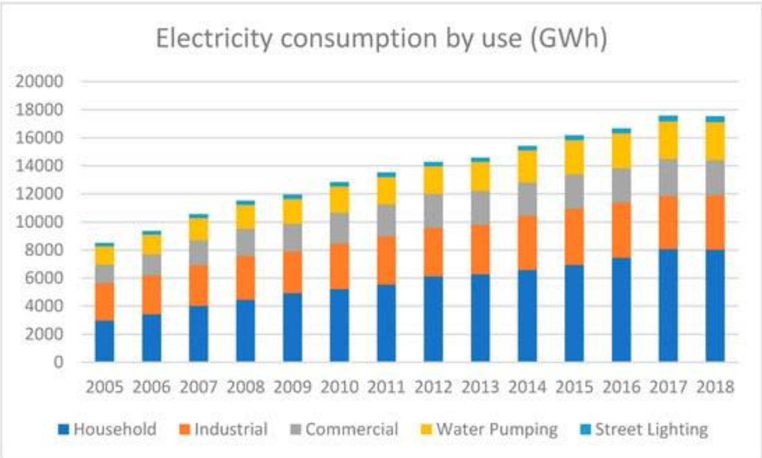


Figure 3: Electricity Consumption by Sector in Jordan [9]

In its 2021 annual report, Jordan's National Electric and Power Company illustrated the summer and winter peak trends. This suggests that there are two significant peak loads during the year, which occur in the winter and summer. As seen in Figure 4, power demand begins to rise at 5 a.m. Peak demand occurs in the evening between 5 and 6 p.m. Then it begins to fall throughout the night. Figure 5 demonstrates that throughout the winter, people experience the same patterns as during the summer, but with slightly reduced power use. During the summer, daily peak demand might exceed 3770 MW. During the winter, daily peak demand could reach 3450 MW [13]. Nonetheless, Jordan consumed around 19619 GWh of electricity in 2021 [13].

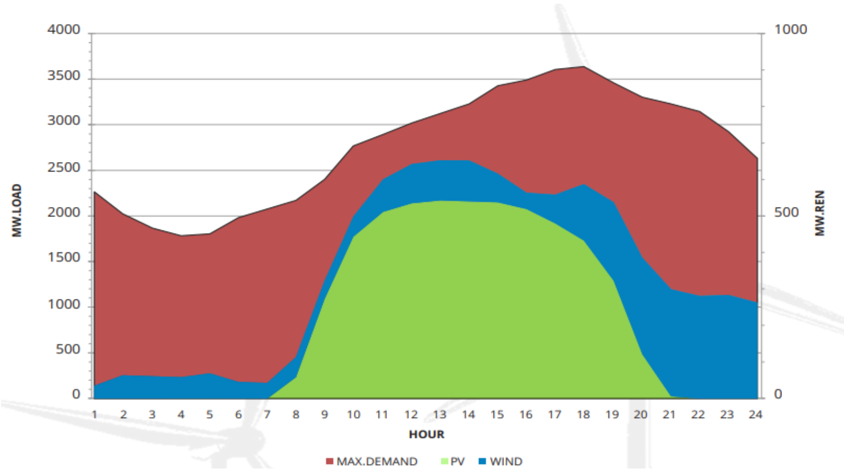


Figure 4: Summer Peak load Curve on July 19, 2021 [13]

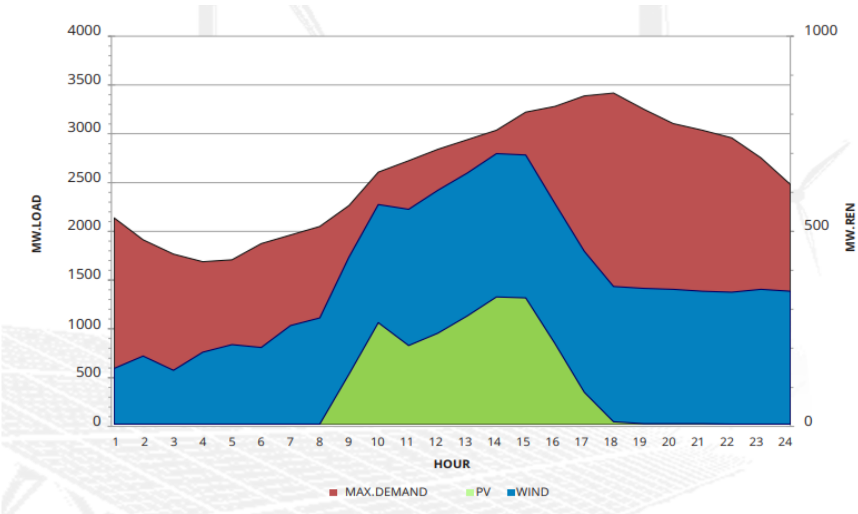


Figure 5: Winter Peak Load Curve on December 20, 2021[13]

2.1.3 Renewables in Jordan

Due to factors such as its 316 days of annual sunshine, wind speeds averaging between 7 to 8.5 m/s, and desert regions with low population, Jordan possesses enduring prospects for expanded utilization of renewable energy sources. Within this context, the establishment of renewable energy power facilities in Jordan has played a critical role, effectively contributing to Jordan's strategic efforts to diversify energy sources, reduce reliance on conventional fuels, and promote the advancement of sustainability. In the previous decade, significant progress has been achieved by Jordan in the formulation and execution of diverse renewable energy initiatives, emphasizing on solar and wind energy. Within the Middle East region, Jordan has established itself as a frontrunner in the integration of renewable energy sources. Therefore, solar and wind energy collectively contribute to more than twenty percent of Jordan's electrical grid, and the nation has set forth an ambitious objective of attaining a 31% share by the year 2030 [14]. Jordan's National Energy Strategy 2020-2030 focuses on promoting energy security by improving energy efficiency and boosting renewable energy. It expects that by the end of 2030, 48.5 percent of the country's electricity would be generated locally. Furthermore, in accordance with Jordan's Paris Agreement commitments, the Jordanian government increased its 2016 Nationally Determined Contribution (NDC) objective in October 2021, vowing to reduce greenhouse gas emissions from 14% to 31% by 2030 [14]. In addition to large-scale solar power plants, Jordan has been promoting rooftop solar installations in residential, commercial, and industrial buildings. These distributed solar projects contribute to decentralized energy generation and encourage individual stakeholders to participate in the country's renewable energy transition.

Some of the notable renewable energy power plants in Jordan include:

1. Shams Ma'an Solar Power Plant: Located in Ma'an governorate, with a capacity of around 52.5 MW [15].

2. Tafila Wind Farm: Situated in Tafila governorate, with a capacity of approximately 117 MW [15].

3. Quweira Solar Power Plant: located in Aqaba governorate and has a capacity of around 103 MW [15].

To attract new investments, the government is also taking further steps to expedite the licencing of renewable energy projects by establishing a "one-stop-shop" office at the Jordan Investment Commission [9]. As a result, several renewable power facilities are now under development, such as the Baynouna solar energy project. The 200 MW photovoltaic system will serve 110,000 houses with yearly power and replace an estimated 360,000 tonnes of CO2 emissions. The project will create 563.3 GWh of power, which is comparable to 3% of Jordan's annual energy consumption [15].

2.2 The Case Study Governate of Jordan: Irbid

Irbid is the country's third-largest city and one of its major urban centres. Irbid is located in the northern region of Jordan, approximately 50 kilometres north of the capital Amman and 15 km south of the Syrian Jordanian border [18]. As a historical city with a rich heritage, Irbid has experienced significant growth and transformation over the years, becoming a vibrant hub of education, commerce, and culture.

The population of Irbid has grown dramatically over the years, driven by economic possibilities, educational institutions, and improved living conditions. According to official estimates, the population of Irbid is 2,050,300 in 2021, making it the most populated city after Amman. Irbid has a land area of approximately 1,572 km^2 [6]. Internal and external migration from rural regions and other parts of the country seeking improved economic prospects, work opportunities, and access to higher education institutions has contributed to the city's population expansion. The presence of Yarmouk University and Jordan University of Science and Technology has also brought many students to Irbid, making it a lively atmosphere [19]. Figure 6 shows a map of Irbid indicating it as an urban area.

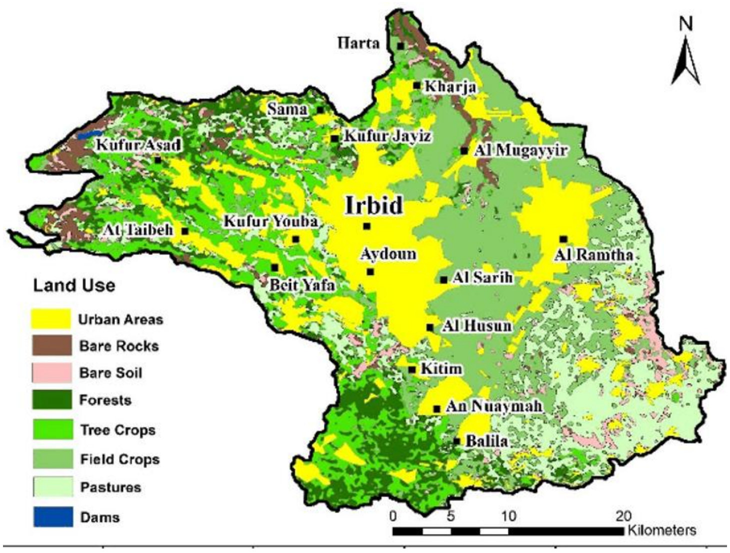


Figure 6: Irbid Map [62]

2.2.1 Climate in Irbid

The seasonal variations in Irbid's climate, including hot summers and cooler winters, can cause fluctuations in electricity consumption. The demand for electricity is typically higher during extreme weather conditions when residents and businesses rely on electrical appliances to regulate indoor temperatures. The climate in Irbid can have a significant impact on electricity consumption patterns. According to Irbid Climate Data summer months are June, July, August, and September. The driest month is July. Irbid experiences hot and dry summers, with temperatures often exceeding 35 degrees Celsius (95 degrees Fahrenheit) [20]. During the winter months, Irbid experiences cooler temperatures, with occasional rainfall. As the temperature drops, there is a higher demand for heating systems, such as electric heaters or central heating systems. Figure 7 shows the maximum, minimum, and the average temperature in Irbid thought the year. In July and August, the temperature can exceed 34 ˚ C. In January, the maximum temperature is 15 ˚ C, and minimum is 4.9 ˚ C [20].

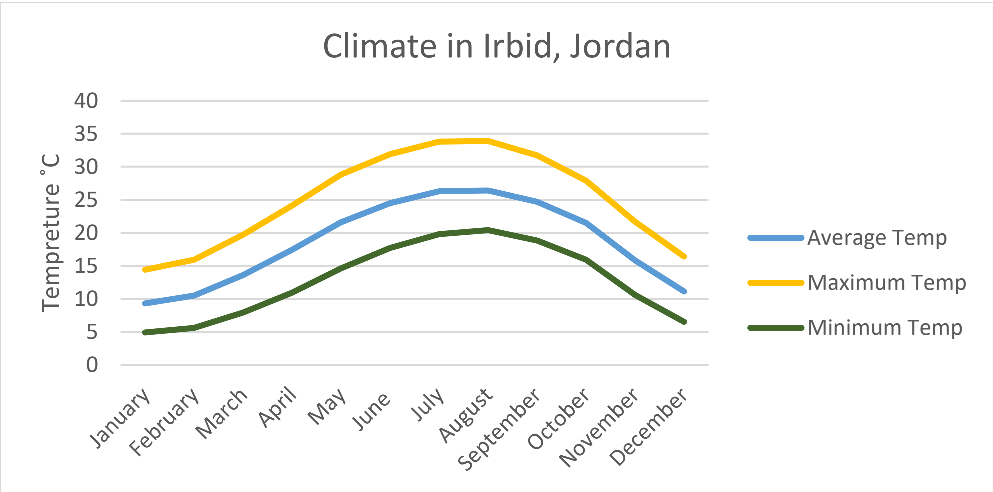


Figure 7: Climate in Irbid, Jordan

The number of daylight hours can also influence electricity consumption. Longer daylight hours during the summer can result in reduced demand for indoor lighting, which can contribute to a decrease in electricity consumption. Conversely, shorter daylight hours during the winter may lead to higher electricity usage for lighting purposes. As shown in Figure 8, the month with the most sunshine in Irbid in June, average of 11.54 hours daily. January is the fewest sunshine hours with an average of 7.11 hours daily [20].

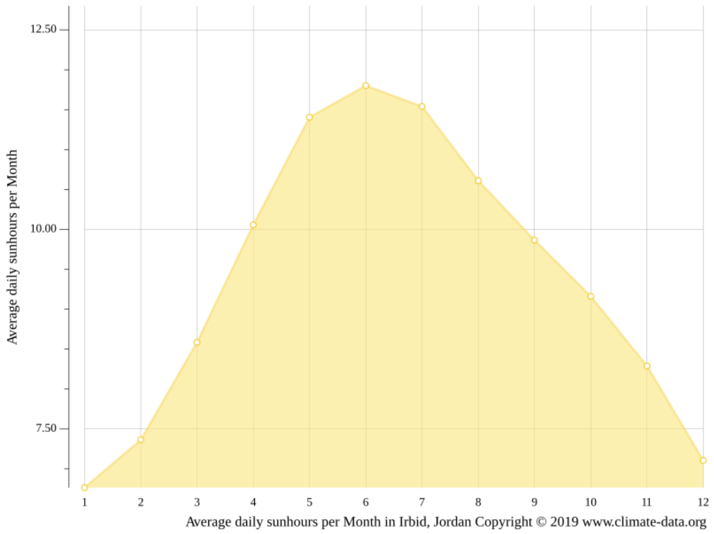
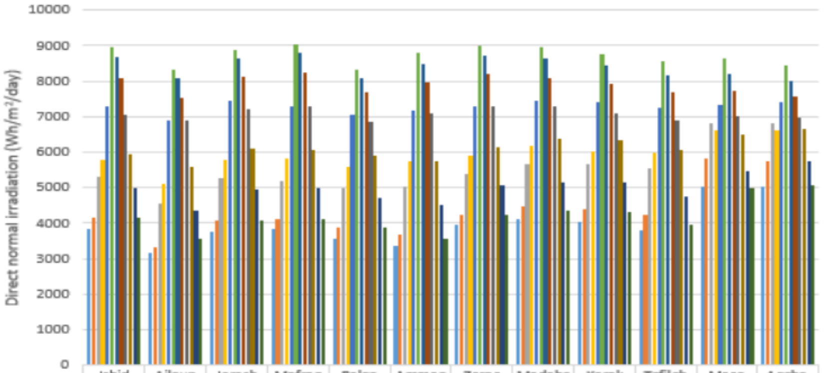


Figure 8: Average Sunlight per Month in Irbid [20]

Electricity demand in Jordan is vast due to the quantity of energy consumed to meet the requirements for heating, cooling, lighting, etc. The availability of solar radiation information becomes critical in this regard to aid in the design and construction of solar energy applications. The quantity of solar energy received on a surface per unit area from the sun's rays directly in line with the surface is termed as direct normal irradiance [21]. Figure 9 depicts Jordan governorates' direct normal radiation in Wh/m2/day. It is stated that Irbid experiences the highest levels of direct normal radiation in June, July, and August. The greatest radiation level is 8950 Wh/m2/day in June. The most direct normal radiation occurs in June for all Jordan governorates, with an average irradiation of around 8500 Wh/m2/day. While January has the lowest direct normal radiation in Irbid, with an irradiation of 3820 Wh/m2/day [21].



	Irbid	Ajloun	Jerash	Mafraq	Balqa	Amman	Zarqa	Madaba	Karak	Tafilah	Maan	Aqaba
Jan	3820	3160	3740	3850	3570	3370	3960	4110	4040	3790	5010	5020
Feb	4150	3320	4070	4100	3870	3690	4240	4480	4390	4240	5820	5730
Mar	5300	4550	5270	5190	4980	5030	5390	5660	5650	5550	6830	6820
Apr	5780	5120	5800	5840	5590	5740	5890	6180	6030	5970	6610	6630
May	7310	6890	7470	7290	7040	7190	7310	7460	7430	7240	7330	7430
Jun	8950	8310	8890	9040	8330	8800	8980	8940	8750	8570	8650	8430
Jul	8700	8070	8660	8810	8100	8490	8730	8660	8430	8160	8210	8010
Aug	8090	7530	8120	8230	7690	7970	8190	8100	7920	7670	7720	7560
Sep	7040	6880	7210	7310	6870	7080	7280	7290	7090	6900	7020	6960
Oct	5940	5570	6090	6060	5920	5730	6140	6390	6330	6050	6490	6640
Nov	4980	4350	4940	4970	4710	4500	5050	5130	5160	4740	5470	5730
Dec	4160	3560	4060	4130	3860	3570	4230	4340	4330	3960	5000	5060

Figure 9: Solar Direct Normal Radiation of Jordan Governorates in Kwh/M2 /Day. [21]

Throughout the year, Irbid has low rate of rainfall. Figure 10 demonstrates that January is the wettest month, with 43mm (1.7in) of rain in Irbid. Figure 10 illustrates June, July, August, and September as dry months with 0 mm of precipitation. Figure 11 indicates the average number of rainy days in Irbid every month. The month of January has an average of 10 days with rainfall; however, the summer months lack the probability of rain [22].

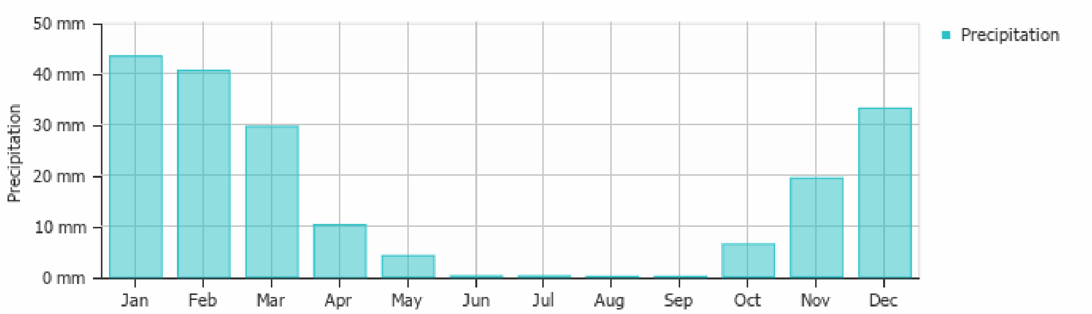


Figure 10: Average precipitation in Irbid [22]

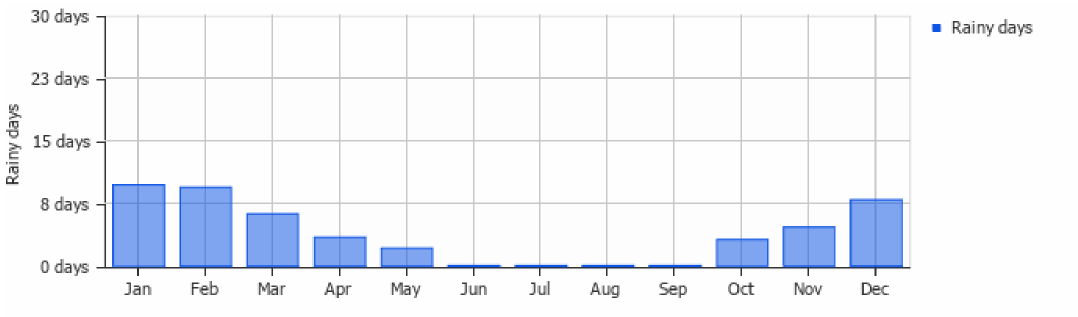


Figure 11: Average rainy days in Irbid [22]

2.2.2 The Electric Provider

Irbid receives its electricity supply through the national grid managed by the National Electric Power Company (NEPCO). NEPCO is responsible for generating, transmitting, and distributing electricity across the country, including Irbid. Irbid, being one of the major cities in Jordan, is well-connected to the national grid infrastructure. High-voltage transmission lines carry the electricity from the power plants to the city. The distribution of electricity within Irbid is handled by the local distribution company that is the Irbid District Electricity Company (IDECO), which is a subsidiary of the Electricity Distribution Company (EDCO) [23].

The Irbid District Electricity Distribution Company (IDECO) is a significant entity responsible for electricity distribution and related services in the Irbid Governorate, Jordan. Irbid electricity company was established in 1957 to which the company obtained the right to generate, transmit and distribute electric power. IDECO has control of distribution of electricity in northern Jordan, covering a concession area of 23,000 km² that includes Irbid, Jerash, Ajloun, Mafraq, and sections of Balqa. Operating under the National Electric Power Company (NEPCO), IDECO plays a crucial responsibility in guaranteeing dependable and effective electricity provision to the local inhabitants, commercial establishments, and industrial sectors within the area [24].

2.2.3 Electricity Demand in Irbid

According to the annual report of the Irbid District Distribution Company, the governorates utilised a total of 3421.800 GWh in 2022. As stated in Table 3, Irbid consumed roughly 1900.804 GWh in 2022, accounting for more than half of total consumption. This is the result of Irbid's larger size and population [25]. Refer to Chapter 4 for analysis of the electricity consumptions patterns in Irbid.

Table 3: Consumption by Governorate in 2022 [25]

Governorate	Consumption (GWh)	Percentage
Irbid	1900.804	55.55%
Mafraq	1045.478	30.553%
Jerash	275.044	8.038%
Ajloun	200.474	5.859%
Total	3421.800	100%

According to Irbid Electricity annual report, residentials in Irbid accommodate for more than half of the electricity consumption with a percentage of 50.83%. As shown in Figure 12, industrial and commercial sectors include banks, hospitals, telecommunication companies, and other sectors use up to 37.77% of electricity. Water pumping takes around 7.09%, streetlights around 4.28% and electric cars around 0.04% [25].

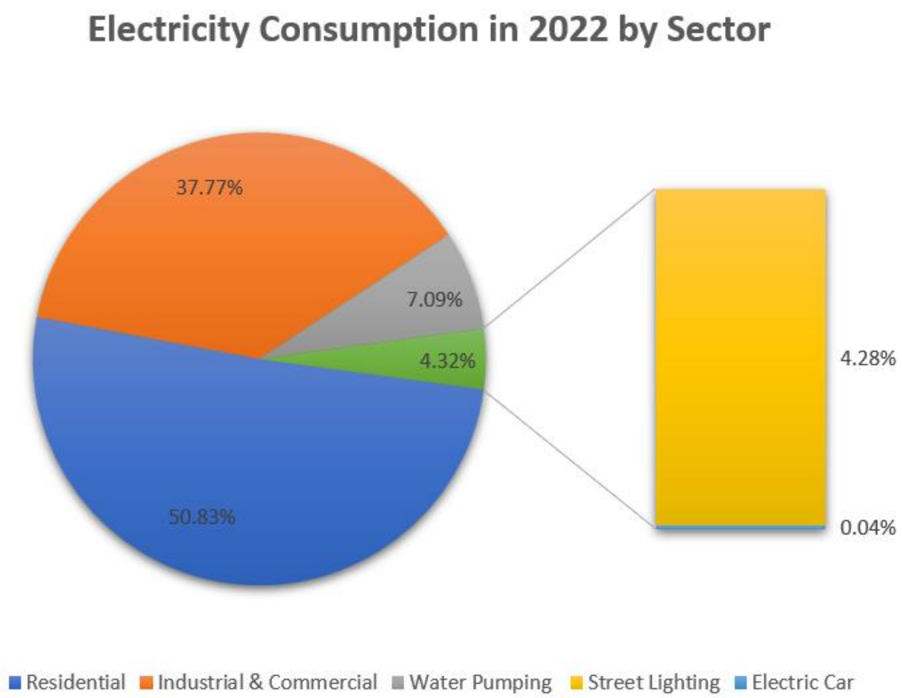


Figure 12: Electricity Consumption by Sector, 2022

2.3 Renewable Energy

As governments attempt to address the critical concerns of energy security, climate change, and environmental sustainability, the worldwide shift to renewable energy sources has gained substantial traction in recent years. With increasing concern about greenhouse gas emissions and the limited nature of fossil fuels, renewable energy technologies have emerged as a feasible answer to address the world's escalating energy demands.

Many energy models were recently designed and computerised to aid in planning. Every model serves a distinct goal, such as policy evaluation, environmental effect, or demand-supply matching. Also, many scholars from across the world have recently examined the transition to a 100% renewable power grid. Wind, PV, pumped hydro, and a small amount of biomass were used in a simulation of 90-100% renewable power scenarios for portions of Australia. They determined that renewable energy systems of 90% and 100% could fulfil power demand at a reasonable cost [28]. In Germany, several techniques for increasing the amount of renewable energy in the energy system were presented. A cost-effective transition path to 100% renewable energy in Germany was investigated. Savings were demonstrated to be essential to keep within renewable energy and biomass resource potentials. Furthermore, some technologies, such as electric vehicles, heat pumps, and electrolysers, improve energy system efficiency while also enhancing system flexibility and allowing for the incorporation of additional renewable electricity [29]. In Japan, another study was done, this time focusing on the practicality of such systems as well as the issue of synchronous generation. Analysis of solar and wind power generation using batteries and pumped storage found that a 100% renewable energy electricity mix was feasible [30].

The Middle East and North Africa (MENA) region has the world's largest potential for renewable energy generation. However, as fossil fuel-generated power continues to dominate many countries' total energy mix, only a few nations have taken use of this potential. Morocco has made a significant investment in renewable energy by constructing a large solar power plant; nevertheless, this investment has yet to deliver any notable environmental benefit. In 2010, fossil fuels accounted for approximately 93% of Algeria's entire energy mix. As a result, Algeria has set a target of producing 22,000 MW of electricity from renewable sources between 2011 and 2030. Bahrain aims to generate 5% of its power from renewable sources by 2030. Iran presently generates 0.2% of its energy from renewable sources, whereas Israel and Jordan produce 2.6% and 11%, respectively [31].

Nonetheless, researchers in Jordan have performed several studies to transition to 100% renewable energy. A study was done to achieve a fully sustainable energy system throughout Jordan's power, heat, transportation, and desalination sectors by 2050, demonstrating that Jordan's transition to a 100% Renewable energy system would be possible. According to the findings, Jordan will need around 25 GW of solar PV, 11 GW of CSP, and 5 GW of wind power, together with 90 GWh of storage capacity, to reach a 100% RE-based system by 2050. According to the authors, a 100% renewable electricity scenario is cost-effective and reduces

CO_2 emissions and the requirement for energy imports to zero by 2050 [32]. Another research was undertaken to fully address Jordan's power requirement in 2050. According to this estimate, the kingdom requires around 43 CSP (250 MW, 8 h storage), 39 wind farms (117 MW), and 500 PV projects (50 MW). A 90 GWh storage system can stabilise the grid and address the dispatchability problem [33].

2.3.1 Photovoltaics (PV)

Photovoltaic technologies are crafted by directly transforming sunlight into energy through the utilization of semiconductors, typically composed of silicon. When sunlight impacts the surface of these cells, photons within the semiconductor material dislodge electrons, leading to the generation of an electric current [34]. Solar photovoltaic (PV) cells, responsible for converting solar radiation into electrical power, represent a well-established renewable energy technology undergoing swift expansion. Evidence suggests that solar PV performance is now comparable to conventional energy sources in terms of energy payback duration, greenhouse gas emissions, and levelized cost of electricity [35]. One of the drawbacks with PV technology is its reliance on sunshine, which means that power generation is confined to daylight hours and sensitive to changes according to weather conditions [35]. PV systems may be used for large-scale utility installations as well as small-scale distributed energy applications like rooftop solar panels on residential and commercial buildings. Rooftop PV systems have recently seen widespread installation because to their technical, economic, and socio-environmental benefits. Rooftop PV systems connected to the grid may be a critical component of Jordan's transition to energy sustainability, with fast decreases in the cost of PV modules and increases in their efficiency [36].

2.3.2 Photovoltaics Types

Photovoltaics technology has experienced remarkable advances in efficiency, cost-effectiveness, and durability in recent years. As a result, understanding the differences between different PV cell types has become crucial for selecting the most suitable technology for certain applications and geographical locations. There are varieties of solar cells in the photovoltaic domain, each with a particular set of features and performance characteristics. Monocrystalline PV cells have a high efficiency, often ranging from 15% to 20%, making them more expensive than other systems. Polycrystalline PV cells have a lower efficiency, from 13% to 16% on average. The efficiency of amorphous Si PV cells is the lowest ranging from 6% to 10% [39].

In Casablanca, researchers investigated the performance of silicon-based photovoltaic modules of Monocrystalline, Polycrystalline, and Amorphous. The results show that mono and polycrystalline provide the maximum performance. However, in adverse weather circumstances, the amorphous modules begin to operate better because to their improved management of diffused irradiation [37]. According to another case study conducted in Morocco, monocrystalline has the greatest yearly average AC energy output, followed by polycrystalline and amorphous [38]. The selection of the most suitable PV type depends on the project's budget, performance requirements, and environmental factors.

2.3.3 Battery Energy Storage

PV systems often require independent energy storage options such as batteries to overcome intermittency [34]. An ideal energy storage system (ESS) would be able to store the energy provided by renewable energy technologies. Compressed air energy storage (CAES) systems use surplus energy to compress air into an underground storage tank through compressors. The CAES system has the benefit of a quick reaction time and strong performance at partial load. Additionally, this technology may be linked with renewable energy sources to increase output power [40]. In the Pumped Hydro Storage (PHS) system, water in a storage tank reservoir is pushed at a high altitude utilising minimised energy. PHS has the benefit of being able to store and return a substantial quantity of power to the grid also, this system has a rapid reaction time of up to a few seconds when discharging and charging [41]. Battery storage systems are recognised as critical technology for decarbonizing mobility and promoting the integration of intermittent renewable energy into EU policy. Battery storage technologies have a substantial disadvantage in terms of cost and afterwards disposal [42]. Many battery technologies, including lead-acid, nickel cadmium, sodium (sulphur), lithium-ion, and sodium (nickel chloride), are suitable for use in PV systems. Because of their low cost, and high effectiveness, lead-acid and lithium-ion batteries are often regarded as the most advanced technology [44].

Jordan's energy storage system must be carefully chosen since Jordan has limited energy and water resources [43]. Pumped hydro storage systems are not practical in Jordan due to the scarcity of water. However, for CAES systems, it is recommended that empty subsurface natural gas catchments be utilised for storage. As Jordan has a limited number of natural gas wells, compressed air energy storage is not recommended. Finally, batteries are recommended for use because of their cost benefits over alternative energy storage methods. Also, integration of batteries with renewable energy systems decreases CO2 emissions by 16% [43]. Batteries have the capability to release stored energy when demand reaches its peak, thereby alleviating pressure on the grid and potentially sidestepping the necessity for expensive enhancements to grid infrastructure to accommodate peak usage [44].

3.0 Methodology

The methodology used in this research is to investigate and address the electricity-related challenges faced by Jordan's Irbid city, with a focus on the use of renewable energy resources to meet its power requirements. Irbid's rapid urbanisation has resulted in increasing energy needs, prompting an investigation into sustainable options that reduce dependency on fossil fuels and mitigate environmental impacts. In this regard, the methodology revolves around a comprehensive assessment of Irbid's electricity demand, simulation of Photovoltaics (PV) and PV + Battery technologies using SAM software, a cost-benefit analysis to evaluate the feasibility and potential benefits of adopting renewable energy systems, and risk analysis to include any uncertainty and limitations. This study aims to pave the road for informed decision-making in Irbid, Jordan, towards a greener and more profitable electricity resources.

The chosen methodology is a structured progression through distinct stages, designed to comprehensively analyse renewable energy integration for electricity demand coverage in Irbid city. It initiates with an information gathering phase, transitions to the determination of a representative demand profile using Microsoft Excel, and then progresses to scenario analysis. The initial stage employs scenarios with fixed assumptions, effectively illustrating the methodology's application and presenting preliminary outcomes. Subsequently, a parametric study investigates a spectrum of system sizing options, cost ranges, energy demands, and uncertainties. The final goal is to achieve an optimized and robust configuration that anticipates future energy requirements and evolving market dynamics. This study is based on practical and theoretical approaches for collecting and analysing data from Irbid, Jordan, as demonstrated in Figure 13:

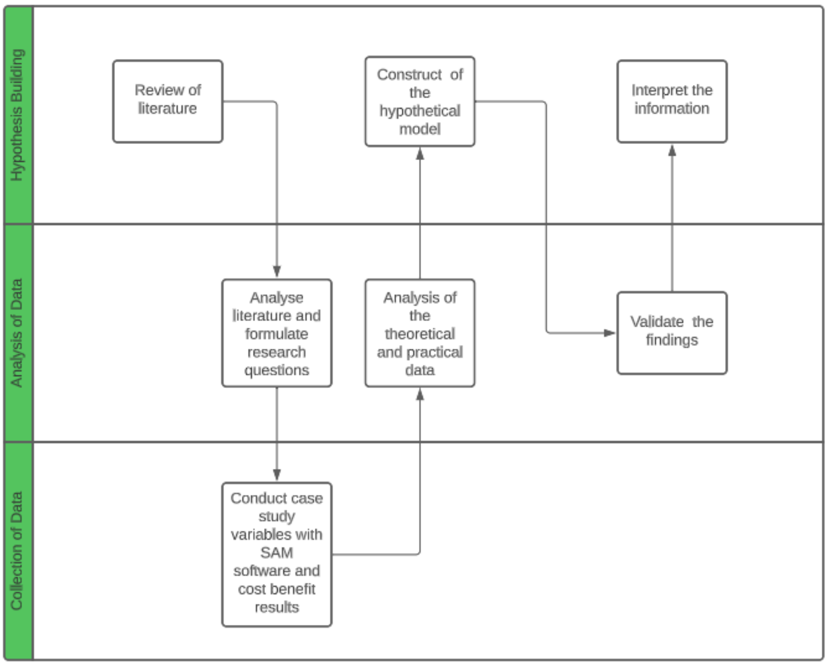


Figure 13: Flowchart of the Methodology

3.1 Electricity Demand Analysis

The initial phase of the methodology involves extensive data collection and analysis of Irbid's electricity consumption patterns, demographic trends, and other factors influencing energy demand. The information is gathered through an examination of Irbid District Electricity Distribution Company's annual report data. The consumption trend is evaluated through data from Jordan's National Electric Power Company. Time-series analysis and regression techniques will be used to uncover trends and patterns concerning electricity consumption. Finally, using Microsoft Excel programme, the obtained data on energy use will be evaluated yearly, monthly, and hourly.

3.2 Modelling and Simulation

System Advisor Model (SAM) software, a widely used tool for renewable energy system simulation, will be employed to model and simulate the performance of PV and PV + Battery systems. System Advisor Model is a free modelling programme that uses a techno-economic mode to help renewable system designers make decisions. The National Renewable Energy Laboratory in SAM model can build a variety of renewable energy systems, including photovoltaic systems, battery storage, concentrated solar power systems, wind power, and marine energy [26].

The goal of this study is to analyse the generated energy from two scenarios: PV scenario, and PV+ battery scenario. The simulation and modelling technique displays the electrification of a city using renewable solar energy resources, investigates the requirements for several scenarios, and determines which scenario is most suited for installation.

Prior to conducting simulations through SAM software, the following information will be explained and entered into the software:

Weather Data: The programme extracts the ambient weather conditions that will affect the output from a weather data file, either by uploading the file or by using the latitude and longitude.

Photovoltaic System (PV): Specifications for PV and inverter features are required to be selected in the software. The tilt and azimuth of the PV plates, as well as the number of PV models and inverters, may be determined by the designer.

Battery Storage: enables the designer to evaluate the performance of several battery types such as lead-acid, lithium-ion, vanadium redox flow, and all iron flow. The battery capacity and required bank power may be selected and examined as well.

3.3 Cost-Benefit Analysis

Cost Benefit Analysis is a systematic technique used by organisations to choose which measures to take and which to disregard. Before establishing a fresh business or project, the strategic manager does a cost-benefit analysis to assess all the potential expenses that a user might encounter. The outcome will indicate if the project's activity is financially possible or whether another step should be taken [27].

The cost-benefit analysis will assess the overall economic impact of integrating PV and PV+ Battery systems into Irbid's electricity infrastructure. The analysis will consider capital costs, Net Present Value (NPV), and Payback Period (PBP). Financial benefits of potential revenue from surplus energy sales, and avoided costs associated with conventional fuel imports. The outputs from SAM software simulation and the analysis of cost associated with each scenario will help in guiding which scenario to consider.

3.4 Risk Analysis

Risk analysis is a comprehensive process that involves identifying, evaluating, and quantifying potential uncertainties, threats, and vulnerabilities associated with a specific project, decision, or situation. This systematic assessment aims to understand the likelihood and potential impact of various risks, allowing for informed decision-making, strategic planning, and the implementation of appropriate mitigation measures to minimize the negative effects of unforeseen events and maximize the chances of achieving desired outcomes.

4.0 Electricity Demand Analysis

Electricity usage in Irbid city has increased significantly over the years, owing to reasons such as rapid urbanisation, population expansion, economic development, and changes in lifestyle patterns. Irbid, one of Jordan's major urban centres, has seen tremendous development and modernization, resulting in an increasing demand for electrical power to suit the demands of its population, industries, and commercial organisations. Figure 14 indicates the rapid utilisation of electricity in Irbid. Irbid has seen rapid urbanisation, with an increasing number of individuals migrating from rural to urban regions in search of greater economic possibilities and higher living conditions.

The rising demand for housing, infrastructure, and services has resulted in increased use of energy for domestic purposes such as lighting, cooling, and home appliances. Furthermore, 16,941 additional counters of various stages were placed in 2022, and an estimated 614,869 new customers subscribed for energy distribution, a 2.65% increase from 2021 [25]. During 2022, 53 new lighting units and 40,090 lighting units were installed as part of a project to replace, install, operate, and maintain traditional street lighting equipment. Nonetheless, 98,805 km of 33 kV medium voltage overhead networks were developed, built, and operated. And the deconstruction of 7,064km of these networks, which contributed to 91,741km of overhead network. The bought electric energy in 2022 was 3885.5 million kWh, up from 3683 million kWh in 2021, representing a 5.49% increase [25], [45], [46].

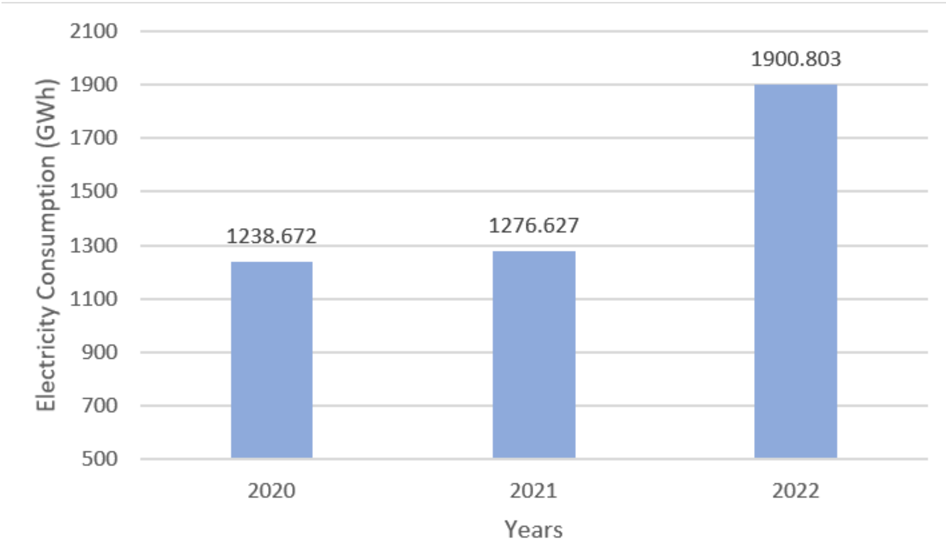


Figure 14: Electricity Demand Consumption Over the Years in Irbid [25],[45],[46]

According to Irbid District Distribution Company, Irbid consumed around 1900.804 GWh in 2022 [25]. Jordan uses more power in the summer, according to the National Electric and Power Company. Furthermore, there are two principal peaks each year, occurring throughout the winter and summer, with the peaks themselves growing annually due to increased demand [13]. Electricity usage peaks in the winter and summer due to the demand for heating and cooling, as seen in Figure 15. The higher power use in January and December could be attributed to greater heating demand and fewer daylight hours. Other customers, on the other hand, attempt to cover their heating demands by alternative methods such as gasoline and diesel, despite the high expenses of fossil fuels, in order to avoid being charged the higher electricity bill [47].

The summer peak, which occurs in July and August, is mostly due to higher cooling usage in air conditioning and refrigeration. The more the temperature scales over the thermal comfort zone, the more likely that less effective heat exchange cooling applications will be used, raising the demand for electricity [48]. Jordan's yearly peak load comes every year in summer, notably in July and August, due to the holiday for many returning Jordanians who generally work in the Gulf States [49]. As illustrated in Figure 15, the greatest substantial change was seen during the spring months of March to May. Due to high electricity rates, most homes save energy during these months. As a result, they employ a variety of strategies to reach the required degree of comfort, such as opening windows at night to air the interior [47].

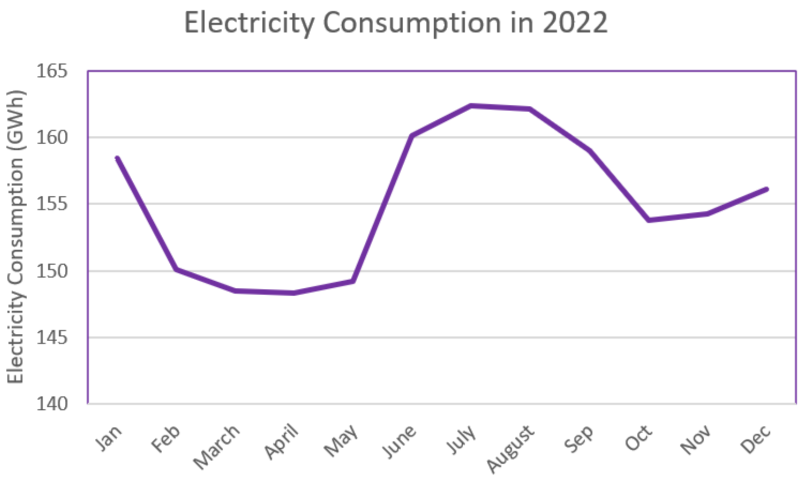


Figure 15: Electricity Consumption over the months of 2022

Figure 15 indicates that January has the greatest winter electrical consumption, whereas July has the highest summer demand. As a result, the consumption pattern throughout these months was observed, as shown in Figure 16. The weekend in Jordan refers to both Fridays and Saturdays. However, many private-sector firms and private schools are open on Saturdays, although government organisations and administrations are closed. It is worth noting that many private-sector businesses work shorter hours on Thursdays, particularly if they are open on Saturdays. As a result, Sundays through Wednesdays are full working days that contribute significantly to power consumption [48]. As observed in Figure 16, January 7 and July 11 of 2022 were Fridays with lower electricity consumption. Nonetheless, a study of Jordanian households' consumption found that homes exhibited the same pattern in both summer and winter with increased heating and cooling needs [47].

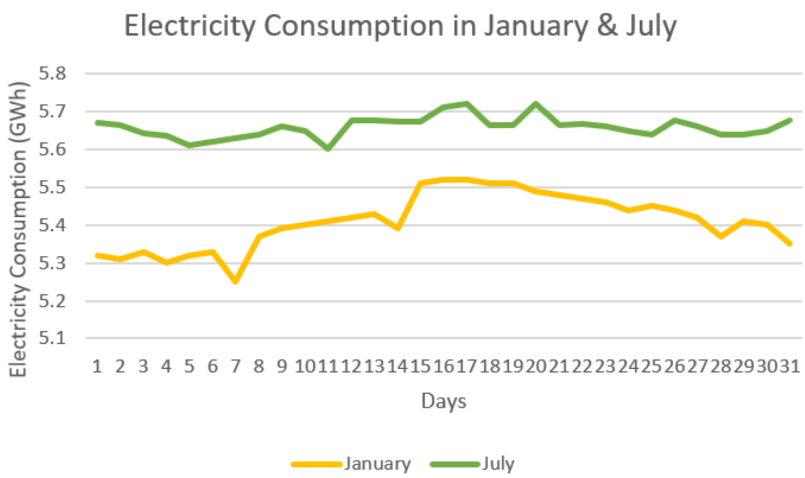


Figure 16: Electricity Consumption in January and July

As shown in Figures 17 and 18, the use of electricity on weekdays rises steadily after 5:00 a.m., with early morning prayer being the most likely candidate for such an early start of the occupied region [48]. The rise continues throughout the day, with the peak hours in a summer day being from 13:00 to 17:00 (1:00-5:00 pm). The steady rise might be attributed to schools, companies, and institutions operating throughout working hours. And the peak hours are just before sunset, when most people are at home and the air conditioning is switched on, noting that residentials accounted for more than 55% of Irbid's electricity consumption. The power use then begins to decrease throughout the night till 5:00 a.m. This implies that Irbid has the largest electricity use during the day. Summer peaks are attributed to a high air conditioning load during working hours for the 1 pm peak and the start of night activities with the lights turned on for the 8 pm peak [48]. As seen in Figure 18, winter daily electricity demand follows the same pattern as summer daily electricity demand; however, on colder days, electricity consumption is lower than the summer. Electricity demand begins to rise from 6 a.m., with peak consumption occurring between 7:00 am and 10:00 am because of the cold mornings. Another peak is seen at 6 pm when the sun is gone, and heating is needed.

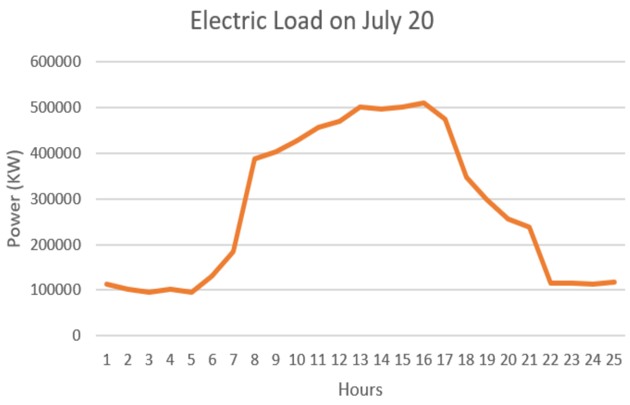


Figure 17: Electricity Demand on July 20,2022

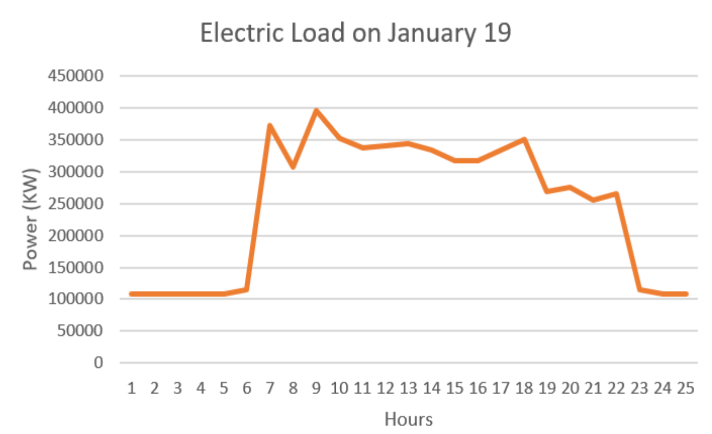


Figure 18: Electricity Demand on January 19,2022

5.0 Modelling and Simulation

This section presents the application of the System Advisor Model (SAM) software to model and simulate two scenarios: a standalone PV system and a PV system integrated with battery storage. The study site is located at the Jordan University of Science and Technology (JUST) in Irbid city, Jordan, with a geographical position at latitude 32.4950° N and longitude 35.9912° E to extract the weather file.

5.1 Scenario 1: Photovoltaics

A monocrystalline silicon-based PV with an efficiency of 18.7% and a maximum power output of 375 W dc was chosen. The photovoltaics had a fixed tilt angle of 30 degrees and an azimuth angle of 180 degrees, which produced the most energy. The PV system is connected to inverters with 98.226% efficiency that convert the DC power generated by the PV panels into AC electricity that can be delivered into the grid. Table 4 shows the characteristics of the PV system that was chosen.

Table 4: Characteristics of the PV system

PV Type	SunPower SPR-P19-375-COM
PV Efficiency	18.67%
PV Material	Monocrystalline silicon
Module Area	2.010 m2
Tilt Angle	30°
Azimuth Angle	180°
Inverter Type	PVS-60-TL-US
Inverter Efficiency	98.226%

With no losses assumed, a 1020MW dc PV capacity can cover Irbid's power need and provide an annual energy of 2072.74 GWh, whereas Irbid's electricity consumption is 1900.8 GWh. Figure 19 demonstrates that the system generates more electricity throughout the warmer months and can meet Irbid's electricity demand except in February and December. Figure 20 displays the power generated by the system as well as the hourly changes that occur throughout the year.

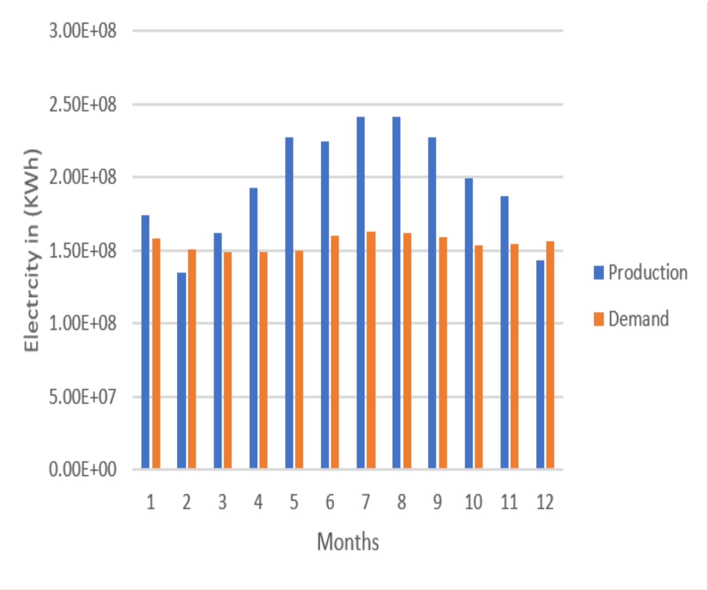


Figure 19: Produced Energy Vs. Demand per Month (kWh)

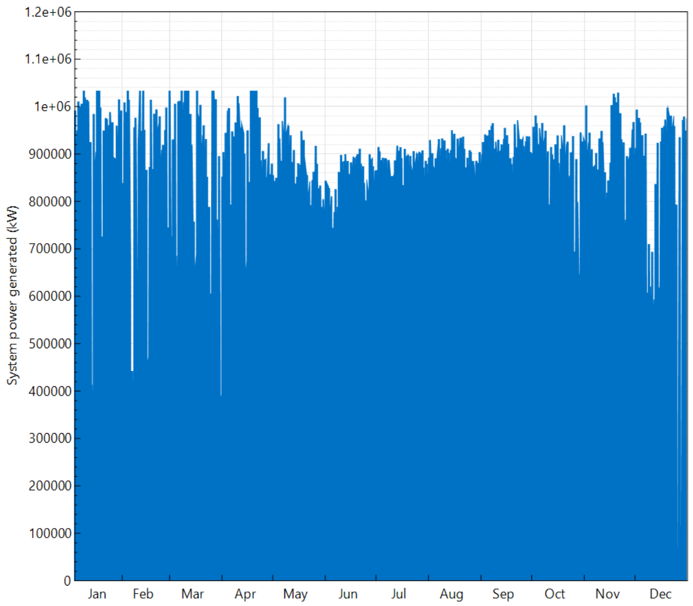


Figure 20: System Power Generated (kW)

5.1.1 Solar Irradiance and Efficiency of the Module

Although the sun irradiation is strong and can surpass 10000 W/m2, the hourly electricity generated in the summer does not exceed 900 MW. In the winter, electricity generation can surpass 1000 MW, although solar irradiance is less than 700W/m2. Figures 21 and 22 show the power generated (in blue) and the sun global horizontal irradiance (in brown) throughout the summer and winter seasons, respectively.

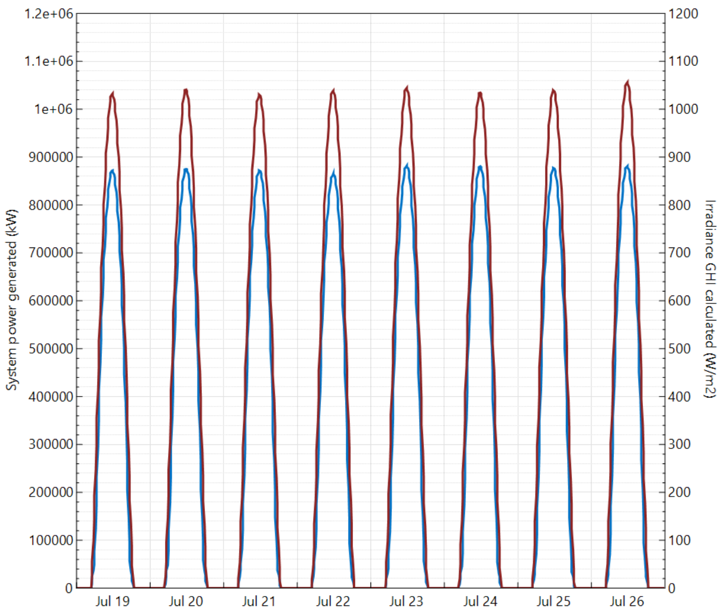


Figure 21: Power Generated Vs. Solar Irradiance in Summer Week

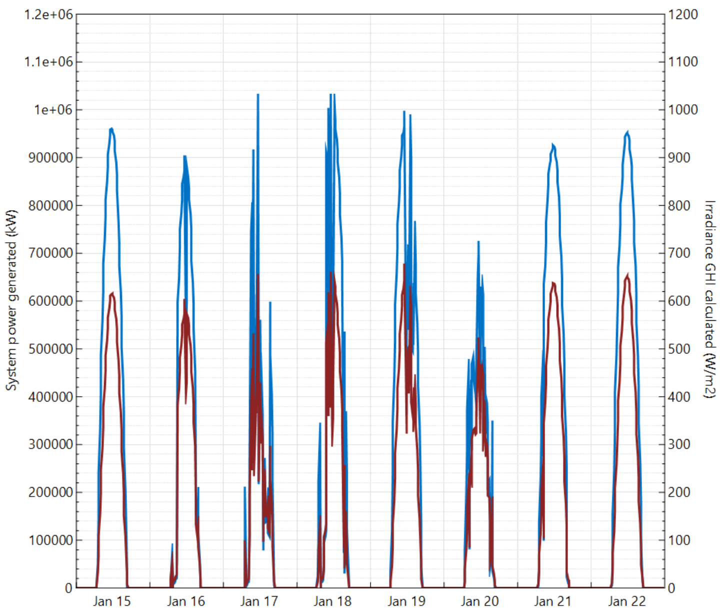


Figure 22: Power Generated Vs. Solar Irradiance in Winter Week

Figure 23 demonstrates that the efficiency of the PV panels in summer (in orange) is less than the nominal efficiency. The nominal efficiency of the panels is 18.67%, while the efficiency in summer does not exceed 17%. Figure 24 indicates the power generated (in blue) and the efficiency of the panels (in orange) in winter, which is within the nominal efficiency range.

Studies has shown that when the solar irradiation is strong and the temperature is high, the PV panel warms up due to direct sun exposure. The quantity of light absorbed by the module's components other than the solar cells adds to module heating, resulting in decreased power production. The efficiency declines as module temperature rises, causing the PV to convert only 20% of solar energy into electricity and 80% into heat [52]. Another research found that in arid regions, dust and soiling on the surface of the panels, as well as high temperatures, affect the efficiency of solar PV panels and hence raise the cost of power produced [51]. As a result, in this module, during periods of high solar irradiation (Figure 21), the efficiency of the PV panels falls (Figure 23), resulting in lower power output. Additionally, even if there is less solar irradiation in the winter, the PV module may still produce more electricity due to its better efficiency as illustrated in Figures 22 and 23. A remedy would be to install ventilation, fans, or cooling systems to aid in the passage of air around the panels to boost power production [52].

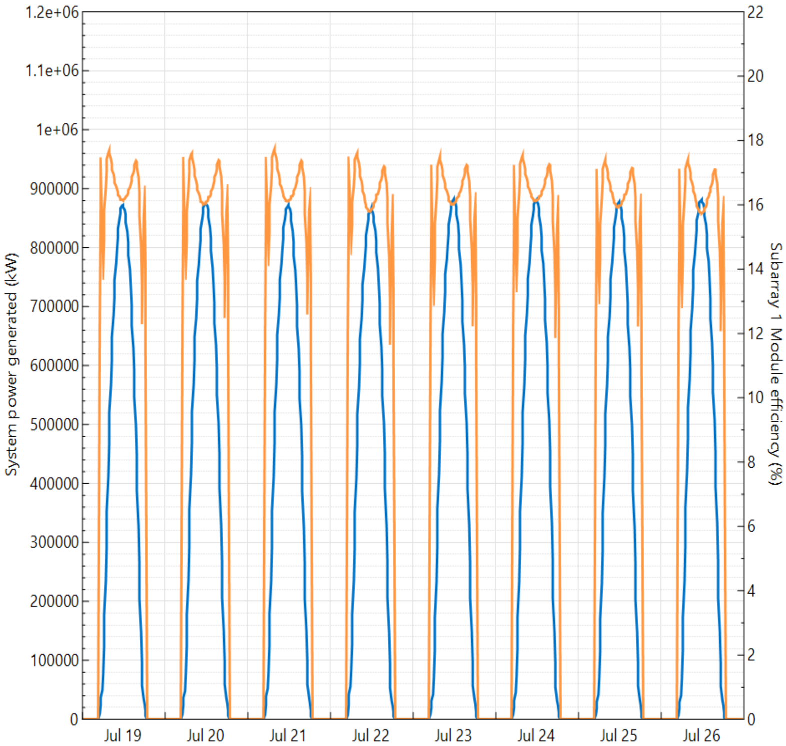


Figure 23: Power Generated Vs. Module Effiency in Summer

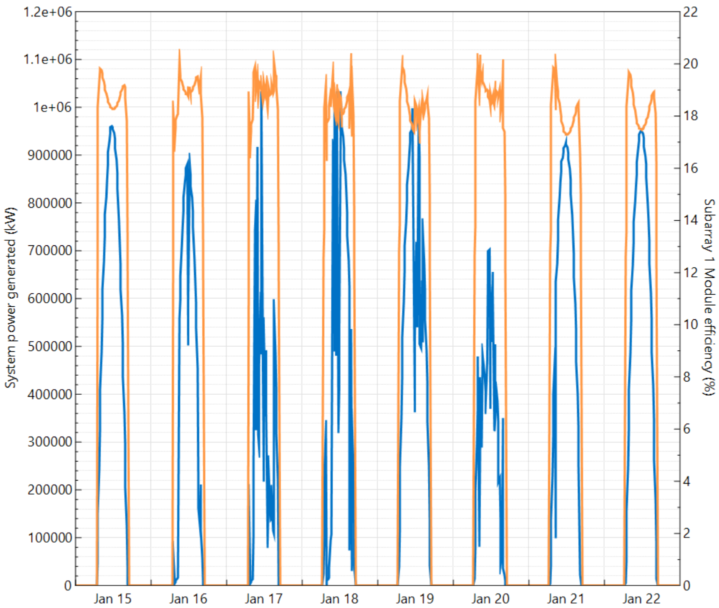


Figure 24: Power generated Vs. Module Efficiency in Winter

5.1.2 Supply Vs. Demand of the PV system

The power output of the PV system fluctuates dynamically over time due to the variability of environmental factors. Figure 25 reveals that on July 20th, the power output curve is smooth and begins to produce electricity as the solar irradiation increases during the day and decreases with the sunset. On a clear-sky day, the PV power production closely matches the solar irradiance curve [50]. Figure 26, on the other hand, depicted the power output on January 19. On this day, the power curve is not smooth, indicating that it was influenced by external factors such as a cloud moving above the panels, blocking sunlight from reaching the panels. As a result, the power generated by the system may be influenced by clouds, rain, snow, and dust, which reduce the quantity of solar energy received by the module [52]. Furthermore, air temperature, module temperature, wind speed and direction, and humidity are also possible factors influencing PV power production [50].

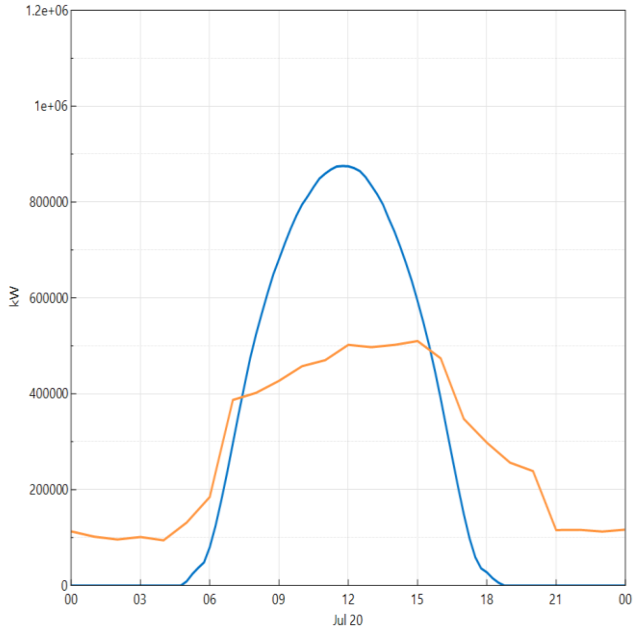


Figure 25: Power Produced Vs. Demand on July 20.

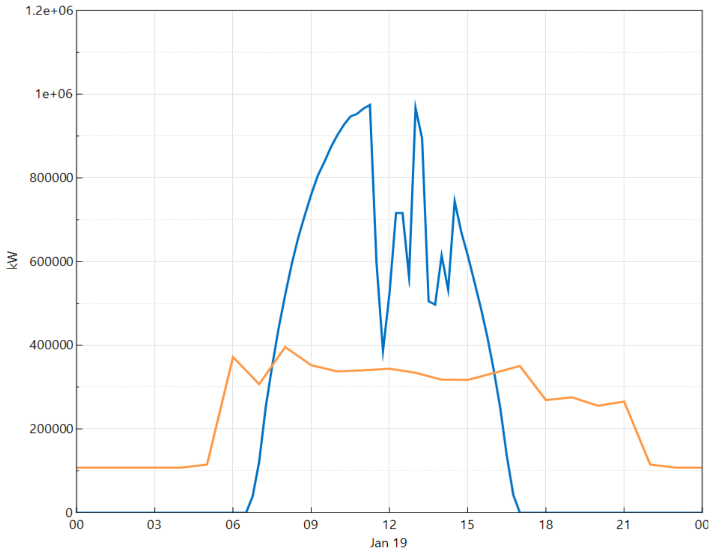


Figure 26: Power Produced Vs. Demand on January 19.

The PV power output pattern closely matches the daylight time. As seen in Figure 25, the PV generates power from 5 am to 6 pm (in blue) throughout the summer. In the winter, Figure 26, the PV produces power from 6 am to 5:30 pm owing to the shorter daylight hours (in blue). The PV power generation is absent when there is no sunlight [50]. As a result, the PV system will not provide the demand for Irbid city before and after the sun shines. Instead, to fulfil the demand patterns, power will be drawn from the grid, as seen in Figure 27 (in orange). Due to the lack of battery storage technologies, the surplus power would end up being wasted.

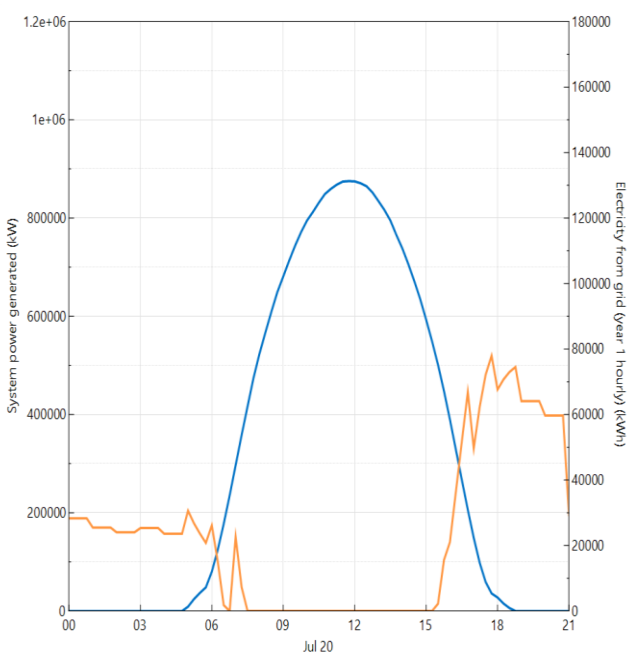


Figure 27: Electricity from the Grid

5.2 Scenario 2: PV + Battery

For multiple reasons, integrating a battery storage system alongside a photovoltaic (PV) system is necessary. The absence of a battery, in particular, results in the loss of surplus power generated by the PV system during peak production periods since it lacks the ability to be properly stored for later use. This condition also increases reliance on conventional energy sources during periods that have limited PV production. Second, due to the intermittent nature of solar energy, the absence of a battery storage component might lead to grid instability. Surplus electricity generated during periods of sufficient sunshine may place an unnecessary strain on the grid, whereas the absence of power during cloudy or night hours may result in supply shortages. By implementing battery storage capabilities, excess energy may be stored and then released to the grid during times of peak demand, encouraging a more harmonic and dependable energy distribution system. Finally, integrating battery storage with PV systems optimises the use of renewable energy resources while also improving the grid's overall resilience and sustainability.

5.2.1 Battery Capacity

The peak shaving battery system is intended to address both excess energy during high PV generating periods and to offer additional power during peak demand periods. Peak shaving is a systematic approach to energy management that optimises energy use and grid efficiency [26].

The selection of the battery capacity and the maximum charge and discharge power are critical factors to ensure optimal system performance. The PV system's generating profile and the load needs of the facility it serves are considered when determining the optimum battery capacity. The greatest energy usage should be taken from the demand profile to compute the minimum battery capacity. In the instance of Irbid's electricity consumption, its maximum electricity need is 5700 MWh which occurs in July. Furthermore, the battery's depth of discharge is set at 80% [53]. The following formula will then be used to calculate the minimum battery capacity:

$$Emin = \frac{110 * Ereq * D}{DOD\%} \qquad (1)$$

Ereq: is the peak energy consumption per day (MWh)

D: is the days of anatomy

DOD%: is the depth of discharge.

Therefore,

$$Emin = \frac{110 * 5700 * 1}{80} = 7837.5\ MWh$$

The minimum battery capacity is determined at 7840 MWh as a consequence of this formula. Furthermore, the maximum charge and discharge power are precisely determined to balance the charging and discharging capacities of the system. This includes determining the peak power output of the PV system as well as the peak load needs of the facility. As a result, the desired bank power is set at 500MW based on the demand analysis profile's peak power consumption. The chosen charge and discharge power must allow the battery to absorb energy from the PV system efficiently during high generation times while also smoothly discharging energy during peak demand periods. Table 5 presents the properties of the selected battery.

Table 5: Characteristics of the Chosen Battery

Battery Type	Lithium Ion: Nickel Manganese Cobalt Oxide
Minimum state of Charge	15%
Maximum State of Charge	95%
AC to DC conversion Efficiency	96%
DC to AC conversion Efficiency	96%
Maximum discharge power	500MW
Maximum charge power	500MW

Furthermore, the battery in this integrated system is intended to be charged completely by the PV system, rather than by the grid. This architectural strategy promotes self-sufficiency and lowers dependency on external energy sources. Nonetheless, the replacement threshold for battery banks is set at 50%. The lithium-ion battery type was chosen because of its market availability and high conversion efficiency.

Excess energy generated during sunny hours is retained for later use by charging the battery only from the PV system, thereby shaving off energy peaks during periods of high demand. As illustrated in Figure 28, the battery can charge when the system's output exceeds its production during the day from 6 a.m. to 15 p.m. (in Brown). Furthermore, the battery charges the grid during peak demand (in orange) that is not covered by the system (in Green). In Figure 28, the demand curve is illustrated in orange, the battery charge is in brown, and the battery discharge is shown in green colour. However, minimal electrical demand will be provided from the grid in the early morning and late night.

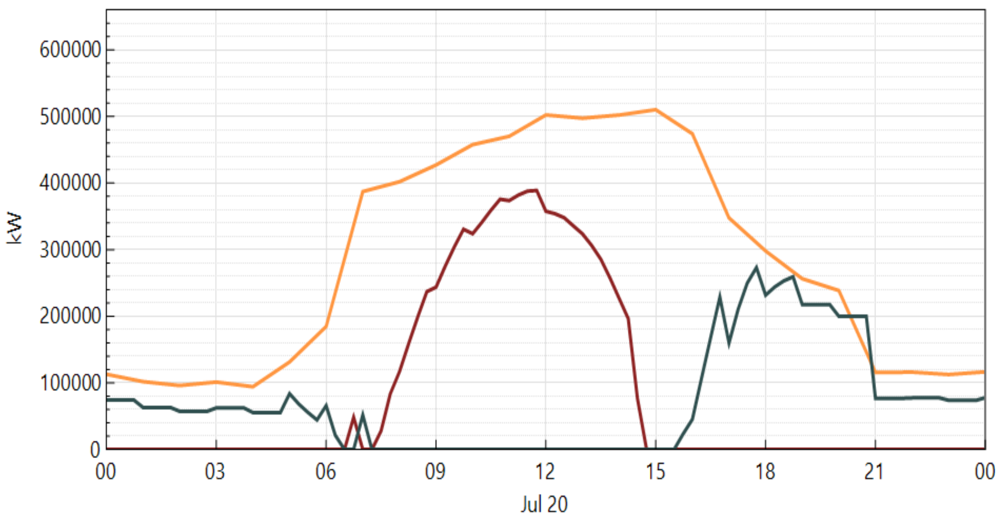


Figure 28: Battery Charge Vs. Discharge Periods

Overall, combining a peak shaving lithium-ion battery system with the PV system characteristics established in Scenario 1, as well as careful selection of battery size and charge/discharge power, improves energy management efficiency and grid stability. The battery capacity is selected to be sufficient to store excess PV-generated energy during peak production periods, as well as to meet energy demands during periods of low or no PV generation. This optimised solution not only maximises the utilisation of clean solar energy, but also contributes to reducing grid strain during peak periods, promoting a more sustainable and resilient energy infrastructure.

5.3 Model Validation

The observed fluctuations in the simulation results exhibit a reasonable consistency with real-world outcomes, as corroborated by actual climate data and the documented efficiency characteristics of the PV panels. This alignment suggests that the simulation accurately captures the inherent variability inherent in renewable energy systems, demonstrating its ability to mirror the complex interplay between external factors and technology performance. The correspondence between simulated and actual results underscores the software's reliability in providing insights into how renewable energy systems respond to dynamic environmental conditions and validates its potential to guide decision-making in real-world applications. Furthermore, the validation process also included a comparison of the results with those obtained from similar PV analysis performance from other case studies and literature review.

A case study conducted in Brazil's semi-arid region advocated the development of a solar photovoltaic system integrated with the grid to meet the region's energy needs. The authors compared the findings of the SAM programme to those of HOMER, indicating that the system generates a minimum of 3,500 kWh/month and a maximum of 5,500 kWh/month based on the HOMER's results. SAM findings, on the other hand, showed numbers of 4,257.01 kWh/month and 5,504.01 kWh/month, respectively. While the SAM values slightly outperformed those of the HOMER programme, the key point is the constant trend between the two software's results, indicating that they correspond [60].

Another article compares and validates three distinct simulation software programmes that utilise satellite data from separate databases: SAM, RETScreen, and PVsyst. The three software applications are used to model and simulate a 98.4 kW power of photovoltaic system in Tirana, Albania. The simulation findings revealed that the energy produced by the simulation in SAM was closer to the value of the energy produced by the system during the study year [61].

Another research compared the outputs of SAM software to PVSyst software with the same characteristics and settings to predict the technical and economic performances of CSP and PV systems to deliver electricity to a mining scenario in Zimbabwe. The results demonstrate that the energy produced by the two software packages varied by just 1.65%, with the performance ratio being the most different. The energy produced by SAM was 1.65% more than that produced by PVSyst. SAM's performance ratio was 2.5% greater than PVsyst's [53]. As a result, the diverse validation technique reinforces the credibility of the simulation results and confirms their use in influencing actual renewable energy initiatives.

6.0 Cost- Benefit Analysis

From investors perspective, Net Present Value (NPV) and Pay-Back Period (PBP) are among the most essential criteria to evaluate the economic feasibility of the project [54]. Therefore, the net capital cost, payback period, and the net present value will be calculated for Irbid Distribution Electricity Company as interested investors in the PV scenario and PV+ Battery system. Irbid Electricity company buys electricity at USD 0.078 per kWh. In 2022, the consumed 1900.8 GWh of electricity were valued at an expense of USD 167,847,923 paid from Irbid's electricity Company [25].

6.1 Capital Cost

Based on the findings of the PV scenario, it can be determined that the system fulfils 60% of the electricity demand while only producing power from 7 a.m. to 6 p.m. As a result, the yearly expenditures for purchasing power will be decreased by 60%, resulting in a savings of

USD 100,708,745 for the company. The findings of PV + Battery, on the other hand, suggested that more power might be generated throughout the day and maintained for usage at peak hours. Consequently, it was estimated that 90% of annual spending, or USD 151,063,131, might be transferred to savings. These savings will be accounted for as cash inflow from PV systems.

To evaluate the capital cost, the installation cost of the PV systems was assumed as USD 0.531 per Watt DC and the inverters as USD 0.100 per Watt DC from a comparable project completed in Jordan [55]. This gives a net capital cost of USD 695,034,432 from the weighted installation cost of SAM's software. For the second scenario, the Lithium-ion battery DC capacity were rated at USD 100 per kWh which conducts a Net Capital Cost of USD 1,477,598,372 [56]. This indicates that PV + Battery module's initial cost is approximately twice of the PV module alone.

6.2 Payback Period

The Payback Period, a financial concept, determines the duration needed for an investment to generate adequate cash flows to offset its initial investment expenditure. Generally, shorter payback periods are favoured as they reflect a faster recovery of funds and reduced vulnerability to risks [57].

To calculate the Payback Period the following equation can be used:

$$PBP = \frac{Initial\ Investment\ Cost}{Cash\ Inflow} \qquad (2)$$

For Scenario 1: PV alone

$$PBP = \frac{695{,}034{,}432}{100{,}708{,}745} = 6.9 \ \simeq 7\ years$$

For Scenario 2: PV+ Battery

$$PBP = \frac{1{,}477{,}598{,}372}{151{,}063{,}131} = 9.8 \ \simeq 10 years$$

It will take the second scenario three more years than the PV alone to recoup the capital cost since the initial investment cost is higher even though the cash stream is larger.

6.3 Net Present Value

The Net Present Value (NPV) serves as a financial metric employed to assess the viability of an investment, achieved by computing the disparity between the current value of projected cash inflows and the current value of anticipated cash outflows across a designated timeframe.

This cumulative current value of all anticipated forthcoming cash flows produced by the investment is weighed against the initial investment expenditure to ascertain the financial feasibility of the endeavour. A positive NPV signifies a probable successful investment, while a negative NPV suggests the potential lack of financial advantage in the undertaking [57].

The Net Present Value can be calculated using the following equation:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - C_0 \qquad (3)$$

Where:

- CF_t represents the expected cash flow in time t.
- n is the number of time periods.
- r is the discount rate, representing the minimum required rate of return or cost of capital.
- C_0 is the initial investment cost.

To calculate the Net Present Value (NPV) for a perpetuity, another modified formula can be used that accounts for the infinite series of cash flows generated by the perpetuity. A perpetuity is a financial instrument or investment that generates a constant stream of cash flows that continue indefinitely [59]. Therefore, it is assumed that n= ∞.

To calculate the NPV of a perpetuity, the following equation can be used:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{r} - C_0 \qquad (4)$$

NPV considers the time value of money, meaning that future cash flows are discounted back to their present value using the discount rate. Therefore, from the Central Bank of Jordan the main rate was conducted as 7.5% [58]. If the calculated NPV is positive, the investment is potentially worthwhile, as it indicates that the potential returns exceed the cost of the investment. If the NPV is negative, the investment might not be advisable, as the costs outweigh the expected returns.

For Scenario 1: PV alone

$$NPV = \sum_{1}^{\infty} \frac{100{,}708{,}754}{7.5\%} - 695{,}034{,}432 \qquad = USD\ 647{,}748{,}955$$

For Scenario 2: PV+ Battery

$$NPV = \sum_{1}^{\infty} \frac{151{,}063{,}131}{7.5\%} - 1{,}477{,}598{,}372 \quad = USD\ 536{,}576{,}708$$

From the Net Present Value results, it can be concluded that the PV installation alone has a higher NPV than PV + Battery. This indicates that the potential returns in the first scenario exceed the cost of the investments better than the second scenario. But both scenarios have a positive NPV indicating both scenarios' investment are worthwhile.

6.4 Analysis of Results

In the PV alone scenario, the calculated NPV signifies that the project generates positive returns over its lifetime. The net capital cost, which considers the initial investment, is lower compared to the PV + Battery scenario. Additionally, the Payback Period (PBP) is shorter for the PV alone scenario, indicating a faster recovery of the initial investment. However, despite the favourable financial indicators for the PV alone scenario, the decision to favour the PV + Battery scenario is driven by several key factors.

Firstly, the PV + Battery scenario demonstrates a positive NPV, suggesting that it is also financially viable. While the net capital is higher due to the battery system, the benefits derived from the battery's ability to store excess electricity are significant. Without the battery, surplus electricity generated by the PV system during peak production periods would go to waste. The inclusion of the battery enables the storage of this excess energy, which can be utilized during periods of low solar output or high electricity demand.

A PV system combined with battery storage has proven to be a highly effective solution for addressing a substantial portion of Irbid's annual electricity demand. This integrated approach results in a remarkable 90% coverage of the electricity needed, leading to significant cost savings for Irbid's electricity company. By relying on this PV + Battery system, the company stands to save an impressive USD 151,063,131 in comparison to conventional electricity procurement methods. The PV + Battery configuration lies in its minimized dependency on the grid. This system is projected to draw just 10% of its electricity needs from the grid during fluctuations in demand, translating to a cost of USD 16,784,792.

In contrast, considering the adoption of PV system alone, capable of covering approximately 60% of the required electricity demand, there is a significant reduction in potential savings for the company. While this approach would still offer commendable savings of USD 100,708,745, it comes with a significant drawback. Such a setup would necessitate a heavy reliance on the grid for the remaining 40% of electricity demand, incurring an expenditure of around USD 67,139,183. The PV alone scenario would necessitate a higher percentage of electricity purchases from the company to cover Irbid's demand, leading to an increasing reliance on imported electricity over time. Notably, the current trend of rising electricity import prices must be considered. This growing reliance on external sources could have both economic and strategic implications for the region. The battery's capacity to store excess energy not only maximizes the utilization of the PV system but also enhances energy resilience, minimizing waste and external energy dependencies. Furthermore, the ability to participate in the local energy market as a reliable supplier positions the PV + Battery system as a sustainable and strategic choice for Irbid.

With the Irbid Electricity Company charging USD 0.089 per kWh of consumption for household and USD 0.123 per kWh for businesses [25], the PV + Battery scenario becomes even more financially attractive. The battery's ability to store excess energy and discharge it during peak demand periods aligns with the company's pricing structure. By utilizing the stored energy during high demand periods, the PV + Battery system can offset the need for purchasing more expensive electricity from the grid, resulting in significant cost savings for the company.

Where the revenue can be calculated using the following formula [57]:

$$Revenue = Energy\ Produced_i\ X\ Energy\ Price \qquad (5)$$

Additionally, the prolonged ability of the PV + Battery system to cover electricity demand contributes to more stable revenue generation for the company. The longer coverage period enhances the consistency of energy supply, reducing the likelihood of interruptions and the associated costs that might arise from purchasing electricity during peak demand situations.

Furthermore, the PV + Battery scenario's capability to operate independently of the grid during certain periods can also play a role in grid stability. The ability to discharge stored energy during peak demand times can help alleviate strain on the grid and potentially reduce the need for expensive grid infrastructure upgrades.

Considering these factors, the financial benefits of the PV + Battery scenario for both the Irbid Electricity Company and the overall energy ecosystem become evident. The system also contributes to greater energy efficiency, cost-effectiveness, and overall sustainability. The synergy between the PV + Battery system and the company's pricing strategy serves as a compelling argument in favour of this scenario, strengthening the recommendation to adopt it as the preferred solution for covering Irbid's electricity demand.

7.0 Risk Analysis

The deployment of Photovoltaic (PV) and PV + Battery systems to address Irbid's electricity demand entails inherent risks that necessitate careful consideration. Firstly, uncertainties pertaining to the demand profile pose a significant challenge. Due to the absence of hourly electricity demand trends specific to Irbid, assumptions were derived from broader Jordanian data. However, the nuanced demand patterns influenced by local weather conditions and changing consumption behaviours could diverge from projections, potentially impacting energy generation and storage planning accuracy. Furthermore, the feasibility analysis relied on current equipment prices for PV panels, inverters, and batteries. Market dynamics introduce price volatility due to factors such as currency fluctuations and supply chain disruptions. Such fluctuations can affect overall project costs, possibly altering financial projections and the project's financial viability.

Additionally, the feasibility study omitted several crucial cost elements. The purchase price of land area, a fundamental aspect, was not assessed, and variations in local real estate values could lead to unpredicted expenditure. The analysis also excluded ongoing maintenance expenses, labour costs for installation, and the potential for battery degradation over time.

These omissions can affect the overall operational budget and, consequently, the project's profitability. Regulatory and policy changes further contribute to risks. Alterations in energy regulations, incentives, or tariffs could modify the economic landscape and impact financial returns. Energy market fluctuations and changes in electricity prices are additional risks that might influence revenue streams and undermine financial forecasts. Addressing these risks through robust mitigation strategies is imperative to ensure the successful execution, economic feasibility, and long-term sustainability of renewable energy projects in the region.

8.0 Conclusion

In conclusion, this thesis has undertaken a comprehensive examination of the potential and effectiveness of integrating Photovoltaic (PV) technology into Irbid's energy infrastructure to meet its electricity demand. This study's methodological progression, encompassing scoping studies with fixed assumptions followed by a comprehensive parametric analysis, ultimately leads to the identification of an optimized and robust renewable energy configuration. By effectively capturing uncertainties and considering evolving energy demands and market dynamics, the study contributes valuable insights to inform sustainable energy planning in urban contexts like Irbid city, Jordan. The findings underscore the critical significance of renewable energy solutions in addressing Jordan's energy challenges, particularly in a city like Irbid. The study's objectives were systematically pursued, yielding valuable insights into various aspects of the renewable energy integration process.

However, it is essential to acknowledge certain limitations that could influence the study's outcomes. Data limitations, such as the unavailability of localized hourly electricity demand trends for Irbid, compelled the use of broader Jordanian data, potentially leading to discrepancies in demand pattern projections. The omission of detailed local data also restricted a comprehensive analysis of transitioning non-electrical loads to electricity, a facet with significant potential but requiring city-specific data collection efforts.

Moreover, the risk analysis highlighted several uncertainties that could impact the feasibility and implementation of PV and PV + Battery systems. Price volatility in equipment procurement, variations in land acquisition costs, and the exclusion of ongoing maintenance and installation expenses pose potential challenges to the projected financial outcomes.

Despite these limitations and risks, the simulation results obtained through the System Advisor Model (SAM) software substantiate the efficacy of the PV + Battery scenario. While both scenarios yield positive NPV and indicate financial viability, the PV + Battery scenario emerges as the more prudent choice. Its capability to effectively store and manage energy, coupled with its potential to mitigate waste, dependency, and market uncertainties, provides a compelling case for its adoption despite initial cost differentials. The long-term benefits of energy security, reduced waste, and increased local energy independence underscore the recommendation to opt for the PV + Battery scenario, ensuring a sustainable and resilient energy future for Irbid.

Employing a PV system combined with battery storage has proven highly efficacious in addressing a substantial portion of Irbid's annual electricity demand, resulting in a 90% coverage and cost savings of USD 151,063,131 for the electricity company. This PV + battery system minimizes grid reliance, drawing just 10% of its power from the grid during demand fluctuations, amounting to a cost of USD 16,784,792. In contrast, relying on a PV system alone covering around 60% of required electricity demand yields savings of USD 100,708,745, yet necessitates heavy grid reliance for the remaining 40%, costing USD 67,139,183. Such a scenario increases dependence on imported electricity, considering the ongoing trend of rising import prices.

This study has successfully achieved its primary hypothesis, affirming that the incorporation of a Photovoltaic (PV) system into Irbid's grid holds the potential to substantially impact the city's electricity demand coverage, decrease reliance on conventional energy sources, and promote sustainability. Furthermore, the secondary hypotheses have also been substantiated. The utilization of a PV system, when coupled with a battery, effectively addresses Irbid's electricity demand and its fluctuation patterns, indicating a need for battery integration to ensure optimal coverage. The correlation between the PV system's electricity generation and solar irradiance levels in Irbid has been validated, although the efficiency decline during high solar radiation has been noted. While the integrated PV system's energy storage capacity, in conjunction with appropriate battery technology, facilitates continuous electricity supply during low solar irradiance periods, the battery dispatch primarily during peak demand reveals a 10% reliance on the grid. Lastly, the economic analysis has confirmed a favourable return on investment for the PV and PV+ Battery systems integration, demonstrating the financial viability of transitioning to renewable energy sources within Irbid's grid.

9.0 Future Work

While the current analysis has presented promising scenarios involving PV and PV + Battery solutions for Irbid's electricity demand, there are several exciting avenues for future exploration. The integration of CSP, wind energy, energy demand reduction measures, and a holistic approach to energy planning can contribute to a more sustainable and resilient energy future for Jordan. Collaborative efforts, comprehensive assessments, and innovative solutions will play a pivotal role in achieving a transition to a cleaner, more cost-effective, and reliable energy landscape.

9.1 Integration of Concentrated Solar Power

In future analyses, the potential of integrating Concentrated Solar Power (CSP) systems could be explored as a complementary solution. CSP systems utilize mirrors or lenses to concentrate sunlight onto a receiver, generating heat that can be used to produce electricity even after sunset. By combining CSP technology with PV systems, a hybrid solution could emerge that provides continuous power generation, even during nighttime hours. Such an integrated system could offer a more consistent and reliable energy supply, contributing to further energy security and independence for Irbid.

9.2 Wind Energy

Incorporating wind energy into the renewable energy mix is another avenue for future exploration. Wind farms have shown potential to provide consistent electricity generation, particularly during windy periods. Assessing the wind energy potential in Irbid and its surrounding areas could provide valuable insights into the feasibility of incorporating wind power to further diversify the renewable energy portfolio. Future research could delve into integrated energy planning, considering the synergies between various renewable energy technologies. A comprehensive analysis that optimally combines PV, battery storage, CSP, and wind energy could result in a well-balanced and resilient energy system that maximizes energy generation, minimizes waste, and ensures a stable power supply.

9.3 Transition of Non-Electrical Loads to Electricity

A significant avenue for future exploration lies in assessing the feasibility and implications of transitioning current non-electrical loads, such as transportation and heating, to electricity. This transition aligns with the broader goal of enhancing energy sustainability and reducing dependence on fossil fuels. However, due to the unavailability of localized data for Irbid city, this study was unable to comprehensively analyse this aspect. Future research should focus on collecting city-specific data that accurately represents the energy consumption patterns of non-electrical loads.

9.4 Mitigation Measures for Energy Demand Reduction

To alleviate the burden of high electricity demand and costly imports, future studies could focus on identifying and implementing measures to reduce energy consumption. Energy efficiency initiatives, including building retrofitting, advanced energy management systems, and public awareness campaigns, could help curtail excessive energy usage. Additionally, incentivizing industries to adopt cleaner and more energy-efficient practices could contribute to a more sustainable energy landscape.

9.5 Economic and Environmental Impact Assessment

Exploring the economic and environmental impact of transitioning Jordan to a higher percentage of renewable energy sources is a critical area of future investigation. Assessing the potential benefits in terms of reduced greenhouse gas emissions, job creation, and economic growth can provide valuable insights for policymakers and stakeholders.

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