Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Economic Optimization of Grid-Connected Photovoltaic Solar Systems in Industrial Energy: Case Study SULFO Ltd - Rwanda

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ARTICLE INFO.

Article history:
Received 8 Jul 2024
Received in revised form 9 Jul 2024
Accepted 20 Aug 2024
Available online 5 Sep 2024

KEYWORDS

Solar Energy Technology, Energy Optimization, Environmental Impact Assessment.

ABSTRACT

This research investigates the economic optimization of grid-connected photovoltaic (PV) solar systems through a case study at SULFO Industry, specifically its soap manufacturing department. It addresses the urgent need for sustainable energy solutions in industrial settings to cut greenhouse gas emissions and achieve financial savings, focusing on high energy consumption issues. The study aims to optimize energy usage, financial efficiency, and environmental sustainability by integrating solar PV technology.

The cost-benefit analysis of the PV system evaluates initial costs, payback period, return on investment (ROI), levelized cost of energy (LCOE), and net present value (NPV). Findings reveal a payback period of approximately 10 years with an anticipated total profit of around $768,767 over 30 years. The system generates 502.2 MWh annually, reducing energy costs to 51,726,600 RWF from 120,519,000 RWF, and decreases CO_2 emissions by 6,555.1 tons. These results support existing research on the economic and environmental benefits of solar PV systems, validating their effectiveness in reducing costs and emissions. The study confirms that solar PV systems are a viable and practical option for enhancing energy sustainability in industrial operations.

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DOI: https://doi.org/10.51646/jsesd.v13i2.242

الفعالية الاقتصادية من أنظمة الطاقة الشمسية الكهروضوئية المتصلة بالشبكة في قطاع الصناعة: درسة حالة شركة SULFO الصناعية المحدودة - راوندا

أوستاش هاكيزيمانا، أونورين أوموهوزا، إيمانويل مانيشيموي ، كاييباندافينانت.

ملخص: تقوم هذه الدراسة بمحاولة الحصول على التصميم المثالي لأنظمة الطاقة الشمسية الكهروضوئية المتصلة بالشبكة على اساس اقتصادي وتم اتخاذ شركة SULFO الصناعية المحدودة في رواند كحالة دراسة، وتحديداً قسم صناعة الصابون التابع لها. ويتناول البحث الحاجة الملحة لحلول الطاقة المستدامة في البيئات الصناعية لخفض انبعاثات الغازات الدفيئة وتحقيق اقتصاد مستدام، مع التركيز على مشاكل الاستهلاك المرتفع للطاقة. وتهدف الدراسة إلى تحسين استخدام الطاقة والكفاءة والاستدامة والمحافظة على البيئة من خلال دمج تكنولوجيا الطاقة الشمسية الكهروضوئية في مزيج توليد الطاقة الكهربائية. يستند التحليل الاقتصادي لمنظومة الطاقة الشمسية على تحليل التكلفة والعائد للنظام وتقييم التكاليف الأولية، وفترة الاسترداد، والعائد على الاستثمار، والتكلفة المستوية للطاقة (LCOE)، وصافي القيمة الحالية (NPV). كشفت النتائج المتحصل عليها أن فترة استرداد رأس المال قدرت بحوالي 10 سنوات مع إجمالي ربح متوقع يبلغ حوالي 768,767 دولارًا على مدار 30 عامًا. يولد النظام 502.2 ميجاوات في الساعة سنويًا، مما يقلل تكاليف الطاقة إلى 51,726,600 RWF من 120,519,000 RWF، ويقلل انبعاثات ثاني أكسيد الكربون بمقدار 6,555.1 طن. تدعم هذه النتائج الأبحاث الحالية حول المردود الاقتصادي والبيئي لأنظمة الطاقة الشمسية، والتحقق من فعاليتها في تقليل التكاليف والانبعاثات. وتؤكد الدراسة أن أنظمة الطاقة الشمسية الكهروضوئية تعد خياراً عملياً وقابلاً للتطبيق لتعزيز استدامة الطاقة في العمليات الصناعية.

الكلمات المفتاحية – تقنيات الطاقة الشمسية، الطاقة المثالية، تقييم التأثير البيئي .

1. INTRODUCTION

The industrial sector drives economic growth but faces challenges such as high energy consumption and environmental concerns. Solar power offers a clean, sustainable, and cost-effective solution for optimizing industrial processes. Harvesting sunlight reduces reliance on non-renewable fuels and lowers carbon emissions, thereby cutting costs associated with environmental conservation measures. This study explores the design of solar systems tailored to meet industrial needs, aiming to reduce dependence on traditional energy sources and enhance overall effectiveness. In the period of increasing global industrialization, the demand for sustainable energy solutions is more pressing than ever. Recent data on global energy consumption indicate that the industrial sector is a major consumer, accounting for approximately 41.9% (IEA statistics, 2021) of all electricity supplied worldwide [1]. The global photovoltaic (PV) market has experienced remarkable growth driven by technological advancements, declining costs, supportive policies, and increasing environmental consciousness. Technological improvements in PV panels have significantly enhanced efficiency and reduced manufacturing costs, making solar energy increasingly competitive with conventional sources. According to the International Energy Agency (IEA), the cumulative installed capacity of solar PV exceeded 1,000 GW by the end of 2020, marking a substantial increase from previous years. Policy support, including subsidies, tax incentives, and renewable energy targets, has further bolstered PV deployment worldwide, with countries like China, the United States, and several in Europe leading in installed capacity. Environmental concerns and commitments to reduce greenhouse gas emissions have also propelled the adoption of solar energy globally. Investments in grid integration technologies and energy storage solutions have addressed intermittency challenges, ensuring more reliable integration of solar power into electricity grids. These trends underscore the PV market's rapid expansion and its critical role in the global energy transition. The global photovoltaic (PV) market has experienced remarkable growth driven by technological advancements, declining costs, supportive policies, and increasing environmental consciousness. Technological improvements in PV panels have significantly enhanced efficiency and reduced manufacturing costs, making solar energy increasingly competitive with conventional sources. According to the International Energy Agency (IEA), the cumulative installed capacity of solar PV exceeded 1,000 GW by the end of 2020, marking a substantial increase from previous years. 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These trends underscore the PV market's rapid expansion and its critical role in the global energy transition. SULFO Ltd faces significant challenges related to its substantial energy consumption in industrial processes, which has resulted in economic issues and environmental degradation. The primary issue is the heavy reliance on traditional energy sources, particularly grid electricity and fossil fuels, which contributes to high operational costs and greenhouse gas emissions. As industrial energy consumption continues to rise, driven by increasing demand and dependency on these non-renewable resources, the company experiences not only financial strain but also contributes to broader environmental concerns. The reliance on grid and fossil fuel energy sources leads to several critical challenges. Economically, fluctuations in energy prices create instability, impacting budget forecasts and increasing operational expenses. This volatility is compounded by the risk of supply disruptions, which can further strain financial resources and operational efficiency. Environmentally, the continued use of fossil fuels exacerbates greenhouse gas emissions, contributing to climate change and causing significant ecological damage. This environmental impact is not only a global concern but also has localized effects, with disadvantaged communities often bearing the brunt of pollution and degradation. These communities face disproportionate environmental and social consequences, such as health issues and reduced quality of life. The failure to address these energy challenges results in ongoing environmental degradation, energy insecurity, and geopolitical tensions. The reliance on non-renewable energy sources undermines long-term sustainability goals and contributes to broader issues such as climate change and resource conflicts, disproportionately affecting marginalized communities. Integrating solar energy systems into SULFO Ltd's industrial processes is proposed to address these issues. Solar energy offers several benefits that can mitigate the current problems. It can enhance energy resilience by reducing dependency on grid power and fossil fuels, thereby insulating the company from price volatility and supply disruptions. The use of solar energy can also lower operating costs over time, aligning with sustainability goals and reducing greenhouse gas emissions. By adopting solar systems, SULFO Ltd can promote economic prosperity while contributing to environmental conservation, ultimately benefiting both the company and the broader community. This shift towards renewable energy aligns with global efforts to combat climate change and supports the transition to a more sustainable and equitable energy system. The global installed capacity of solar photovoltaic energy reached 1,177 GW. This growth in the solar photovoltaic market reflects a global shift towards renewable and sustainable energy technologies. China and the United States lead the global PV market, with 307 and 122 GW of installed solar PV capacity, respectively. On the other hand, Chile and Honduras had the highest share of photovoltaic energy mix in total energy produced in 2022 [18]. Despite the relatively smaller share of electricity consumed by Rwanda's industrial sector approximately 32.0% of the total electricity consumption by industries amounting to 338,334,921 kWh (RURA electricity report, 2023) factories and plants still require significant amounts of energy [2].

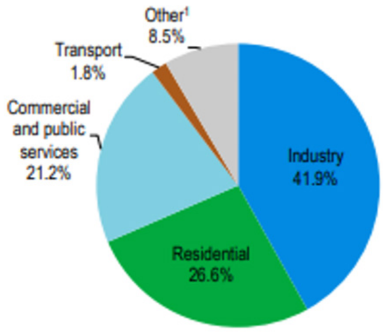


Figure 1. Total electricity consumption by sector[1].

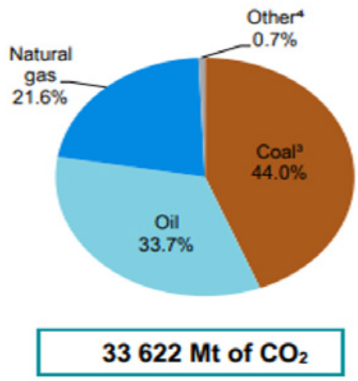


Figure 2. CO_2 emission by fuel [1].

The IEA statistics reveal that our reliance on fossil fuels contributes to environmental degradation, air pollution, and resource depletion, highlighting the urgent need for alternative power options and a reduction in CO_2 emissions as seen in Figure 2.

2. RELATED WORK

Ashok and Banerjee developed an innovative optimization model for Industrial Load Management, resulting in a 95% decrease in peak electricity consumption and a 29% cost-saving strategy at a flour mill. They emphasized the need for continuous improvement in load forecasting techniques [3]. Buoro et al. conducted a study on multi-objective optimization models for energy and district heating systems. Their research revealed the complex dynamics of these models and their potential for reducing emissions and improving energy efficiency. The study prompted further investigation into optimization techniques in various industrial scenarios [4]. Similarly, Bany Mousa and Taylor's study suggests that solar solutions can reduce emissions in the industrial sector by integrating solar thermal and photovoltaic systems. They emphasize the importance of integrated solar solutions for sustainable practices, promoting overall energy efficiency and reducing the impacts of climate change. This approach fosters a more environmentally friendly industrial environment [5]. Anser et al.'s research on solar energy integration in Turkey highlights the importance of incorporating economic factors into decision-making processes. They provide a comprehensive framework for evaluating the cost-effectiveness of solar projects, underscoring the potential for cost savings and long-term sustainability in industrial energy systems [6]. Pino et al. conducted a techno-economic analysis of microbreweries in southern Spain, finding that integrating photovoltaic systems could significantly reduce energy costs. They identified attractive payback periods and lower operating costs under favorable conditions. This research underscores the potential of renewable energy solutions in maximizing operational efficiency and supporting financial sustainability [7]. Mekhilef et al. analyzed the economic viability of solar power systems, particularly in isolated areas, highlighting their competitiveness and potential to empower communities and improve energy accessibility. This underscores the role of solar energy in inclusive and sustainable development [8].

The nominal electrical characteristics are often evaluated at standard test conditions (STC). These characteristics are maximum power [Watts], maximum power voltage [Volts], maximum [Amps], open circuit voltage [Volts], and Short-circuit current [Amps], which are evaluated at STC as surface cell temperature of 25°C, solar radiation of, and air mass of 1.5 [29].

The Role of Renewable Energies in Sustainable Development of Ghana by Mark Amoah Nyasapoh et al. examines the potential for renewable energy sources to drive sustainable development in Ghana. It highlights the critical role that renewable energies play in advancing economic growth, addressing environmental concerns, and promoting social equity in developing nations. Despite facing significant barriers to large-scale implementation, renewable energies are identified as environmentally friendly options for electricity generation. The study reveals that Ghana's green economy agenda requires a substantial investment of US$22.6 billion to meet ten years of Nationally Determined Contributions (NDCs). Currently, only 1.12% of the electricity generation mix comes from renewables, primarily solar, indicating a significant underutilization of renewable energy potential. Renewable energy sources are essential for enhancing electricity security, reducing CO_2 emissions, and contributing to climate goals, such as maintaining the earth's temperature below 2 °C. The paper recommends policy adjustments to increase renewable energy integration and emphasizes the need for an effective National Development Plan to support the renewable energy sector. Overall, the study underscores the transformative potential of renewable energies in Ghana's energy landscape and stresses the importance of strategic investments and robust policy frameworks to harness these resources for sustainable development [32].

Estimation of CO_2 Emissions of Fossil-Fueled Power Plants in Ghana: MESSAGE Analytical Model" by Mark Amoah Nyasapoh et al. analyzes the impact of fossil fuel consumption on CO_2 emissions within Ghana's energy sector. Utilizing the MESSAGE analytical tool, the study models the electricity generation system to evaluate the environmental effects of various fuel options. The key findings indicate that incorporating low-carbon emission technologies, such as renewables and nuclear energy, is essential for reducing CO_2 emissions. The study underscores the need for a shift toward climate-friendly energy sources to achieve sustainable and clean electricity generation. To meet Ghana's climate change mitigation goals, reliance on fossil fuels must be decreased, and zero-emission sources integrated into the energy mix [33].

3. MATERIALS AND METHODS

Collecting data on photovoltaic(PV) modules and inverters involves a methodical approach to ensure that the systems evaluated or installed meet specific requirements and perform efficiently.

When selecting photovoltaic(PV) modules, several key criteria must be considered to ensure optimal performance and reliability. First, assess the performance specifications, including efficiency, which indicates how effectively the module converts sunlight into electrical energy higher efficiency translates to greater power output per unit area. Evaluate the nominal power output under standard test conditions (STC), typically measured in watts, and consider the temperature coefficient, which reflects how the module's performance degrades with temperature increases; a lower coefficient indicates better performance in hot conditions. In terms of durability and reliability, examine the module's ability to withstand environmental challenges such as high winds, heavy snow, and hail, and review the manufacturer's warranty, which usually ranges from 10 to 25 years. Material and construction are also crucial; modules can be made from monocrystalline, polycrystalline, or thin-film cells, each with distinct efficiency and cost characteristics. Additionally, assess the quality of encapsulation materials like EVA (ethylene-vinyl acetate) and the durability of the glass and back sheet. Ensure the modules meet industry certifications such as International Electrotechnical Commission(IEC) Standard, Underwriters Laboratories (UL)Standard Bottom of Form, [IEC 61215, IEC 61730, and UL 1703], which guarantee adherence to international quality and safety standards. Lastly, consider the physical characteristics including dimensions, weight, and frame material, typically aluminum, which should be corrosion-resistant and durable.

For inverters, performance specifications such as conversion efficiency are critical, as they determine the efficiency of converting DC power from the PV modules to AC power, with higher efficiency meaning less power loss. Evaluate the maximum power point tracking (MPPT) capabilities, noting the number of MPPTs and their efficiency, as they optimize power output by adjusting to varying sunlight conditions. Ensure the inverter is compatible with your system's voltage range and has a power rating that matches or exceeds the output of the PV modules. Choose the type of inverter based on your system needs string inverters for similar panel conditions, micro inverters for varying conditions, or power optimizers to enhance output when used with string inverters. Features such as built-in monitoring capabilities and grid-tie compliance are important for tracking performance and meeting local regulations. Durability and reliability should be assessed by reviewing the manufacturer's warranty, which typically spans from 5 to 10 years but can extend to 20 years, and environmental ratings to ensure the inverter can handle the local conditions. Confirm the inverter meets certifications like IEC 62109 and UL 1741 for safety and performance. Finally, consider physical characteristics such as size, weight, and cooling method, whether air or liquid, to ensure proper installation and long-term reliability.

3.1. Geographical Location of Sulfo ltd

Sulfo Rwanda Industries is one of the largest fast moving consumer goods manufacturing companies in Rwanda. It was established in 1962 by Mr. Tajdin H. Jaffer and Khatun Jaffer. At that time, Sulfo Rwanda Industries was the only industrial soap producer in Rwanda. The case study is Sulfo Ltd, located in Kigali City, Nyarugenge District, Nyarugenge Sector, Rwanda, with coordinates (latitude -1.944852583834557, longitude 30.057040310401355).

Figure 3: Geographical location of Sulfo ltd (Source: google map).

3.2. Methodology Used

The study operates under several key assumptions to frame its findings. Firstly, it assumes that the historical growth trends in the PV market will continue based on current technological advancements and policy trajectories. Secondly, assumptions are made regarding the stability and reliability of data sources used for market analysis, including government reports, industry publications, and academic research. Additionally, assumptions are made regarding economic conditions, regulatory frameworks, and geopolitical stability influencing the deployment of solar PV technologies globally.

Several limitations impact the results of this study. Firstly, the accuracy and completeness of data sources may vary, potentially affecting the reliability of market forecasts and trends identified. Secondly, the study's geographical scope may not encompass all regional nuances and variations in PV market dynamics, potentially leading to generalized findings. Furthermore, the study's reliance on historical data and projections may overlook unexpected disruptions or technological breakthroughs that could alter market outcomes. Lastly, the analysis may not fully capture the socio-political factors and cultural contexts influencing PV adoption in different regions.

Uncertainties in the study's findings stem primarily from future unknowns and variables outside the study's control. These uncertainties include shifts in government policies and regulations impacting PV incentives and subsidies, changes in global economic conditions affecting investment flows into renewable energy sectors, and technological advancements in competing energy technologies that could alter the cost competitiveness of PV. Moreover, uncertainties in climate change impacts and adaptation strategies may influence future energy demand patterns and consequently, the uptake of solar PV technologies globally. Finally, uncertainties related to public acceptance and societal readiness for large-scale PV deployment could affect market growth trajectories unpredictably [28].

3.2.1. Mathematical Modeling of PV

A photovoltaic (PV) system converts sunlight into electrical energy using solar cells. The fundamental unit of a PV system is the solar cell, which is commonly modeled as a current source with distinct characteristics. Mathematical modeling of PV systems involves developing mathematical representations to understand and predict their performance. These models enable engineers and scientists to design, optimize, and analyze PV systems effectively for a range of applications.

PV modeling: The real power (P_{PV}) of the PV panel under real operation and climatic conditions is:

$$P_{PV} = P_{STC}\left[1+\beta_p(T_{cell}-T_{STC})\right]\frac{H_t}{H_{STC}} \qquad ......(1)$$

Where: T_{STC} and T_{cell} are the celll's surface temperature at Standard Test Condition, β_p is the power temperature coefficient (equ.1).

3.2.2. Mathematical Modeling of Inverter

Inverters are essential components in renewable energy systems because they convert the direct current (DC) voltage produced by solar panels or batteries into alternating current (AC) voltage, which is suitable for the electrical grid or household use. Mathematical modeling of inverters is crucial for understanding and optimizing their performance in this conversion process. By accurately modeling the inverter's behavior, engineers can enhance its efficiency and effectiveness in integrating with electrical grids and powering AC appliances.

Inverter modeling: The equation below shows (equ. 2) that the power output of the inverter is calculated by dividing the input power by the inverter's efficiency, reflecting the power that is effectively converted and delivered to the output.

$$P_{inv}(t) = \frac{P_l^m}{\eta_{inv}} \qquad ....(2)$$

$P_{inv}(t)$: The power output of the inverter at time t.
P_l^m :The maximum power that the inverter can handle or the power input to the inverter at time t.
η_{inv} : The efficiency of the inverter.

3.3. Data Collection

Throughout the process of improving industrial energy costs through solar integration, data collection is essential. Initially, we compiled current meter data and past utility bills to establish baseline energy usage trends over the past three years (annually, monthly, and daily). This data was collected through archival research and interviews conducted at Sulfo Ltd. The analysis of the collected data shows that the average annual energy consumption is 978,738 kWh, with average annual energy expenses amounting to 120,519,000 RWF. Therefore, our goal was to cover approximately half of Sulfo Ltd's energy consumption in the soap department.
Archival data collection involves gathering information from historical records and documents stored in Sulfo Ltd's archives. This process included analyzing past utility bills and energy demand based on usage trends for the past three years, categorized annually, monthly, and daily, as well as their corresponding expenses. Additionally, data on the industry's size, equipment, and hours of operation were recorded to provide context for the energy statistics. During the interview data collection phase, information was obtained through face-to-face in-depth conversations with Engineer Gopal from Sulfo Ltd. In the data collection process, several biases and limitations may impact the accuracy and comprehensiveness of the findings. Historical data bias is a concern, as incomplete records or missing critical data can create gaps in understanding energy trends or financial impacts. Additionally, past utility bills and energy demand data may contain inaccuracies that were not identified at the time of recording. Selection bias also plays a role; relying solely on archived documents and specific interviews may not provide a comprehensive view if the chosen records or participants are not representative of broader conditions. Participant bias is another factor, as information from individuals like Engineer Gopal might reflect personal or departmental perspectives rather than a full organizational overview. Interview limitations include subjectivity, where responses may be influenced by personal opinions or memory recall issues, and response bias, where participants might provide answers they perceive as desirable rather than completely honest. Contextual factors such as changes in the operational environment or equipment variability over time can affect the relevance of historical data. Finally, data integration issues arise when inconsistencies between quantitative data and qualitative insights make it challenging to create a coherent interpretation of energy statistics and related expenses. Addressing these biases and limitations requires careful cross-referencing, validation of information, and a thorough understanding of the industry context.

Table 1: Sulfo industry in soap manufacturing department electricity consumption (Source: Sulfo ltd).

	Years			
Month	**2021/kWh**	**2022/kWh**	**2023/kWh**	**Average/kWh**
January	61440	82850	81750	75346.67
February	63200	79560	74710	72490
March	75040	93270	90960	86423.33
April	70090	79280	79060	76143.33

May	72820	86550	70700	76690
June	74750	88990	78500	80746.67
July	75870	92680	75321	81290.33
August	77020	93930	99872	90274
September	89430	85840	92957	89409
October	82690	89760	89870	87440
November	82660	88160	78735	83185
December	81630	81610	74659	79299.67
Sum	906640	1042480	987094	978738

Note: this table show us the electricity consumption of Sulfo ltd for past three years and the average of these three years, to show the average annual consumption of Sulfo ltd.

Table 2: Electricity expenses of Sulfo industry in soap manufacturing department (Source: Sulfo ltd).

	Years		
Month	**2021/Rwf**	**2022/Rwf**	**2023/Rwf**
January	7409305	10143665	10090111
February	7691519	9851673	9292905
March	9196721	11351871	11176437
April	8713132	9701289	9887838
May	9016409	10538984	8923718
June	9329353	10894603	9776841
July	9160576	11378034	9433868
August	9537899	11477305	12218704
September	10882728	10591969	11325880
October	10155512	11058533	11053414
November	10052136	10863031	9852126
December	9950785	10201621	9376505
Sum	111096075	128052578	122408347
Average/year		120519000	

Note: this table show the energy consumption expenses of sulfo ltd in soap department for past three years and the average expenses per year.

4. DESIGN OF PHOTOVOLTAIC(PV) SYSTEM

In designing a photovoltaic (PV) system for SULFO Ltd in Rwanda, several critical steps are undertaken. This includes conducting a comprehensive load analysis to assess energy requirements, considering daily and seasonal variations in electricity demand, and reviewing historical consumption data to understand peak loads and usage patterns. Solar resource assessment is conducted to analyze solar irradiance data and determine the site's solar potential. The sizing of the solar PV array is then based on energy demand and solar resource availability, factoring in tilt angle, orientation, and shading. Energy storage capacity is sized to ensure adequate autonomy and stability, considering daily cycles and weather variability, while a backup generator is specified for periods of low renewable energy production or emergencies. Power electronics such as inverters and charge controllers are selected to suit the hybrid system configuration, and a microgrid architecture is designed to manage power flow, balance supply and demand, and ensure system stability. Implementation includes a robust control and monitoring system with remote capabilities to optimize performance and diagnose issues promptly. Financial aspects are evaluated through cost-benefit analysis to determine economic viability, assessing initial investment costs, operational expenses, and potential savings from reduced reliance on diesel generators. Return on investment (ROI) calculations are crucial to justify the project to stakeholders and secure financing. Environmental impact assessments focus on reducing greenhouse gas emissions and fossil fuel reliance, while regulatory compliance ensures adherence to local regulations for renewable energy installations and grid connections where applicable. The PV system design includes specifying the arrangement and components of the solar installation (Figure 4), which entails selecting suitable PV modules, inverters, and mounting structures based on the solar irradiation and load requirements of the location, determined through system sizing. The cost-benefit analysis helped us evaluate the economic feasibility of integrating a PV system. This involved assessing the expenses of initial installation, including equipment, labor, and permits. To determine the payback period, return on investment (ROI), levelized cost of energy (LCOE), and net present value (NPV), projected energy savings were compared to the investment, taking into consideration electricity prices and consumption patterns. Summaries of the analyzed parameters are presented in Table 3.

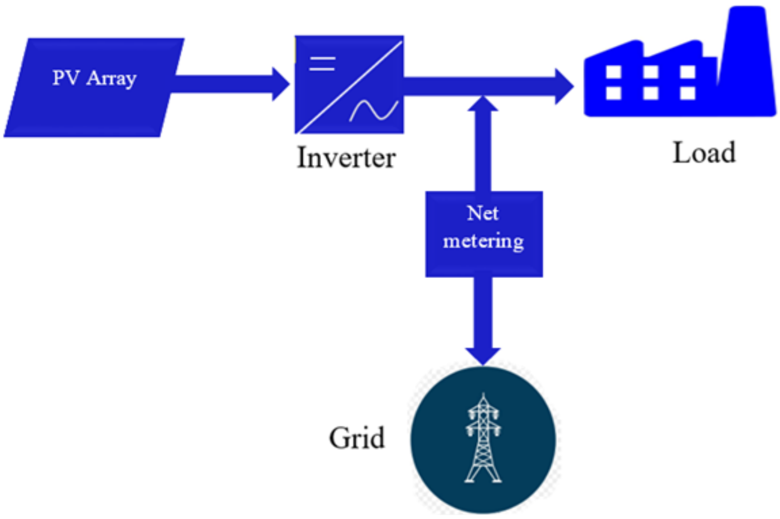


Figure 4. Schematic diagram of PV system.

Table 3: Cost-benefit analysis parameter.

Parameter	Formula
Net present value (NPV)	**NPV**=-Upfront cost+∑ annual electricity savings
Return on investment (ROI)	**ROI**=(Gross return-initial investment)/(initial investment)×100
Payback period	**Payback period**=(initial installation cost)/(annual energy saving)
Levelized cost of energy (LCOE)	**LCOE**=(total expenses over project lifetime)/(total energy output over project lifetime)

i. Load analysis:

In load analysis we need to find the energy consumption per day of Sulfo ltd, that will be used as demand in sizing.

$$Average\ annual\ demand = \frac{\sum(y_1 + y_2 + y_3 + ... + y_n)}{n} \qquad (3)$$

Where:

y_1: electricity consumption of first year for sample n years, y_2: electricity consumption of second

year, y_3: electricity consumption of third year, and y_n: electricity consumption of n years .
From data in table1, and using formula (3), we had: $y_1= y_{2021}$=906640 kWh, $y_2=y_{2022}$=1042480 kWh, and $y_3= y_{2023}$ =987094 kWh.

$$Average\ annual\ demand = \frac{906640+1042480+987094}{3} = 978738\,kWh$$

$$Daily\ electricity\ consumption = \frac{annual\ demand}{days\ of\ year} = \frac{978738}{365\,days} = 2681.5\,kWh/day$$

ii. PV array sizing:

First, we needed to find the total PV power needed:

$$PV\quad pwer = \frac{Daily\ electricity\ consumption}{sun\ peak\ hour\ of\ location} \times standard\ energy\ loss \qquad (4)$$

Where: Standard energy loss in PV system is 30% which is 0.3[21], then, on our needed power we must exceed 30% of PV power output in order to recover the loss. So, that standard energy loss will be 130% which is 1.3.
Sun peak hours in Rwanda is approximately 5hours, with potential of 4.5 kWh per m^2 per day[22].

$$So,\ total\ PV\ power = \frac{2681.5\,kWh/day}{5h} \times 1.3 = 697.18kW/day$$

From the annex A of PV panel specification,

$$Number\ of\ solar\ panels = \frac{Total\ PV\ power}{PV\ power\ rating} \qquad (5)$$

$$= \frac{697.2\times 1000W}{660W/panel} \approx 1056.00 \quad panels$$

iii. Inverter sizing:

Inverter size must have the specification where its maximum power output is greater, or slightly closer than total PV array power output. For safety, the inverter should be considered 25-30% bigger size.

$$Inverter\ power \geq PV\ power\ rating \times Number\ of\ solar\ panels \qquad (6)$$

$$= \frac{660W}{panel} \times 1056.00 \quad panels = 696960W = 696.96kW$$

According to an analysis done with PVSyst software, an area of 3280 square meters would be needed to provide the 1139.32 MWh per year corresponding to 3121.4 kWh per day that sulfo ltd in soap department needs to run daily as their average daily demand is 2681.5 kWh per day.
To assess the project's overall viability for optimizing industrial energy through solar system technology through simulation, we conducted a cost-benefit analysis. This analysis carefully weighed the initial investment required for the solar system installation and any ongoing maintenance expenses against the potential financial gains from reduced energy consumption. By careful considering both the upfront costs and the long-term advantages.
Other information is needed in Cost Benefit Analysis:
Solar panel cost is €0.168 / Wp, approximately \$0.18/Wp [23].
The inverter cost is €7,980 per unit which is roughly \$9,765.13 per unit[24].
The average maintenance cost of solar panel systems ranges from \$300 to \$700 annually, inspections and cleanings are crucial for maintaining efficiency and preventing costly repairs. So the average range will be \$500[26].
Solar panel installation cost is \$876 per kilowatt [26, 27].

In Rwanda, a company for SULFO Ltd engaged in manufacturing sulfuric acid and other products, installing a photovoltaic (PV) solar field requires careful consideration of design parameters to optimize performance. In Rwanda, a tilt angle between 5° and 15° is generally effective. This tilt angle helps maximize energy production by slightly adjusting the panels to capture the sun's rays more effectively, particularly during the morning and evening when the sun is lower in the sky. Despite Rwanda's minimal seasonal variation, this tilt range ensures consistent performance throughout the year. Additionally, PV modules should be oriented towards the north (0° azimuth) to maximize sunlight exposure. Proper row spacing is also crucial; it should be sufficient to prevent shading and is typically about 1.2 to 1.5 times the length of the shadow cast by the tilt angle. By following these guidelines, SULFO Ltd can achieve optimal efficiency and performance from their solar energy system.

Cost of the system

Installation costs

Item	Quantity units	Cost USD	Total USD
PV modules			
TSM-DEG21C-20-660Wp Vertex	468	118.80	55,598.40
Inverters			
Sunny Highpower SHP150-20-PEAK3	2	9,765.13	19,530.26
Other components			
Accessories, fasteners	1	15,000.00	15,000.00
Wiring	1	200.00	200.00
Combiner box	1	50.00	50.00
Monitoring system, display screen	2	650.00	1,300.00
Measurement system, pyranometer	1	200.00	200.00
Surge arrester	4	25.00	100.00
Installation			
Global installation cost per module	468	462.00	216,216.00
Global installation cost per inverter	2	30,888.00	61,776.00
		Total	369,970.66
		Depreciable asset	90,128.66

Operating costs

Item	Total USD/year
Maintenance	
Provision for inverter replacement	1,302.02
Salaries	500.00
Repairs	300.00
Cleaning	20.00
Security fund	100.00
Total (OPEX)	2,222.02

System summary

Total installation cost	369,970.66 USD
Operating costs	2,222.02 USD/year
Produced Energy	502 MWh/year
Cost of produced energy (LCOE)	0.029 USD/kWh

Figure 5. Detailed cost of the system.

Financial analysis

Simulation period

Project lifetime	30 years	Start year	2025

Income variation over time

Inflation	0.00 %/year
Production variation (aging)	0.00 %/year
Discount rate	0.00 %/year

Income dependent expenses

Income tax rate	0.00 %/year
Other income tax	0.00 %/year
Dividends	0.00 %/year

Depreciable assets

Asset	Depreciation method	Depreciation period (years)	Salvage value (USD)	Depreciable (USD)
PV modules				
TSM-DEG21C-20-660Wp Vertex	Straight-line	30	0.00	55,598.40
Inverters				
Sunny Highpower SHP150-20-PEAK3	Straight-line	30	0.00	19,530.26
Accessories, fasteners	Straight-line	20	0.00	15,000.00
		Total	0.00	90,128.66

Financing

Own funds	369,970.66 USD

Electricity sale

Feed-in tariff	0.0800 USD/kWh
Duration of tariff warranty	20 years
Annual connection tax	0.00 USD/kWh
Annual tariff variation	0.0 %/year
Feed-in tariff decrease after warranty	0.00 %

Return on investment

Payback period	9.7 years
Net present value (NPV)	768,767.15 USD
Internal rate of return (IRR)	9.61 %
Return on investment (ROI)	207.8 %

Figure 6. Summarized financial analysis parameter with outcome.

Figure 5 and Figure 6, show the financial parameters needed to analyze the cost-benefit analysis of the project through software simulation, and show the outcomes through return on investment (ROI), NPV, IRR, and payback period and then the installation cost of our PV system is around \$369,971, operating cost is \$2,222, and the produced energy 502.2 MWh/year. From REG (Rwanda Energy Group) tariff of electricity for the medium category industry is 103Rwf/kWh.

$$Annual\ PV\ energy = Annual\ produced\ energy \times energy\ cost \qquad (7)$$

$$= 502.2(MWh / year) \times 103(Rwf / kWh) \times 1000(kWh / MWh)$$

$$= 51726600 Rwf / year$$

Operating cost is \$2222, which corresponds to 2,904,575.16 Rwf per year.

From Table 2, the average annual energy bill of Sulfo ltd soap department without PV system is 120,519,000 Rwf per year.

To calculate Annual energy bill with PV system:

$$Annual\ energy\ saving = Annual\ PV\ energy\ cost - operating\ cost \qquad (8)$$

$$= 51726600(Rwf / year) - 2{,}904{,}575.16(Rwf / year)$$

$$= 48{,}822{,}024.84 Rwf / year$$

$$Annual\ energy\ bill = Annual\ energy\ bill\ without\ PV - Annual\ energy\ saving \qquad (9)$$

$$= 120519000(Rwf / year) - 48822024.84(Rwf / year)$$

$$= 71{,}696{,}975.1 Rwf / year$$

Payback period:

From the above data, installation cost is \$369,971, which corresponds to 477,240,391.74Rwf.

$$Payback\ period = \frac{initial\ installation\ cost}{annual\ energy\ saving} \qquad (10)$$

$$= \frac{477240391.74 Rwf}{48,822,024.84 Rwf\ /\ year} = 9.77\, years$$

Return on investment (ROI):

$$ROI = \frac{Gross\ return - initial\ investment}{initial\ installation\ cost} \times 100 \qquad (11)$$

Where,

$$Gross\ return = Annual\ energy\ saving \times Project\ lifetime \qquad (12)$$

$$= 48,822,024.84 (Rwf\ /\ year) \times 30\ (years) = 1,464,660,745 Rwf$$

From equation (11),

$$ROI = \frac{1464660745 Rwf - 477240391.74 Rwf}{477240391.74 Rwf}$$

$$= 206.9\%$$

Net Present Value (NPV):

$$NPV = -upfont\ cost + Gross\ return \qquad (13)$$

$$= -477240391.74 Rwf + 1464660745 Rwf = 987420353.3 Rwf$$

Levelized cost of energy (LCOE):

$$Total\ expense = installation\ cost + (operating\ cost\ per\ year \times project\ lifetime) \qquad (14)$$

$$= 477240391.74 (Rwf) + (2904575.16\ (Rwf\ /\ year) \times 30\ (years))$$

$$= 564,377,646.5 Rwf$$

Then,

$$LCOE = \frac{total\ expenses\ over\ project\ lifetime}{total\ energy\ output\ over\ project\ lifetime} \qquad (15)$$

$$= \frac{564377646.5 Rwf}{\frac{502.2 (MWh)}{year} \times 1000 (kWh / MWh) \times 30 (years)} = 37.46 Rwf\ /\ kW$$

5. MODELING, SIMULATION AND OPTIMIZATION PROCESS

The Modeling and Simulation Formulas help to understand the performance dynamics of solar PV systems under varying environmental conditions, highlighting their potential for significant CO_2 emission reductions and improvements in energy efficiency.

$$P_{solar} = A \times G \times \eta \qquad (16)$$

Where
P_{solar} : Power output of the solar panel(W).
A: Area of the solar panel(m^2).
G: Irradiance (W/m^2).
η: Efficiency of the solar panel.

$$P_{normal} = k_1 \times G \qquad (17)$$

Where:
P_{normal}: Power output of the solar inverter (W).
G : Irradiance (W/m^2).
k_1: Conversion factor specific to the inverter and panel system.

$$P_{inverter} = P_{normal} \times \left(1 - \beta \times \left(T - T_{ref}\right)\right) \quad (18)$$

Where:
$P_{inverter}$: Adjusted power output of the inverter (W).
P_{normal}: Nominal power output at reference temperature (W).
β : Temperature coefficient of power (%/°C).
T : Operating temperature (°C).
T_{ref} : Reference temperature (°C).

$$P_{inverter} = k_1 \times G \times \left(1 - \beta \times \left(T - T_{ref}\right)\right) \quad (19)$$

Where:
$P_{inverter}$: Power output of the inverter considering both irradiance and temperature (W).

Through modeling and simulation methodology, we modeled the projected solar energy generation based on its governing equation and gave it a behavior of the system due to some external load applied on it using Matlab software. Again, we simulated the sized system to see the outcomes according to the needed energy, to show the outcomes of the system and it indicated the potential for significant CO_2 emission reductions compared to the current energy consumption model from grid. Additionally, the simulation provided insights into the overall energy generation capabilities of the integrated solar system.

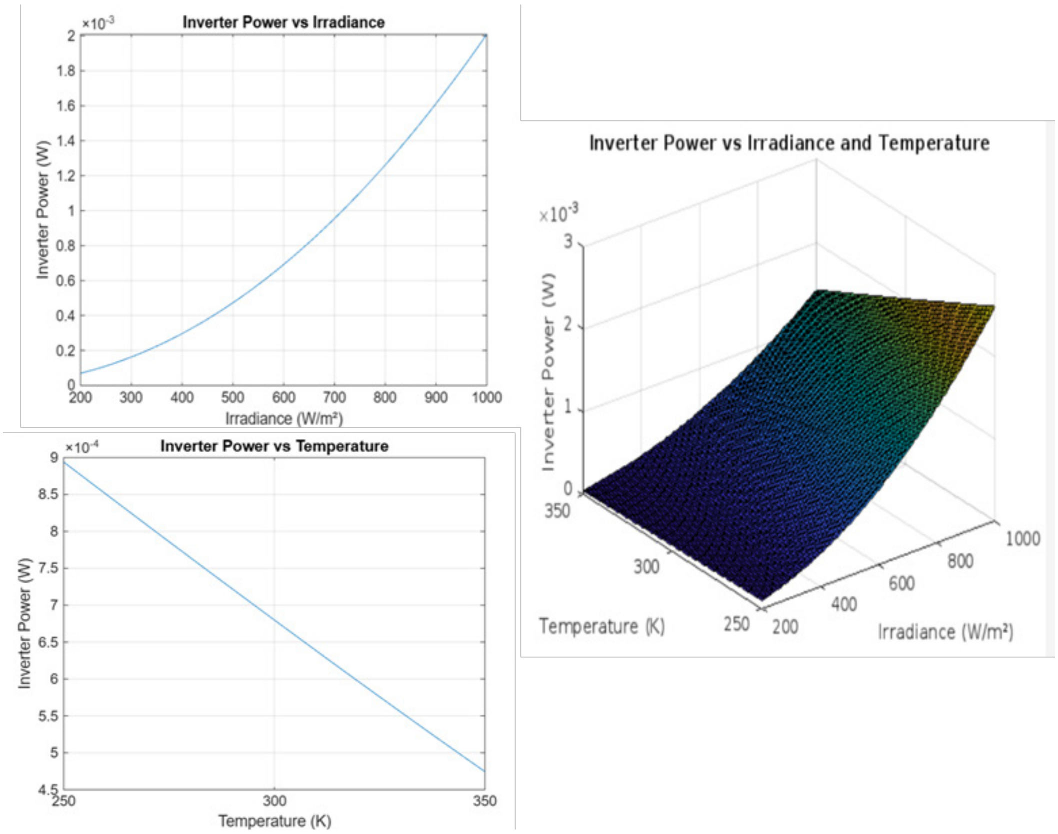


Figure 7. Matlab software simulation results.

Figure 7 shows the graphs of our modeled system behavior when it subjected the different external loads. These graphs are inverter power vs irradiance, inverter power vs absolute temperature, irradiance vs absolute temperature, and inverter power vs irradiance vs temperature.

The graph of Inverter Power versus Irradiance shows the relationship between the irradiance hitting the solar panels the power output panel and the inverter. As irradiance increases, panel inverter and inverter power output also increase. This means that solar panels consist of photovoltaic cells that convert sunlight (photons) into electricity (electrons). As irradiance (amount of sunlight) increases, more photons hit the cells, generating more electrons and consequently, higher power output.

The graph of Inverter Power versus Temperature shows the relationship between inverter temperature and inverter power output. It appears that inverter power output decreases slightly as temperature increases. This is likely because solar panels are made of semiconductors, and their efficiency decreases with rising temperature, as temperature increases, the movement of electrons within the cells becomes less efficient at converting sunlight into electricity when they are hot, leading to a decrease in power output.

A graph showing the inverter power output of a solar PV system versus irradiance (amount of sunlight hitting the panel) and temperature. The efficiency of a solar PV system is affected by both irradiance and temperature. Higher irradiance results in more electricity being produced. Temperature affects the efficiency of the solar panels. As the temperature increases, the efficiency of the panels typically decreases. This is because higher temperatures cause the internal resistance of the panel to increase, which leads to lower power. The graph shows us that, we have high panel power and inverter power when we have high irradiance and lower temperature as seen in the graph.

The optimization process aims are to maximize efficiency, minimize costs, and improve overall performance while considering the complex interactions and trade-offs inherent in decision-making processes. steps are followed:

- Clearly define the objectives and constraints of the system or process that needs optimization. This includes identifying what needs to be optimized (e.g., cost, time, energy efficiency) and any limitations or requirements that must be adhered to.
- Gather relevant data related to the system or process under consideration. This may include historical data, performance metrics, environmental factors, and resource availability. Analyze the data to understand current performance and identify areas for improvement.
- Develop mathematical models, algorithms, or simulations to represent the system or process. These models should accurately capture the relationships between variables, constraints, and objectives.
- Choose an appropriate optimization algorithm or method based on the complexity of the problem, the type of variables involved (continuous, discrete, mixed), and the computational resources available. Common methods include linear programming, genetic algorithms, simulated annealing, and gradient descent, among others.
- Implement the optimization algorithm to find the optimal solution or set of solutions. This may involve running simulations, iterating through possible solutions, and adjusting parameters to achieve the desired outcome.
- Validate the optimized solution through testing and verification. Ensure the solution meets the defined objectives and constraints under different scenarios and conditions.
- Implement the optimized solution in real-world applications. Monitor its performance over time to ensure continued effectiveness and make adjustments as necessary.
- Continuously refine and improve the optimization process based on new data, technological advancements, and changing conditions. This iterative approach helps to sustain improvements and adapt to evolving challenges.

One of the optimization steps was designing a solar PV system to meet the energy requirements of Sulfo Ltd. This involved determining the system size, selecting appropriate solar panels and inverters, and conducting a cost-benefit analysis. Factors such as installation costs, operation and maintenance expenses, potential energy savings, and the payback period were considered during the design phase. Modeling and simulation were conducted using PVsyst and MATLAB software to predict system performance and financial outcomes.

6. RESULTS AND DISCUSSION

6.1. Summary of Results

The integration of the solar PV system at Sulfo Ltd in the soap department resulted in a substantial reduction in energy costs and CO_2 emissions over the project's lifetime. The project generates 502.2 MWh/year of energy, as shown in Figure 8. Based on the Rwanda Energy Group (REG) tariff of 103 Rwf/kWh for medium category industries, the annual cost of energy produced by the PV system is 51,726,600 Rwf.

The project's cost-benefit analysis shows a payback period of approximately 10 years, with a total profit of $768,767 or 987,420,353.3 Rwf over 30 years as shown in Figure 9. The net present value and return on investment are approximately 206.9%. The annual PV energy cost is 51,726,600 Rwf per year, whereas the annual energy bill with the Solar PV system amounts to about 71,696,975.16 Rwf per year. Comparatively, the annual energy bill without the Solar PV system averages 120,519,000 Rwf per year, resulting in a reduction of 40.5% due to solar integration. The system's lifecycle emissions were offset by the significant reduction in emissions from displacing grid electricity use, resulting in net savings of 6,555.1 tCO_2 emissions.

Examining the results in Table 4 reveals a promising outlook for long-term financial returns through optimizing industrial energy consumption costs with solar power integration. The total revenue generated from electricity produced by the solar system remains constant at $40,180 per year, resulting in savings for Sulfo Ltd in the soap department's energy expenses. The project analysis through simulation indicates a recovery of the initial investment of $369,971 within approximately 10 years, factoring in operating costs of $2,222 per year and straight-line depreciation of $3,254 per year. Beyond this point, the solar system is expected to generate positive cash flow. Over the entire 30-year period, the system is projected to accumulate a total profit of $768,767.

Figure 8. visually complements this information by depicting the cumulative cash flow. Initially, the curve trends downward as initial investments and ongoing expenses exceed electricity generation, representing the payback period with negative net profit. However, as the system matures and electricity generation increases, the curve should begin to trend upwards, reflecting positive cash flow or positive net present value (NPV). By year 30, the cumulative cash flow is expected to reach a positive value, aligning with the projected profit in the table. It's important to acknowledge the limitations of this analysis. The discount rate, which significantly impacts the present value of future cash flows, is not specified in the table. Additionally, the table and figure are based on assumptions regarding various factors such as electricity costs, maintenance expenses, and tax rates, which can vary depending on the specific circumstances of the industrial facility. Furthermore, government incentives for solar power systems, which vary geographically and provide additional financial benefits, are not included in the analysis.

A detailed analysis of the payback period and financial savings for a photovoltaic (PV) system must account for the potential fluctuations in electricity prices and maintenance costs over the system's lifespan, typically around 30 years. This extended time frame introduces uncertainties and variables that can significantly impact the financial performance of the investment. Electricity prices are not static; they can fluctuate due to various factors including market conditions, fuel costs, and regulatory changes. Over a 30-year period, these fluctuations can substantially affect the financial benefits of a PV system.

Electricity prices typically increase over time due to inflation and rising energy production costs, making the savings from a photovoltaic (PV) system more significant as prices rise. This can reduce the payback period and enhance overall financial savings. Conversely, if electricity prices decrease or remain stable, the financial benefits of the PV system may be less pronounced. Additionally, regulatory changes, such as new energy policies, subsidies, and tax incentives, can influence electricity costs and net metering rates, affecting how much you save with solar power. Keeping up-to-date with these potential changes is crucial for accurate future savings forecasts. Energy market dynamics also play a role; fluctuations in fuel prices and shifts towards renewable energy can impact electricity costs, with higher natural gas prices potentially increasing electricity rates and greater renewable energy adoption possibly stabilizing or lowering them. Understanding these factors helps in estimating long-term savings and planning effectively for the financial performance of a PV system.

Maintenance costs are another critical factor influencing the payback period and financial savings. Although PV systems are relatively low-maintenance, several aspects need consideration over a 30-year period. Routine maintenance, including tasks like cleaning panels and checking system components, involves ongoing costs that, while generally modest, can accumulate over time. Accurate financial planning requires estimating these costs based on historical data and industry standards. Additionally, the performance of PV panels degrades at a rate of about 0.5% to 1% per year, which can reduce energy output and, consequently, savings. Potential repairs or replacements of components, such as inverters which typically need replacement every 5 to 10 years should also be considered, as they add to maintenance costs. Opting for extended warranties or service contracts can help manage unexpected maintenance expenses, but these come with their own costs. It is essential to compare the cost of these warranties with the potential savings from avoiding repairs to ensure a sound financial decision. To provide a comprehensive financial analysis, these factors should be integrated into a dynamic financial model that accounts for uncertainties over 30 years. Conducting sensitivity analyses is essential to understand how fluctuations in electricity prices and maintenance costs impact the payback period and financial savings of a PV system. This involves creating scenarios with varying rates of electricity price increases and maintenance cost changes to assess their effects on overall financial performance.

Additionally, developing different scenarios such as high, medium, and low based on potential future changes in electricity prices and maintenance costs helps in preparing for a range of financial outcomes. Long-term projections, incorporating historical trends, inflation rates, and expert forecasts, are used to estimate future electricity prices and maintenance costs, which should be integrated into your financial model for accurate long-term savings and payback period estimates. Regularly reviewing and updating the financial analysis to reflect actual changes in these factors ensures that projections remain accurate and supports informed decision-making about the system's financial performance. A thorough analysis of the payback period and financial savings of a PV system must consider potential fluctuations in electricity prices and maintenance costs over its 30-year lifespan. By integrating these factors into a dynamic financial model and conducting sensitivity analyses, investors can better understand the long-term financial impacts and make informed decisions about their PV investment.

Main results

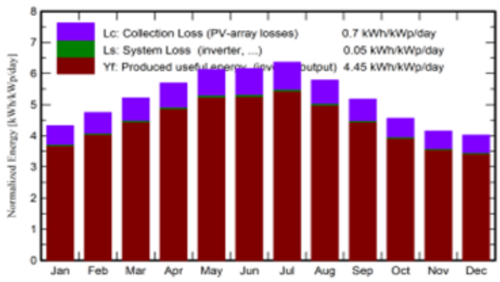
System Production

Produced Energy	502205 kWh/year	Specific production	1626 kWh/kWp/year
		Performance Ratio PR	85.70 %

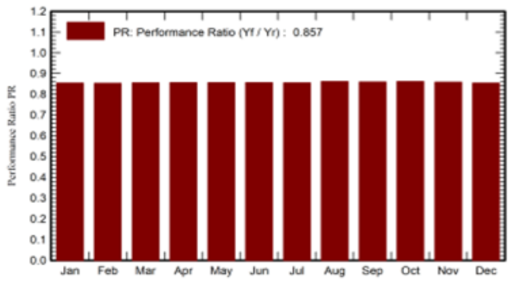
Economic evaluation

Investment		Yearly cost		LCOE	
Global	369,970.66 USD	Annuities	0.00 USD/yr	Energy cost	0.03 USD/kWh
Specific	1.20 USD/Wp	Run. costs	2,222.02 USD/yr		
		Payback period	9.7 years		

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	184.4	70.57	21.27	134.2	127.8	35752	35388	0.854
February	164.6	63.15	21.72	132.9	128.1	35417	35050	0.854
March	177.8	75.73	21.49	161.6	157.2	43125	42667	0.855
April	169.0	69.80	20.78	170.9	167.6	45686	45181	0.856
May	171.8	63.79	21.06	190.2	187.1	50858	50296	0.856
June	161.8	55.51	20.93	184.8	182.5	49430	48874	0.856
July	173.0	55.01	20.43	197.2	194.3	52704	52117	0.856
August	170.3	71.17	20.90	179.5	176.3	48328	47808	0.862
September	164.1	69.45	20.78	155.3	151.5	41689	41242	0.860
October	166.6	77.34	21.33	141.5	136.5	38035	37643	0.861
November	166.2	62.52	20.59	124.5	119.0	33379	33034	0.859
December	176.9	69.18	20.91	124.7	118.1	33246	32906	0.855
Year	2046.5	803.23	21.01	1897.2	1846.0	507650	502205	0.857

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Figure 8: Main results of solar PV system from PVsyst software.

Cost of the system

Installation costs

Item	Quantity units	Cost USD	Total USD
PV modules			
TSM-DEG21C-20-660Wp Vertex	468	118.80	55,598.40
Inverters			
Sunny Highpower SHP150-20-PEAK3	2	9,765.13	19,530.26
Other components			
Accessories, fasteners	1	15,000.00	15,000.00
Wiring	1	200.00	200.00
Combiner box	1	50.00	50.00
Monitoring system, display screen	2	650.00	1,300.00
Measurement system, pyranometer	1	200.00	200.00
Surge arrester	4	25.00	100.00
Installation			
Global installation cost per module	468	462.00	216,216.00
Global installation cost per inverter	2	30,888.00	61,776.00
		Total	369,970.66
		Depreciable asset	90,128.66

Operating costs

Item	Total USD/year
Maintenance	
Provision for inverter replacement	1,302.02
Salaries	500.00
Repairs	300.00
Cleaning	20.00
Security fund	100.00
Total (OPEX)	2,222.02

System summary

Total installation cost	369,970.66 USD
Operating costs	2,222.02 USD/year
Produced Energy	502 MWh/year
Cost of produced energy (LCOE)	0.029 USD/kWh

Figure 9: Detailed assumed cost of the system from PVsyst software.

Table 4: Financial analysis through cash flow of the project from PVsyst software

Financial analysis

Detailed economic results (USD)

Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Cumul. profit	% amorti.
0	0	369,971	0	0	0	0	0	-369,971	0.0%
1	40,180	0	2,222	3,254	34,704	0	37,958	-332,013	10.3%
2	40,180	0	2,222	3,254	34,704	0	37,958	-294,055	20.5%
3	40,180	0	2,222	3,254	34,704	0	37,958	-256,097	30.8%
4	40,180	0	2,222	3,254	34,704	0	37,958	-218,139	41.0%
5	40,180	0	2,222	3,254	34,704	0	37,958	-180,181	51.3%
6	40,180	0	2,222	3,254	34,704	0	37,958	-142,223	61.6%
7	40,180	0	2,222	3,254	34,704	0	37,958	-104,265	71.8%
8	40,180	0	2,222	3,254	34,704	0	37,958	-66,307	82.1%
9	40,180	0	2,222	3,254	34,704	0	37,958	-28,349	92.3%
10	40,180	0	2,222	3,254	34,704	0	37,958	9,609	102.6%
11	40,180	0	2,222	3,254	34,704	0	37,958	47,567	112.9%
12	40,180	0	2,222	3,254	34,704	0	37,958	85,524	123.1%
13	40,180	0	2,222	3,254	34,704	0	37,958	123,482	133.4%
14	40,180	0	2,222	3,254	34,704	0	37,958	161,440	143.6%
15	40,180	0	2,222	3,254	34,704	0	37,958	199,398	153.9%
16	40,180	0	2,222	3,254	34,704	0	37,958	237,356	164.2%
17	40,180	0	2,222	3,254	34,704	0	37,958	275,314	174.4%
18	40,180	0	2,222	3,254	34,704	0	37,958	313,272	184.7%
19	40,180	0	2,222	3,254	34,704	0	37,958	351,230	194.9%
20	40,180	0	2,222	3,254	34,704	0	37,958	389,188	205.2%
21	40,180	0	2,222	2,504	35,454	0	37,958	427,146	215.5%
22	40,180	0	2,222	2,504	35,454	0	37,958	465,104	225.7%
23	40,180	0	2,222	2,504	35,454	0	37,958	503,062	236.0%
24	40,180	0	2,222	2,504	35,454	0	37,958	541,020	246.2%
25	40,180	0	2,222	2,504	35,454	0	37,958	578,978	256.5%
26	40,180	0	2,222	2,504	35,454	0	37,958	616,935	266.8%
27	40,180	0	2,222	2,504	35,454	0	37,958	654,893	277.0%
28	40,180	0	2,222	2,504	35,454	0	37,958	692,851	287.3%
29	40,180	0	2,222	2,504	35,454	0	37,958	730,809	297.5%
30	40,180	0	2,222	2,504	35,454	0	37,958	768,767	307.8%
Total	1,205,398	369,971	66,661	90,129	1,048,609	0	1,138,738	768,767	307.8%

6.2. Comparison of Results

Examining the results in Table 4 and the data in Figure 9, the cost-benefit analysis evaluated the economic viability of our proposed PV system. The analysis projected significant financial savings of 40.5% due to the integration of solar system technology, with a projected payback period of around 10 years and a total profit of $768,767 by the end of 30 years.

Ashok and Banerjee (2001) developed an innovative optimization model specifically designed for Industrial Load Management (ILM). Their research at a flour mill produced compelling findings, including a noteworthy 95% decrease in peak electricity consumption and a significant 29% cost-saving strategy.

Similarly, Pino et al. (2016) examined the financial feasibility of photovoltaic solutions in a microbrewery setting, resulting in a considerable reduction in energy costs. Their analysis illustrated how timely investments in solar technology can lead to lower operating costs and attractive payback periods.

Mekhilef et al. (2019) focused on the economic competitiveness of solar power systems, especially in isolated areas not connected to the grid. Their research demonstrated how solar energy could provide affordable options for electricity production and distribution in rural areas, emphasizing financial benefits and potential improvements in electricity accessibility.

Furthermore, Anser et al. (2020) researched solar energy integration in Turkey, highlighting the importance of incorporating economic factors into decision-making processes. They provided a comprehensive framework for evaluating the cost-effectiveness of solar projects, emphasizing potential cost savings and long-term sustainability in industrial energy systems. The system's lifecycle emissions were offset by a significant reduction in emissions from displacing grid electricity, resulting in net savings of 6,555.1 tCO_2 after accounting for annual degradation of 1%, contributing to an 81% overall savings in CO_2 emissions for the solar energy project.

Bany Mousa and Taylor (2020) suggested that solar solutions can reduce emissions in the industrial sector through the integration of solar thermal and photovoltaic systems. They emphasized the importance of integrated solar solutions for sustainable practices, promoting total energy efficiency and reducing emissions, with their findings showing a net saving of 205.8 kt CO_2. Similarly, Buoro et al. (2013) conducted a study on multi-objective optimization models, revealing their complex dynamics and potential for reducing emissions and improving energy efficiency.

6.3. Impacts of the research results on the economy, environment, and society

By generating electricity on-site, companies can reduce their dependence on grid power, which is vulnerable to fluctuating prices and additional transmission costs. Solar systems typically offer a high return on investment due to their low operational and maintenance costs. Over time, the savings from reduced energy bills can outweigh the initial capital expenditure, thereby stabilizing energy costs and enhancing financial planning for industrial operations. Furthermore, solar energy systems produce electricity without emitting greenhouse gases. By integrating solar technology, industries can significantly shrink their carbon footprint. This reduction in greenhouse gas emissions supports global efforts to mitigate climate change and its associated impacts, such as extreme weather events and rising sea levels. Moreover, the cost savings from solar technology can democratize access to energy across various sectors and populations, thereby promoting greater energy equity. Solar energy can play a pivotal role in improving access to electricity in underserved or remote areas, thereby enhancing quality of life and fostering economic development in those regions.

7. CONCLUSION

This research project successfully demonstrated the potential of solar photovoltaic (PV) systems to optimize energy consumption costs within an industrial setting. Focused on a case study of SULFO LTD's soap manufacturing department, the study yielded promising results, including a reduction in CO_2 emissions by 6555.1 metric tons and financial savings of $768,767 over a 30-year period through reduced reliance on grid electricity. The solar investment also showed a feasible payback period of approximately 10 years. These findings directly address the ongoing need for sustainable solutions in the industry, contributing to both economic and environmental benefits through solar energy integration. However, the study acknowledges limitations, such as assumptions made in the cost-benefit analysis, potential variations in energy costs, and limited expertise in software usage. Despite these challenges, the research offers significant practical applications. Industrial facilities can use these insights to explore solar PV integration as a strategy to reduce their carbon footprint, achieve financial savings, and enhance overall energy sustainability. Implementing solar systems has the potential to create long-term profitability and contribute to a cleaner future for industrial operations.

Building upon this foundation, future research can focus on refining cost-benefit analysis methodologies through real-time data integration. Additionally, exploring the synergies between solar PV and other renewable energy sources such as wind or geothermal could broaden on-site energy generation options. Investigating control strategies for seamless integration with existing infrastructure and monitoring the long-term performance of solar systems in diverse industrial contexts would provide valuable insights for further advancements in industrial energy optimization. By continuing research in these areas, industries can confidently chart a course towards a more sustainable future and achieve greater energy cost-effectiveness.

The study's findings on cost savings and return on investment provide valuable insights for policymakers aiming to design incentives and subsidies that promote the adoption of photovoltaic systems in industrial settings. By understanding these economic benefits, policymakers can develop strategies to lower initial capital costs and improve financial viability. Additionally, the optimization techniques employed at SULFO Ltd serve as a model that can be adapted and applied to other industries and regions, facilitating the evaluation of solar system impacts and feasibility in various contexts. The case study also demonstrates how photovoltaic systems can enhance energy reliability and reduce reliance on grid power, supporting policies focused on improving energy security and resilience. Moreover, the study's results may reveal environmental benefits, such as reduced carbon emissions, which can guide the creation of regulations that foster sustainable energy practices. Ultimately, other industries can leverage these insights to develop effective energy strategies, utilizing the economic models and optimization findings to achieve cost efficiency and sustainability.

Author Contributions: Eustache Hakizimana: Made substantial contributions to conception and he was also involved in data interpretation and contributed to writing and revising the manuscript. Honorine Umuhoza: She provided editorial support and helped with manuscript preparation. KayibandaVenant: led the data analysis, and drafted the manuscript and he contributed to the interpretation of results and reviewed the manuscript for important intellectual content.

Data Availability Statement: Not applicable.

Funding: The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Acknowledgments: We would like to extend our sincere gratitude to the individuals and institutions that supported this research, including the staff of SULFO Ltd, Rwanda, for their cooperation and access to critical information. We also wish to acknowledge the constructive feedback and guidance provided by the reviewers and the editorial team. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the supporting organizations.

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Annex A: Solar PV panel specification (Source: [30]).

ELECTRICAL DATA (STC)	
Manufacturer	Trina solar
Product Name	TSM-DEG21C-20-660Wp Vertex
Peak Power Watts-PMAX (Wp)	660
Power Tolerance-PMAX (W)	0 ~ +5
Maximum Power Voltage-VMPP (V)	38.1
Maximum Power Current-IMPP (A)	17.35
Open Circuit Voltage-VOC (V)	45.9
Short Circuit Current-ISC (A)	18.45
Module Efficiency η m (%)	21.2
MECHANICAL DATA	
Solar Cells	Monocrystalline
No. of cells	132 cells
Module Dimensions	2384×1303×35 mm (93.86×51.30×1.38 inches)
Weight	38.7 kg (85.3 lb)
Front Glass	2.0 mm (0.08 inches), High Transmission, AR Coated Heat Strengthened Glass
Back Glass	2.0 mm (0.08 inches), Heat Strengthened Glass (White Grid Glass)
Cables	Photovoltaic Technology Cable 4.0mm^2 (0.006 inches2), Portrait: 280/280 mm (11.02/11.02 inches) Length can be customized
STC: Irrdiance 1000W/m^2, Cell Temperature 25^{o}C, Air Mass AM1.5	

Annex B: Inverter specification (Source: [31]).

Input (DC)	
Max. PV array power	225000 Wp
Max. input voltage	1500 V
MPP voltage range / rated input voltage	880 V to 1450 V / 880 V
Max. input current / max. short-circuit current	180 A / 325 A
Number of independent MPP trackers	1
Number of inputs	1 or 2 (optional) for external PV array junction boxes
Output (AC)	
Rated power at nominal voltage	150000 W
Max. apparent power	150000 VA
Nominal AC voltage / AC voltage range	600 V / 480 V to 690 V
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz or 60 Hz / 54 Hz to 66 Hz

Rated grid frequency	50 Hz
Max. output current	151 A
Power factor at rated power / displacement power factor adjustable	1 / 0 overexcited to 0 under excited
Harmonic (THD)	< 3%
Feed-in phases / AC connection	3 / 3-PE
Efficiency	
Max. efficiency / European efficiency	99.1% / 98.8%
General Data	
Dimensions (W / H / D)	770 mm / 830 mm / 444 mm (30.3 in / 32.7 in / 17.5 in
Weight	98 kg (216 lbs)
Operating temperature range	−25°C to +60°C (−13°F to +140°F)
Cooling method	OptiCool, active cooling, speed-controlled fan
Manufacturer	SMA
Product Name	Sunny Highpower SHP150-20-PEAK3