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Implementation of a carbon-neutral PV+BESS system - A case study of KNAUF gypsum Tanzania

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Battery Energy Storage System (BESS);
Decarbonization;
Greenhouse Gas (GHG),
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PVSyst Software;

Abstract

This study presents a decarbonization pathway for Tanzania’s industrial sector by integrating a 2.966 MWp solar photovoltaic (PV) system with a 2 MW/8 MWh battery energy storage system (BESS) at KNAUF Gypsum Tanzania. A comprehensive techno-economic analysis was conducted using PVSyst simulations software. The simulation integrated site-specific meteorological data, component specifications and the factory’s electricity load profile to model annual generation patterns, system losses and battery charging and discharging cycles. The model accounted for system degradation to ensure realistic long-term performance projections. The PV+BESS solution reduces the energy-related carbon footprint to 64% and cuts annual energy costs by 65%, achieving a 6-year payback period. Despite physical constraints, the system meets 52% of the factory’s total electricity demand, demonstrating the viability of PV+BESS to enhance energy reliability, slash emissions, and lower costs in diesel-dependent industrial settings.

Introduction

GHG emissions are among the critical environmental challenges, significantly impacting the global climate system and ecological stability. According to the Environmental and Energy Study Institute, about 78-80% of the world’s commercial energy comes from fossil fuels (EESI, 2021). The use of such sources as coal, petroleum and natural gas for electricity generation contributes to GHG emission and therefore global warming (Hefner et al. 2024). The consequences are far-reaching, affecting the ecosystems, public health and the economic system worldwide(Ngwaka et al. 2025). This makes decarbonization and energy efficiency become topics of great interest.

The mining, metal, mineral, cement, steel and plastic industries are said to be some of the most carbon intensive industries which are sometimes referred to as energy intensive and natural resource-based industries (Andersson 2020). These energy intensive industries make a significant part of the economy and are large contributors to energy use, resource consumption and emissions (Ji et al. 2022). Decarbonizing these sectors is therefore important for mitigation of global climate change and making this monumental sector sustainable (Nurdiawati and Urban 2021). Replacement of the non-renewable energy sources with clean energy alternatives, particularly renewables is essential for achieving the global climate objectives of reaching net zero emissions by mid-century (Karlilar and Balcilar 2024).

To decarbonize energy intensive industries across the globe, all the countries have a role to play, in order to achieve the climate neutral targets (Nurdiawati and Urban, 2021). Renewable energy plays a major role in displacing the use of fossil fuels and they are progressively advancing towards effective displacement of fossil fuels (Karlilar and Balcilar 2024).

Tanzania being one among the countries in sub–Saharan Africa whose GHG emissions are fewer, than the high-income countries, it is still crucial to make immediate action towards identifying sustainable approaches for decarbonization (Ul-Durar et al. 2025). This is even more crucial to Tanzania whose recent economic growth is driven also by the industrialization majorly from the energy intensive sector.

Tanzania has taken steps in making sure that energy performance of each sector is focused on reducing the energy demand and helping improve energy intensity by employing specific measures (United Republic of Tanzania 2024) . Such measures include decarbonization of the energy intensive sector using renewable energy sources such as solar PV plants and other energy efficiency mechanisms.

Despite the challenges of renewable energy resources such as PV plants in grid integration, and not being dispatchable, the decarbonization process is yet transitioning more quickly because of the contribution from the technological innovations and scientific developments (Azwardi et al. 2024).

This paper presents a case of the efforts towards decarbonization process, a design and installation of 2.966 MWp together 2 MW/ 8 MWh BESS, behind the meter.

Case study Description

The KNAUF gypsum factory depends on grid electricity to power all the factory processes. Before the extension of the factory, the peak power of the factory

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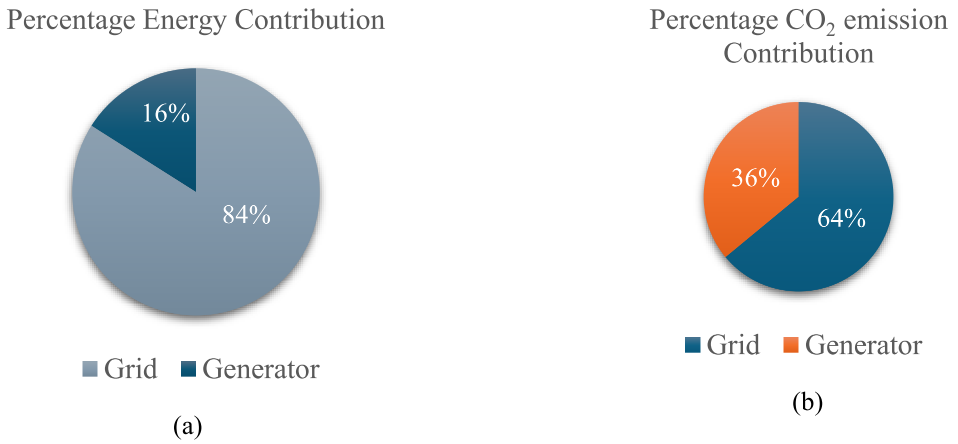
was 1.1 MW. To maintain reliability and continual gypsum production, there is a back-up diesel generator of 1.5 MVA used to power the factory when the grid is out. From the raw data received from the factory for last two years 2023 and 2024, a total of 4.6 GWh and 5.1 GWh respectively from TANESCO, 0.669 GWh and 0.969 GWh respectively from the use of the diesel generator when the grid was unavailable, depicting 84% by 16% share of the total energy consumption of the factory from the grid and diesel generator. This is evident from as the System Average Interruption Duration Index for the 2023/2024 was 703.25 minutes (EWURA, 2025).

Due to the extension of the factory, the peak power is expected to be 1.8 MW. The estimated energy consumption if all the production process behaves the same using linear proportionally ratio, 8.361 GWh and 1.586 GWh for the energy consumption contribution from the grid and diesel generator respectively. Making the total energy consumption to be 9.947 GWh. From this energy consumption the factory had an emission of 4.099 $ktCO_2$ of which 64% is contributed by the grid and 36% is from the genset. Figure 1(a) and (b) depicts the plant energy consumption and the CO_2 emissions respectively.



(a)

(b)

Figure 1: KNAUF's energy and CO_2 emissions contribution by source

Given the power interruption due to unavailability of the grid and the sense of decarbonization, the PV+BESS project aims at creating low carbon, safe and reliable power supply to the factory while adhering to standards.

System Architecture

Rooftop photovoltaic plant

Using PVsyst software, the rooftop PV plant was modelled to determine its performance. Using the Jinko 450 Wp model, the plant was modelled into two arrays; 139 strings x 32 where 32 is the number of modules in series forming one string, and 67 strings x 32 making a total of 6592 modules covering 13172 m^2.

A total of three inverter units were selected each rated 873 kVA making the DC/AC ratio to be 1.133 and the AC power delivered to the AC side be 2.619 MWac. The configuration of the strings to the inverter and to the power delivery point is shown in Figure 2 below.

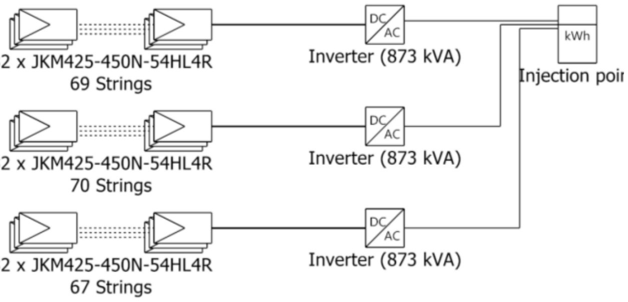
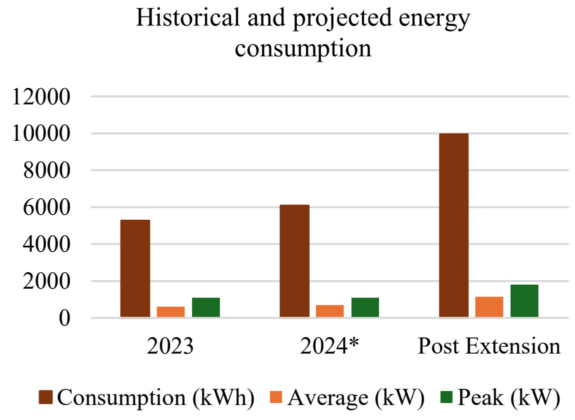


Figure 2: PV array and inverter single line diagram

The PV module strings are connected to DC combiners installed on the roof platform via cables passing through specific cable ducts installed along the walkways. The power is delivered to the power center located on the northern side of the factory though the main DC cabling installed along the roof platform.

Expected peak power and energy production

The power consumption of the plant is expected to rise from 1.1 MW to 1.8 MW due to the extension of the factory size and operations. If all the operations of the factory remain the same, using the 2023 and 2024 energy consumption data, the estimated energy consumption data of a typical year full operative after factory extension was obtained using linear proportionality.



11 months available, estimation*

Figure 3: Factory's historical and projected energy consumption

The rooftop PV plant data produced from the PVsyst software report are shown in Table 1 below

Table 1: Rooftop PV plant data

Description	**Value**
Module Area	13172 m^2
Estimated peak PV power	2.966MWp
Estimated energy yield	1769 kWh/kWp/y
Estimated yearly production	5.221GWh/y

Considering the plant's projected energy consumption and the PV plant's producibility, it is estimated that the PV plant will be able to satisfy 52% of the future energy consumption of the gypsum factory. This creates a dual effect of reducing the cost of purchasing electricity from the grid and eliminating the use of the diesel generator. Equation (1) is used to calculate the estimate PV plant coverage

$$\%PV\ Coverage = \frac{Expected\ PV\ production}{Expected\ consumption} \times 100 \quad (1)$$

In Figure 4, from the excel model incorporated with the production data from PVSyst, the PV plant production curve and the load profile (a 24/7 flat load is considered) on two solstices of the year. The flat profile is considered because of the unavailability of the sub-hourly and daily energy records, making the average consumption provide a feasible basis for modeling.

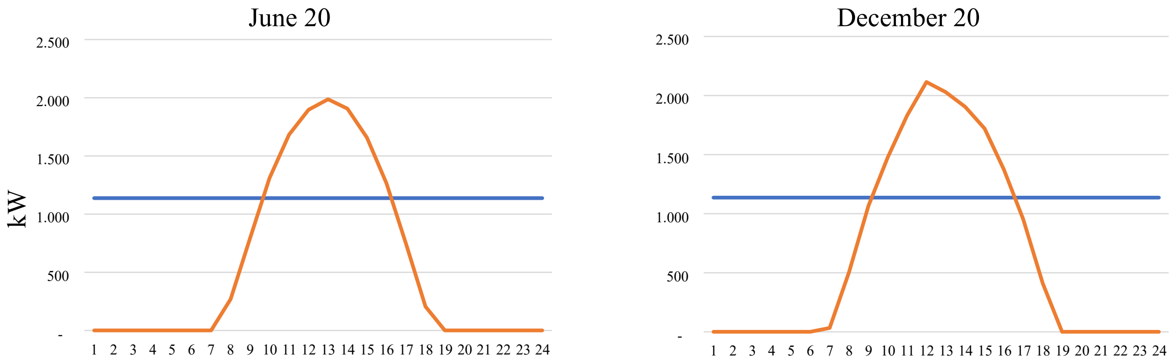


Figure 4: PV production curve and factory's load profile for two typical days

During peak production hours, the energy produced by the PV system exceeds the electrical load of the whole factory, while during the night the rooftop PV does not produce. However, the excess energy produced during the day cannot be fed to the distribution grid due to technical complexities and issues with management and regulations.

To ensure self-consumption of the total energy produced by the PV plant, a battery energy storage system (BESS) is installed to store the excess energy during the day and use it during night-time when the PV plant is not producing.

Battery energy storage system (BESS)

Storage capacity and technology

To determine the size of the storage required, the producibility data from PVsyst were used in an Excel model, the following Equation (2) governs the sizing of the storage

$$Storage\ size = 1.25 \times Max \sum_{to}^{tn} \left[PV\ energy\ production\ - Self\ used\ energy \right] \quad (2)$$

Where the 1.25 factor accounts for 80% utilization, t_o and t_n represents time in hours.

From the production curve and load profile of the two solstices in the year, the daily stored energy is estimated as shown in Figure 5

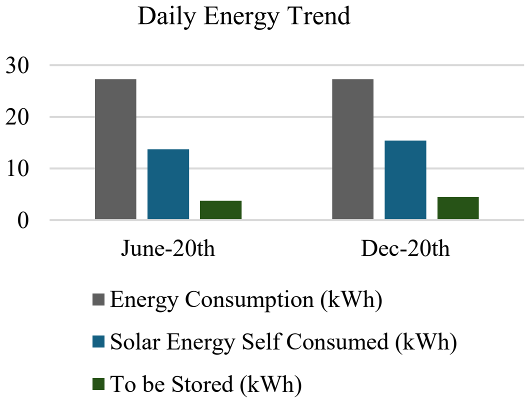


Figure 5: Daily energy trend

From the estimated storage required, to meet both the peak load demand of the factory and excess power of the PV, but also with consideration of the recommended Depth of Discharge (DOD) and the natural degradation of the BESS system along its lifetime, the BESS is sized to have a total energy storage capacity of 8 MWh and a total power of the Power Conversion System (PCS) of 2 MW.

Connection to the factory's power system

The PV+BESS is connected to the Medium Voltage (MV) main busbar of the factory, as in Figure 6.

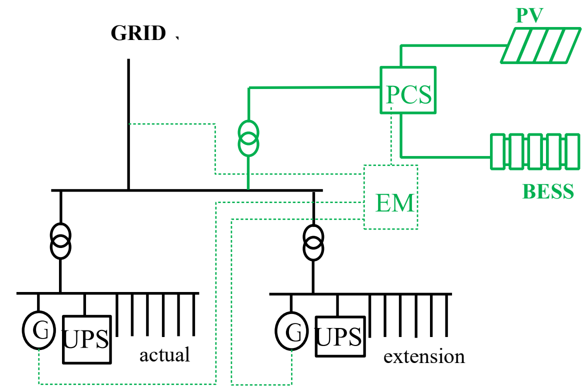


Figure 6: PV+BESS connection to the MV bus bar

The energy management system (EMS) of the PCS is in charge of selecting the right power source according to the defined hierarchy: self-consumed energy from PV first, then energy from the battery (until the defined DOD to provide emergency generation services), then the distribution grid, then energy from the battery (in substitution of diesel genset) until the characteristic DOD from the datasheet, then at last, the diesel backup genset. This ensures that the renewable energy produced onsite is fully utilized and minimizes the use of the carbon emissive electricity coming from grid and the diesel genset.

Results and Discussion

Decarbonization

CO_2 emissions are calculated in accordance with the GHG Protocol Corporate Standard (Greenhouse Gas Protocol, 2020). Scope 2 emissions from grid electricity are estimated using location-based emission factors derived from the national generation mix (kg CO_2/kWh), where for Tanzania is 0.313 kgCO_2/kWh (IRENA, 2022). Scope 1 emissions from the diesel generator are calculated based on actual diesel consumption, derived from the generator's electrical output and efficiency, multiplied by the standard emission factor of 2.67 kgCO_2/lt (Greenhouse Gas Protocol, 2020) and the generator fuel efficiency is estimated to be about 0.35 lt/kWh, the emission factor of diesel per kWh is 0.935 kgCO_2/kWh. This approach ensures consistent and transparent accounting of both grid and on-site generation sources as shown in Equations (3) to (5)

Scope 2 grid electricity emissions

$$Grid\ emission = E_{grid,elec} \times E_{f\ grid} \qquad (3)$$

Where:

$E_{grid,elec}$ = Annual grid electricity consumption (kWh/y)

$E_{f\ grid}$ = Location based emission factor (0.313 kgCO_2/kWh)

Scope 1 diesel generator emissions

$$Generator\ emission = \frac{E_{gen,elec}}{\eta_{genset}} \times \frac{1}{LHV_{diesel}} \times E_{f\ diesel} \qquad (4)$$

Where:

$E_{grid,elec}$ = Annual genset electricity generation (kWh/y)

η_{genset} = Generator efficiency (0.35)

LHV_{diesel} = Lower heating value of diesel

$E_{f\ diesel}$ = Diesel emission factor

Total CO_2 emissions

$$E_{total} = E_{grid} + E_{genset} \qquad (5)$$

Considering that the remaining energy demand of the factory to be met by electricity from the grid, which is 4.726 GWh, approximately equal to 48% of the total energy demand of the factory 9.947 GWh. This is because the use of the diesel generator is replaced by the incorporation of the BESS. The new CO_2 emissions can be calculated by Equation (6).

$$New\ CO_2\ Emission = \Big(Estimated\ Demand(E_{grid,elec}(MWh/y) - PV\ Production(MWh/y)\Big) \times E_{f\ grid} \qquad (6)$$

Setting the prior condition as the Business as Usual (BaU) scenario and the second scenario with PV+BESS intervention as the low carbon scenario, it is observed that the low carbon scenario leads to a reduction in CO_2 emission by about 2.617 ktCO_2 annually.

$$CO_2\ Emission\ reduction = BaU\ Emission - Low\ Carbon\ scenario\ emission \qquad (7)$$

Table 2 provides a comparison in CO_2 emission between the Business as Usual (BaU) scenario and the low carbon scenario

Table 2: Carbon emission comparison before and after PV plant installation

BaU scenario emission (ktCO_2/y)		Low carbon scenario emission (ktCO_2/y)	
Grid	2.617	Grid	1.479
Genset	1.482	PV+BESS	0
Total	4.099	Total	1.479

The results presented in Table 2 indicate that the integration of the PV+BESS leads to a significant reduction of the factory's energy-related C02 emissions. The seen difference between the BaU and the Low carbon scenario emissions corresponds to an overall emission reduction of approximately 64%, highlighting the decarbonization potential of the proposed system configuration. Therefore, replacing the generator with PV and BESS yields a disproportionally large reduction in emissions. Similar emission reduction ranges have been reported in studies analyzing PV-diesel hybrid systems for industrial and commercial applications where renewable penetration and storage integration substantially reduce reliance on fossil-based backup generation (Moner-Girona et al., 2018).

The inclusion of BESS enhances the decarbonization outcome by increasing the effective utilization of the PV generation. This is through shifting to periods of high demand, thereby minimizing the need for curtailment and reducing dependence on carbon intensive sources. This emphasizes the role of energy storage in enabling higher renewable penetration and improving systems flexibility in low carbon power systems (Zakeri & Syri, 2015) (Energy Agency, 2020).

The results indicate that the PV+BESS project reduces the factory's energy-related emissions by 64%.

Cost/Benefit analysis

The cost of a unit of energy purchase from the utility and the generated unit of electricity from the diesel generator at the factory site are summarized in Table 3. It should be noted that the cost of a unit of electricity from the utility excluded the VAT whereas the cost of diesel accounted for 18% of VAT during purchase.

Table 3: Cost Parameters and Data

Source	Description	Value	Unit
Grid	Cost of energy	192	Tshs/kWh
		0.08	€/kWh
Generator	Efficiency	0.35	lt/kWh
	Cost of energy	641	Tshs/kWh
		0.26	€/kWh

The total cost of energy in a typical year for the factory (BaU scenario) is obtained from taking the sum of the energy supplied from the grid and the cost of energy generated on site by the genset. Equations (8) and (9) are used to estimate the cost of energy from the grid and genset respectively.

$$Cost\ of\ Electricity\ from\ grid = Grid\ supply\ (kWh/y) \times 0.08\ €/kWh \quad (8)$$

$$Cost\ of\ Electricity\ from\ genset = Genset\ generation\ (kWh/y) \times 0.26\ €/kWh \quad (9)$$

With the new energy scenario defined as the low-carbon scenario utilising the PV+BESS to cover the energy demand of the factory and eliminating the use of the generator, expected amount of electricity supplied from the grid is as given in Equation (10).

$$Energy\ supplied\ from\ grid = Total\ Energy\ Demand\ -\ Energy\ from\ PV \quad (10)$$

In the presence of the low-carbon scenario, the energy expenditure is calculated using Equation (11)

$$Low\ Carbon\ Scenario\ Energy\ Cost = Energy\ Supplied\ from\ Grid \times 0.08\ €/kWh \quad (11)$$

Table 4: Energy expenditure comparison before and after PV plant installation

BaU scenario cost (k€/y)		Low carbon scenario cost (k€/y)	
Grid	652	Grid	369
Genset	406	PV+BESS	0
Total	1058	Total	369

The energy expenditure comparison shown in Table 4 demonstrates that the low carbon scenario not only reduces the emissions but also delivers economic benefits. The total annual energy costs drop from 1,058 k€/y in the BaU scenario to 369 k€/y in the low carbon scenario, corresponding to a reduction of approximately 65%. This reduction is driven by the avoidance of high-cost diesel-based electricity and the reduced dependence on grid electricity through increased self-generation from PV.

These results align with the findings reported in other studies, which indicate that the PV+BESS systems can significantly lower operational energy costs in industrial facilities, particularly in regions with high diesel fuel prices and relatively high grid tariffs. The economic advantage observed in this study underlines the argument that decarbonization investments can be financially attractive when evaluated over the system lifetime (Lazard, 2024).

To understand the financial soundness of the project, the Net Present Value (NPV) of the project was calculated to assess its profitability. NPV provides an indication of whether the expected cash flows, discounted at the applicable WACC, will exceed the initial investment(Tromp et al. 2022). The total capital cost (CAPEX) for the PV plant $CAPEX_{PV}$ and the BESS $CAPEX_{BESS}$ including the replacement cost of the BESS in the 15th year. The Operational and Maintenance cost (OPEX) were also computed for both PV, $OPEX_{PV}$ and BESS, $OPEX_{BESS}$ discounted to the project lifetime, which is 25 years. The CAPEX and OPEX values are calculated as in Equations (12) to (15).

$$OPEX_{PV} = C_{PV,OPEX} \sum_{1}^{n=25} \frac{1}{(1+WACC)^n} \tag{12}$$

$$OPEX_{BESS} = C_{BESS,OPEX} \sum_{1}^{n=25} \frac{1}{(1+WACC)^n} \tag{13}$$

$$OPEX_{TOTAL} = OPEX_{PV} + OPEX_{BESS} \tag{14}$$

$$CAPEX_{TOTAL} = CAPEX_{PV} + CAPEX_{BESS} + CAPEX_{BESS} \frac{1}{(1+WACC)^{15}} \tag{15}$$

The real weighted average cost of capital (WACC) of the project is computed by the Fisher equation relationship as in Equation (16), which accounts for the interest rate and the inflation rate(Vartiainen et al., 2020).

$$WACC_{real} = \frac{(1+WACC_{nomi})}{1+r_{\inf}} - 1 \tag{16}$$

$$NPV = CAPEX_{TOTAL} + OPEX_{TOTAL} \tag{17}$$

The investment costs to build the PV+BESS, referring to the market value are estimated in Table 5 below including the Net Present Value of the project discounted for 25 years.

Table 5: PV+BESS investment cost including NPV

Cost Component	Total Cost
Rooftop PV CAPEX	1,928 k€
BESS CAPEX at year 1	1,840 k€
10% of the Total Works	376 k€
Initial Total Investment	**4,145 k€**
BESS CAPEX (for 25 years)	2,345 k€
Lifetime OPEX (PV+BESS)	741.9 k€
NPV	**5,018 k€**

Table 6: Selected economic and operational parameters used in NPV analysis

Component	Parameter	Description	Value	Unit
General	n	Lifetime of the project	25	years
	$WACC_{real}$	WACC real	9	%
	$WACC_{nomi}$	WACC nominal	11	%
	r_{inf}	Inflation rate	1.5	%
PV	$C_{PV,CAPEX}$	CAPEX of PV	**1,928**	k€
	$C_{PV,OPEX}$	OPEX of PV (2.5% of $C_{PV,CAPEX}$)	**48.2**	k€
BESS	$C_{BESS,CAPEX}$	CAPEX of BESS	**1,840**	k€
	$C_{BESS,OPEX}$	OPEX of BESS (1.5% of $C_{BESS,CAPEX}$)	**27.6**	k€

It is shown that it is profitable to invest in such green projects not only in terms of emission reduction but also reducing the cost of energy. The ratio of the NPV to the total investment is greater than 1 depicting the viability to invest in this project. It is important to calculate the NPV because it helps you consider the real value of money in the lifetime of the project.

With the total initial investment of 4,145 k€ and the expected annual savings of 735 k€ obtained by comparing the BaU and Low carbon scenario, the estimated payback time is approximately 6 years.

Nonetheless, the PV+BESS project is estimated to reduce the plant's energy expenditure by 65% while catering for 52% of the factory's total load and reduce the factory's energy-related carbon footprints to 64% as has been shown in this paper.

Conclusion and Recommendations

In this paper, a decarbonization pathway employing a PV+BESS system has been presented. The project lowers not only the energy expenditure but also enhances the reliability of the power supply, as the integrated BESS provides backup during grid interruptions. However, the implementation of such systems in Tanzanian industrial sector faces several challenges particularly in terms of policy, permitting and grid integration. Lengthy and unclear permitting procedure, coupled with the absence of comprehensive feed-in tariff or net metering regulations, limit investor's ability to connect to the grid or sell excess energy, an opportunity that could otherwise improve the project revenues and accelerate investment recovery.

To move towards a truly sustainable and low carbon future, policy reforms and regulatory frameworks must be strengthened to facilitate renewable energy integration, promote private participation and ensure grid readiness for variable renewable sources. Furthermore, more research is required to explore innovative decarbonization pathways in the industrial sector. These efforts will be crucial in achieving Tanzania's long term sustainable development goals and establishing a more resilient, inclusive and green energy systems.

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