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Techno-economic analysis of a PV system with a battery energy storage system for small households: A case study in Rwanda

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Due to the inadequacy of distribution networks in developing countries, especially in small residential areas, there are frequent interruptions in the electrical energy provided by the grid. This problem negatively affects the life quality and productivity of the people living in these regions. This problem can be overcome by integrating BESS-supported renewable energy sources into the distribution system. These distributed energy resources contribute significantly to providing energy directly to consumers. On a small scale, such a system is supported by the grid, when possible, to ensure energy supply continuity. This study presents a techno-economic analysis, using PV*SOL simulation software, of a grid-connected solar PV system with BESS that is used to supply a small residential community in Rwanda, Muhanga district, Shyogwe sector. The consumers were a group of one hundred households around a wetland valley. The energy generated from the solar PV system was used to supply home appliances and a water pumping system for agricultural activities. The simulation results showed that the annual energy requirement is 82.34 MWh with a peak load of 30.4 kW. The simulation results also revealed that a PV system, with an installed capacity of 57.33 kWp integrated with a BESS of 89.2 kWh storage capacity, can supply the load with own power consumption of 68.65%, a level of self-sufficiency of 64.38%, and a performance ratio of 86.05% when the desired ratio is set to 110% with a year as the reference period. The financial analysis demonstrated a return on assets of 9.14% and an amortization period of 9.65 years. These results indicate that the proposed method is technically and economically feasible for use in addressing the issue of electrical power outages in developing countries.

KEYWORDS

solar energy, PV system, battery energy storage system (BESS), simulation tools, PV*SOL, energy reliability

1 Introduction

The electricity from solar PV systems has a wide range of applications. Depending on their configuration, PV systems are primarily characterized as off-grid or grid-connected. Off-grid PV systems are most commonly used in remote and rural areas where access to the electrical grid is not possible. Solar-powered home systems, street lighting, water pumping for agriculture use, and large-scale solar PV system mini-grids for the community are examples of off-grid solar PV applications (Jasuan, Nawawi, and Samaulah, 2018). Grid-connected PV systems are often large-scale PV plants that feed generated electricity to the electrical grid. On a small scale, grid-connected PV systems are used for residential and commercial applications (Jasuan, Nawawi, and Samaulah, 2018; Ahmad et al., 2020).

While batteries are used in the off-grid systems to increase the reliability and availability of electricity, grid-connected PV systems supply generated power to the grid (Abdin and Noussan, 2018; Jasuan, Nawawi, and Samaulah, 2018). Batteries are charged when solar PV systems generate more electricity than needed. The stored energy is used during the night and when there is not enough sunlight to satisfy the load. Batteries increase both the reliability and independence of a solar PV system, (Jiang, Kang, and Liu, 2021). For use in residential, commercial, or community (with grid access) applications, battery energy storage systems (BESS) are integrated with grid-connected PV systems to allow more independence from the grid and increase the level of self-consumption (Dorahaki et al., 2022). In such cases, power is taken from the grid only if the power generated by the solar PV system and the energy available in the BESS is not high enough to supply the load. Optimized systems use energy from the grid only to supply the load and batteries are charged from the solar PV systems exclusively, making the overall system more economical.

BESS and solar PV curtailment is a solution to the challenges associated with high PV penetration at distribution networks from a techno-economic perspective. The solutions provided by energy storage integrated with renewable energy sources include discharging stored energy, curtailing or storing energy production, and flexible load (Hargreaves and Jones, 2020). BESS provides energy services such as PV energy time-shift, limiting the PV energy supplied to the grid, and distribution transformer upgrading (Tercan et al., 2022). For more economical PV systems and BESS, a possible strategy is to develop a community energy storage system to reduce individual capital expenditure (Segundo Sevilla et al., 2018).

Various studies have been conducted on the design and simulation of PV systems. Dondariya et al. (2018) conducted a performance simulation study on the grid-connected rooftop solar PV systems for small households in Ujjain, India. The findings showed that 85.30% of the energy generated from the PV system was supplied to the grid, a reduction of 41.09% in energy required from the grid, and a 75.01% performance ratio for the system. Rout and Kulkarni (2020) designed and evaluated the performance of a 2 kWp solar PV rooftop grid-connected system in Odisha using PVsyst. The performance ratio of the system was found to be 0.7. Nhau et al. (2021) analyzed and simulated the economic benefits of different types of PV systems in Shanghai. It was found that the economic profits are different depending on load profile and benefits are higher when residential and commercial load profiles are combined. Segundo Sevilla et al. (2018) conducted a study on techno-economic analysis of battery storage and curtailment in a distributed grid with high PV penetration. It was found that 3.2% and 1.3% of total PV electricity generation should be curtailed to avoid the need for distribution transformer upgrading for fixed and dynamic control techniques. Panjwani et al. (2021) conducted a design and performance analysis of a grid-tied PV system of 8 kWp and an energy storage system. In the designed system, batteries contributed to an increased overall system efficiency of 2%. Shahzad et al. (2017) analyzed the techno-economic feasibility of a solar-biomass off-grid hybrid for the electrification of a remote rural area. The purpose of the study was to design an economical and optimized system to supply electricity for residential loads and irrigation activities in a small village of the Layyah district, Punjab province, Pakistan. Krishan and Suhag (2019) performed techno-economic analysis of a hybrid energy system for the energy-poor rural community of the Yamunanagar district, Haryana state, India, to meet the residential and agricultural energy load. Three configurations of the hybrid system were simulated and analyzed using HOMER software: wind/battery, PV/battery, and wind/PV/battery. Wind/PV/battery was found to be the most cost-effective configuration. Vides-Prado et al. (2018) analyzed the techno-economic feasibility of a PV system in remote areas for indigenous communities in La Guajira, Colombia. The sizing of the system and energy demand calculations were performed based on the community load profile, with communities classified as small, medium, or large. The analysis via HOMER software showed that PV systems for the target communities were economically feasible and, due to the high solar potential, the initial and commissioning expenses would also be low.

There are various simulation tools available for use in solar PV system-related studies. These tools include PVsyst (Alnoosani1 et al., 2018; Kumar et al., 2021; Rout and Kulkarni, 2020; Jagadale, Choudhari, and Jadhav, 2022), INSEL (Nigam and Sharma, 2020; Ram et al., 2022), TRNSYS (Sekhar et al., 2017; Rafał, Maciej, and Wojciech, 2020; Cao et al., 2022), PV*SOL (Dondariya et al., 2018; Mrehel and Albgar, 2018; Nhau et al., 2021; Pushpavalli et al., 2021), SOLARPRO (Alsadi and Khatib, 2018; Lee et al., 2021), HOMER (Al, Awasthi, and Ramli, 2018; Morad et al., 2018; Khalil et al., 2021), and Solar Advisor Model (SAM) (Panjwani et al., 2021; Chennaif et al., 2022; Umar et al., 2018). Software selection depends on the nature and the objectives of the study (Kumar et al., 2021). When choosing software for PV system simulation, the objectives and

TABLE 1 Comparison of PV system simulation tools.

SNO	Simulation tool	Advantages	Limitations
1	PVsyst (Segundo Sevilla et al., 2018; Mrehel and Albgar, 2018; Rout and Kulkarni, 2020; Tercan et al., 2022)	1. Contains a huge database of meteorological data 2. Various applications like grid-tied, stand-alone, and floating PV systems 3. Helps in designing the configuration of the system 4. Market available PV-components database	1. No interconnection with other software tools 2. Collector configuration sizing restrictions
2	INSEL (Kumar et al., 2021; Jagadale, Choudhari, and Jadhav, 2022)	1. Block diagrams to simulate electrical constituents, meteorological data, and heat/thermal energy 2. Simulation of PV system including sun tracking and shading analysis 3. Grid-connected and standalone system	1. Limitation in the configuration of the software tools 2. No economic analysis
3	TRNSYS (Sekhar et al., 2017; Nigam and Sharma, 2020; Ram et al., 2022)	1. Analysis of HRES 2. Solar thermal energy 3. It is easy to add mathematical models 4. Capability to work with other simulation software 5. Weather database as METEONORM database 6. Load analysis	1. Estimation of CO_2 emission not available in the basic version 2. For HRES, biofuel and hydropower are excluded
4	PV*SOL (Dondariya et al., 2018; Rafał, Maciej, and Wojciech, 2020; Nhau et al., 2021; Cao et al., 2022)	1. Geographical location and meteorological profile 2. System sizing and electrical parameters 3. PV panel orientation 4. Load profile and consumption 5. Grid-connected and standalone PV system 6. PV systems with BESS 7. Economic analysis 8. Shading effect analysis 9. Inverter configuration optimization	1. Only PV systems are simulated 2. No interconnection with other software tools
5	SOLARPRO (Mrehel and Albgar, 2018; Pushpavalli et al., 2021)	1. Field measured data 2. Shading losses calculation 3. Provides output in terms of I-V Curve 4. Economic analysis	1. Only PV systems are simulated
6	HOMER (Al, Awasthi, and Ramli, 2018; Alsadi and Khatib, 2018; Lee et al., 2021)	1. Grid-connected system and off-grid system 2. Analysis of HRES 3. Economic analysis	1. No thermal system 2. Some daily variables are not considered
7	SAM (Morad, 2018; Khalil et al., 2021; Panjwani et al., 2021)	1. Real-time simulation analysis 2. Grid-tied storage system 3. Economic analysis 4. Simulation of different types of RES and hybrid systems	1. 3D shading modeling is not supported 2. No weather database for all locations in the world

the system configuration must be carefully considered. Technical performance and economic feasibility are among the factors to be assessed when choosing the proper simulation tool. Table 1 summarizes the advantages and disadvantages of different PV system simulation software.

This study demonstrates the potential of grid-connected solar PV systems and promote their use for local consumption to increase the reliability and availability of electricity. The design allows support from the grid to be provided when the energy from the PV system and BESS is insufficient to supply the load. The amount of energy received from the grid is then returned when the solar PV system generates energy in excess of the load demand and the BESS are fully charged.

This article includes the methodology, presented in Section 2, and simulation performance results, presented in Section 3. Section 4 provides a conclusion and discussion of our findings.

2 Methodology

2.1 PV system simulation tool selection

Sunlight is pervasive on the earth, allowing us to take advantage of solar energy from any location. However, the mere presence of the sunlight in a particular location is not strong enough rationale to support installation of a PV system. Other factors have to be considered, including solar intensity, weather conditions, and solar potential. These considerations inform design of a solar PV system that is as efficient as possible from a techno-economic perspective. Therefore, it is critical to design and simulate the output from a solar PV system before its installation.

Designing, simulating, and optimizing PV systems require simulation tools. Although many solar PV system design and analysis tools exist, their capabilities, options, and applicability differ. In selecting software for PV system simulation, project objectives and system specifications must be considered, along with technical performance and economic feasibility Table 1 compares the characteristics ofavailable PV system simulation software options per their advantages and limitations.For this study, PV*SOL software was chosen for the design and simulation of a PV system with BESS. PV*SOL is one of the leading PV system design and simulation tools. Engineers, planners, architects, installers, and technicians worldwide use PV*SOL to design and build efficient PV systems. With PV*SOL, different types of modern PV systems can be designed and tested via simulation, from small-scale rooftop PV systems of a few panels to large-scale PV power plants of up to 100,000 modules (PV*SOL® premium, 2022).

2.2 Location

Choosing a location for solar PV system application depends on several factors. Solar PV modules must be installed to face the solar radiation, and loss of sunlight exposure due to shading should be minimized. Location selection has a significant impact on the performance and efficiency of a PV system (Kayhan, Ulker, and Elma, 2015).

An optimized location nearby the consumers should be chosen when installing a PV system. For this study, a solar PV system was installed in Rwanda, Southern province, Muhanga district in Shyogwe sector at −2°5′7″ latitude and 29°46′23″ longitude. The selected location is an equatorial region. Geographically, equatorial regions receive higher levels of solar radiation compared to other regions. In the selected region, the annual global irradiation is 1,853 kW/m^2, with an average temperature of 19.9°C. High solar energy potential with an average ambient temperature ensures effective operation of a solar PV system. Therefore, in the selected location, the PV system takes advantage of high solar potential and the drawbacks associated with high temperature are minimized. The electricity generated from the solar PV system would be used to supply energy for residential loads and water pumping systems for agricultural activities in an area around a wetland valley. The PV*SOL software contains a climate database based on MeteoNorm from the Swiss climate and weather data experts Meteotest (Climate data, 2022). The irradiance onto horizontal and outside temperature values in summer for the first week of June are shown in Figure 1.

2.3 Load profile

Residential load profile is most commonly modeled using hourly demand or by assumption (Elma and Selamogullari, 2012). The consumers in our study were a group of people in the socio-economic middle class in Rwanda. Most of the people lived in small, three-bedroom houses with a sitting room, and a small kitchen built near the main house. There was access to the grid for some of the households. Grid-connected houses used most of the electricity for lighting purposes. The other uses of electricity were for powering home appliances, such as radios and televisions, as well as charging mobile phones. Water pumping systems for agriculture was another possible use of electricity by the community, with the goal of improving the lives of residents by increasing agricultural production. One hundred households were considered for this study, and Table 2 shows the corresponding daily load estimation and consumption. The load profile was estimated after consulting 20 households (20% of the total load) and the power ratings of the most used home appliances. It was assumed that other remaining households would have the same load demand. The detailed load profile data were entered in the PV*SOL software and the yearly energy consumption and peak load demand values were calculated as 82.34 MWh and 30.4 kW, respectively.

2.4 System configuration

2.4.1 PV modules

PV modules convert solar energy to direct current (DC) electricity. A solar cell is the smallest unit in solar modules. PV modules are made of solar cells connected in series and/or in parallel. Materials used for the production of PV modules include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium gallium selenide/sulfide. PV technologies are classified according to the materials from which PV modules are made, such as monocrystalline silicon, polycrystalline silicon, and thin-film technologies. Monocrystalline technology is suitable for long-term solar PV investment due to its lifespan, performance, and efficiency. As with other solar PV technologies, the monocrystalline market continues to grow.

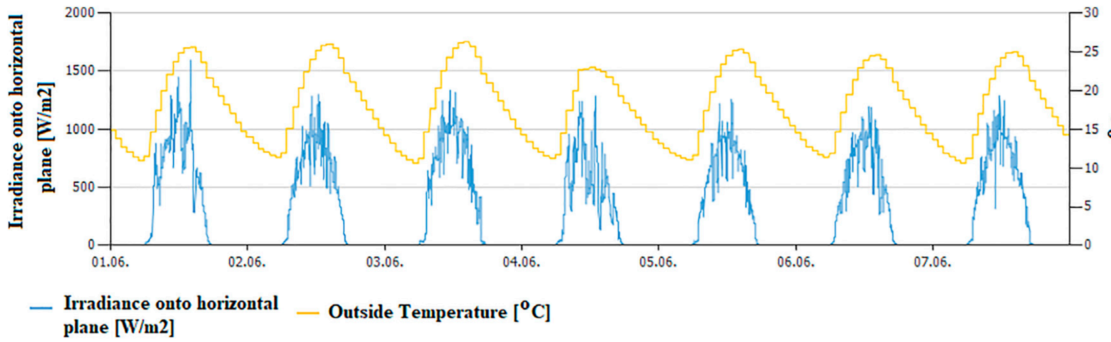

FIGURE 1
Irradiance onto horizontal and outside temperature variation for the first week of June.

TABLE 2 Daily load estimation and consumption for 100 households.

Type of load	Type of appliance	Total number of appliances	Power ratings in W	Total power in kW	Time of use in hours		Daily consumption in kWh		
					Day time	Night time	Day time	Night time	Total energy
House	Incandescent lamp in bedroom	300	15	4.5		6		27	27
	Incandescent lamp in kitchen and sitting room	200	15	3		3		9	9
	Incandescent lamp in hallway	100	15	1.5	2	4	3	6	9
	Incandescent lamp for external light	200	15	3		12		36	36
	Radio	100	60	6	5	4	30	24	54
	TV set	100	80	8	2	6	16	48	64
	Phone charging	200	6	1.2	3		3.6		3.6
Irrigation	Water pump	2	2,200	4.4	4	2	17.6	8.8	26.4
	Total						70.2	158.8	229

The PV*SOL software database lists the PV modules available on the market. PV modules are chosen manually by selecting a list of modules from which PV*SOL then recommends the appropriate module to use. In this study, a list of monocrystalline modules from different manufacturers was selected and PV*SOL recommended the best-fitting modules according to the location and load profiles. The number of modules needed depends on the shading factor, degradation of the module, and desired ratio to consumption. The number of modules can be adjusted as a percentage of the annual or monthly consumption. The desired ratio to consumption has two parameters: the desired ratio (consumption margin) and the reference period. The reference period is defined as the part of the year that PV*SOL takes as a reference for sizing the PV modules to satisfy demand throughout the year. In this study, the shading factor and degradation of the module were set to 5 and 1%, respectively, for a year. For the desired ratio, different values between 90 and 120% were chosen and the results were compared.

2.4.2 Inverters and battery system

Solar PV modules produce DC power as output. Electrical power is transmitted and distributed in AC form and home appliances run on AC power. Thus, the DC power output from the solar PV modules must be converted to AC form. With the help of an inverter, the DC voltage from PV modules is converted into AC voltage. Additionally, PV modules produce electricity only when there is sunlight available, highlighting the importance of storing part of the energy generated via PV modules for later use when sunlight is not available. Batteries are integrated with PV modules for storage of excess energy. The battery system absorbs and supplies electricity through a bidirectional power converter (Batiyah et al., 2020).

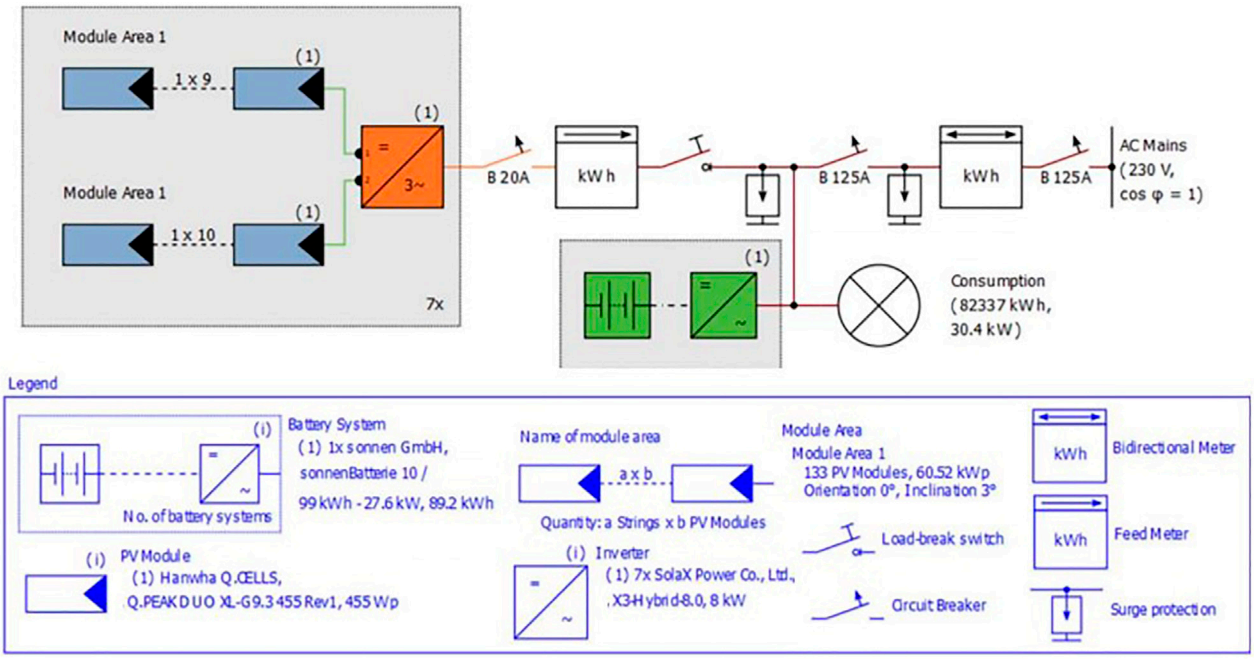

FIGURE 2
Circuit diagram of the proposed system.

TABLE 3 PV panel characteristics at STC and battery and inverter configuration electrical parameters.

PV panel electrical data		Inverter configuration	
Manufacturer	Hanwha Q.CELLS	Manufacturer	SolaX Power Co., Ltd
Model	Q.PEAK DUO XL-G9.3 455	Model	X3-Hybrid-8.0
Cell type	Si monocrystalline	Quantity	7
MPP voltage	44.61 V	Sizing factor	108.1%
MPP current	10.2 A	Configuration	MPPT1: 1 × 9
			MPPT2: 1 × 10
Nominal output power	455 W	**Battery electrical data**	
Efficiency	20.42%	Type	Lithium iron-lithium iron phosphate
Open circuit voltage	53.22 V	Number of Cells	32
Short-circuit current	10.67 A	Nominal voltage	102.4 V
Fill factor	80.13%	Internal resistance	13 mΩ
		Self-discharge	2% per month

In the PV*SOL database, different inverter types with varying configurations are available. Determining the correct inverter type and configuration is done by selecting a list of inverter types from different manufacturers. The PV*SOL software is then used to analyze and optimize the compatibility of the inverters from the selected list and identify convenient inverter configurations for the PV system. The same procedure is followed when choosing the battery system.

Figure 2 shows the circuit diagram of the proposed system and the system's components. Details about the components in the circuit diagram are in the blue legend at the bottom of Figure 2. Hanwha Q. CELLS is the manufacturer of the chosen PV module. The model is Q. PEAK DUO XL-G9.3 455, which is a silicon monocrystalline module. A monocrystalline solar panel was chosen due to its advantages compared to other types of solar panels, including high efficiency, small area requirement per unit power,

TABLE 4 Technical parameters for PV system design and simulation.

Grid-connected PV system with electrical appliances and battery systems		
Climate data	Country: Rwanda	Latitude: 2°5′7″
	Location: Shyogwe	Longitude: 29°46′23″
AC mains	Voltage (N-L1): 230 V	
	Number of phases: 3	
Model for diffuse irradiation: Hofmann model for irradiation on the inclined plane: Hay & Davies		
Load	Annual consumption: 82,337 kWh	
	Peak load: 30.4 kW	
Shading and degradation of PV modules	Shading percentage value: 5%	
	Degradation of module	Linear (straight-line)
		Remaining power after 20 years: 80%
Desired ratio to consumption	90–120%	References period: year and worst month
Installation type	Fix mounted—open space	
Inclination	3°	
Orientation	0°	

TABLE 5 Financial analysis parameters.

Assessment period	20 years
Outgoing cost of system setup parts and labor	2,240 US$/kWp
Operation and maintenance cost	1% of investment
Net metering tariffs	Consumption type: residential (0.24 US$/kWh)
Inflation rate for energy price	2.9%/year

TABLE 6 Simulation results summary.

Desired factor	90%		100%		110%		120%	
References period	Year	Worst month	Year	Worst month	Year	Worst month	Year	Worst month
PV output power (kWp)	46.98	48.8	52.1	53.81	57.33	59.27	62.68	64.61
PV module area (m^2)	230.05	238.95	255.12	263.45	280.72	290.15	306.87	316.35
Modules number	103	107	114	118	126	130	138	142
PV energy (MWh/year)	68.16	71.11	75.84	77.92	83.41	85.96	91.43	93.77
Grid feed-in (MWh/year)	14.53	16.66	20.12	21.71	26.17	28.37	32.97	35.00
Battery charger from PV system (MWh/year)	29.57	30.10	30.95	31.26	31.94	32.17	32.65	32.83
Battery charger from grid (kWh/year)	0.75	0	0	0.75	0.75	1.75	1.75	1.5
Direct own use (MWh/year)	24.06	24.34	24.77	24.95	25.31	25.46	25.83	25.94
Consumption from grid (MWh/year)	32.55	31.76	30.69	30.26	29.35	29.01	28.21	28.00
Consumption from battery (MWh/year)	25.71	26.21	26.91	27.17	27.71	27.91	28.31	28.46
Own power consumption	78.68%	76.55%	73.48%	72.15%	68.65%	67.05%	63.95%	62.70%
Level of self-sufficiency	60.60%	61.38%	62.80%	63.28%	64.38%	64.78%	65.78%	66.05%
Performance ratio (PR)	85.78%	86.15%	86.03%	85.63%	86.05%	85.78%	86.25%	85.83%
Return on assets	9.39%	9.27%	9.26%	9.19%	9.14%	8.69%	7.94%	7.54%
Amortization period (years)	9.6	9.55	9.57	9.62	9.65	9.97	10.55	10.87
Payback energy ratio	44.64%	52.47%	65.57%	71.75%	89.14%	97.65%	116.81%	125.02%

TABLE 7 Simulation results performance analysis.

Desired factor (%)	Reference period	Level of self-sufficiency (%)	Performance ratio (PR)	Return on assets (%)	Amortization period (%)	Payback energy (%)	Total average (%)
90	Year	60	70	100	100	60	78
90	Worst month	70	95	100	100	60	85
100	Year	80	90	100	100	75	89
100	Worst month	80	60	100	100	75	83
110	Year	90	90	95	100	85	92
110	Worst month	95	70	85	85	90	85
120	Year	100	100	70	70	100	88
120	Worst month	100	75	60	60	100	79

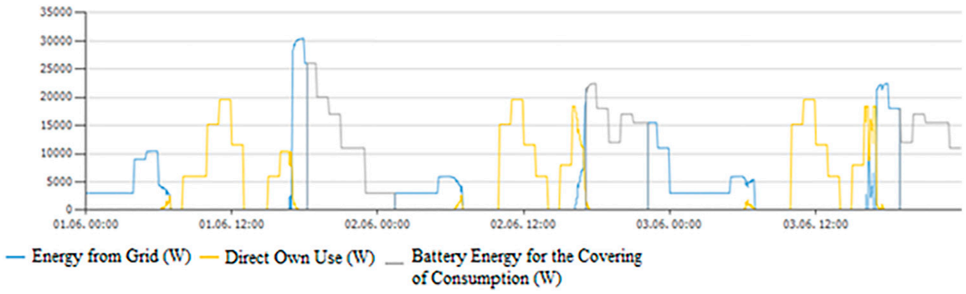

FIGURE 3
Energy consumption between 1 and 3 June: Direct own use, from grid, and battery.

and long lifespan. Sonnen GmbH is the battery manufacturer, and the battery model is sonnenBatterie 10/99 kWh –27.6 kW. Table 3 shows the electrical parameters of the battery, the PV module at standard test condition (STC), and the inverter configuration in the designed PV system. The technical parameters used for the design and simulation of the PV system with BESS using PV*SOL software are shown in Table 4.

2.5 Financial analysis

Financial analysis helps to determine the needed investment for the realization of the designed PV system. Information such as installation cost, the value of production, operating and maintenance cost, return on investment, and amortization period are obtained from financial analysis. Financial analysis helps in making a decision on whether or not to invest in a solar PV system.

PV*SOL software can be used to analyze the financial aspects of a solar PV system. The financial parameters are entered into the software. Other parameters include the energy balance and feed in concept, price of electricity sold to a third party, net-metering tariffs, and inflation rate for energy price. For this study, the designed PV system simulation included financial analysis that covered 20 years. The financial analysis parameters are shown in Table 5.

3 Simulation results

A study of the design and simulation of a grid-connected solar PV system with electrical appliances was conducted. The consumers were a group of 100 households located in Rwanda, Southern province in the Muhanga district, Shyogwe sector. For the system to become more independent from the grid, the desired ratio was varied using values of 90%, 100%, 110%, and 120%. The reference period for simulation was either a year or the worst month for each desired ratio. The worst month is the month of the year during which the solar radiation is at the minimum for that location. The worst month changes from location to location. The PV*SOL software uses accessible data to guide selection of the worst month for a given location. Thus, during the worst month, the PV system generates the least energy compared to any other comparable timeframe throughout the year. When the worst month is chosen as the reference period, the size of the PV system is designed to satisfy demand during the

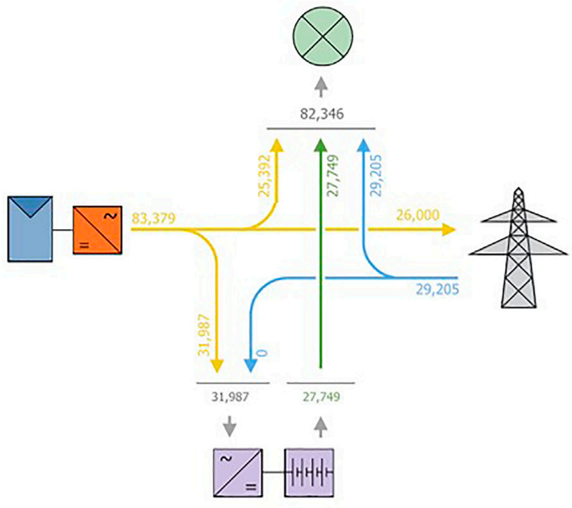

FIGURE 4
Yearly energy flow in kWh for the desired ratio of 110% and a year as the reference period.

month of lowest energy production. This helps in optimizing the combination of desired ratio and reference period to allow the system to become more independent, with the capacity to supply the load demand throughout the year. To analyze the effects of shading, the shading values of 0, 5, 10, and 15% were assessed for each combination of desired ratio and reference period. The average values from different shading levels were taken as the result of the corresponding desired ratio and reference period. In total, eight cases were studied. Table 6 provides a summary of the simulation results from different cases.

The performance results from different scenarios are assessed by grading the results from 100% to 60% according to the best and worst results for each parameter. Parameters considered were the level of self-sufficiency, performance ratio, return on assets, amortization period, and payback energy ratio. Table 7 includes a summary of the results of the performance analysis. In this study, the case with the desired ratio of 110% and a year as the reference period was found to be the best scenario, both technically and financially. The direct power consumption, level of self-sufficiency, performance ratio, and payback energy ratio are 68.65, 64.38, 86.05, and 89.14%, respectively. The amortization period was between 9.55 and 10.87 years for all cases. The load was supplied directly from the PV system, battery, or grid. The battery was charged predominately from the PV system and rarely from the grid. Figure 3 shows how energy was supplied to the load from the solar PV system, battery, or grid. Figure 4 is a graph of the energy flow. The financial analysis results demonstrate that the system's return on assets and the amortization period are 9.14% and 9.65 years, respectively. Figure 5 shows the accrued cash flow.

4 Conclusion

In this study, design and simulation of a grid-connected solar PV system with a BESS is conducted using PV*SOL. The first step was to design the PV system and determine the load profile. System design involved location choice, the load profile, and other solar-related parameters, such as shading value, degradation of the modules, and desired ratio to consumption. The chosen location was Rwanda, Muhanga district, Shyogwe sector. The load profile consisted of 100 small households and water pumping systems for agricultural activities. The annual consumption was found to be 82.34 MWh with a peak load of

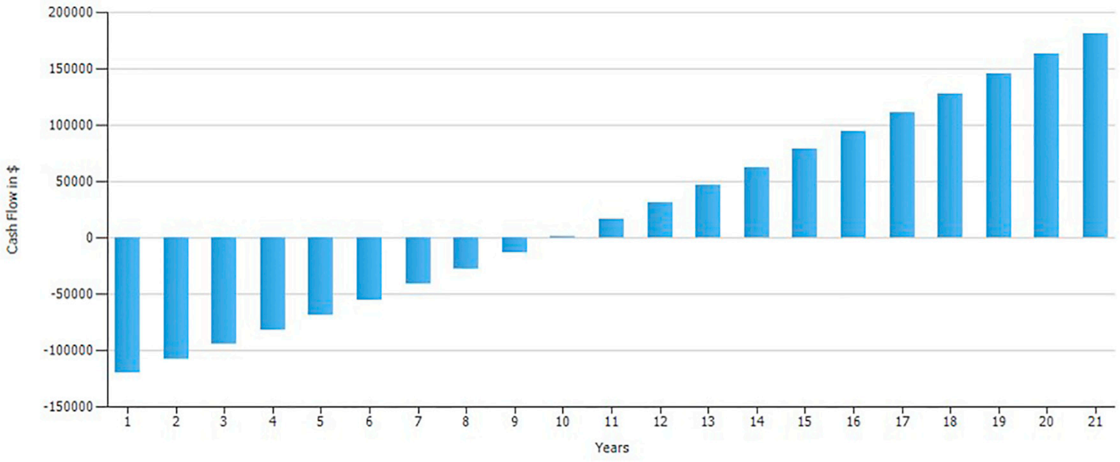

FIGURE 5
Accrued cash flow (cash balance).

30.4 kW. From analysis of the simulation results, we found that this grid-connected solar PV system with a BESS could supply the load with a direct power consumption of 68.65%, a level of self-sufficiency of 64.38%, a performance ratio of 86.05%, and an energy payback ratio of 89.14%. The financial analysis showed that the return on assets and amortization period were 9.14% and 9.65 years, respectively. The results of this study demonstrate that PV systems with BESS are important to reduce grid dependence and increase the availability and reliability of electricity in developing countries. Additionally, the results indicate that grid-connected PV systems with BESS are techno-economically feasible for developing countries. Future work will focus on the impact of connecting such PV systems with BESS, at various locations in Rwanda, on the national electrical grid and overall grid reliability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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