



Article A Techno-Economic Optimization and Performance Assessment of a 10 kW_P Photovoltaic Grid-Connected System

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Abstract: The system under consideration in this paper consists of a photovoltaic (PV) array, described as having a 10 kWp capacity, battery storage, and connection to the grid via a university grid network. It is stated that the system meets a local load of 4–5 kVA. The system is in Ethiopia, and the authors give details of the location and solar resource to provide information to assess its performance. However, the performance assessment will be specific to the details of the installation and the operational rules, including the variable nature of the load profile, charging and discharging the battery storage, and importing from and exporting to the university grid. The nearby load is mostly supplied from PV and grid sources, and hence the battery installed is found to be idle, showing that the PV together with storage battery system was not utilized in an efficient and optimized way. This in turn resulted in inefficient utilization of sources, increased dependency of the load on the grid, and hence unnecessary operational expenses. Therefore, to alleviate these problems, this paper proposes a means for techno-economic optimization and performance analysis of an existing photovoltaic grid-connected system (PVGCS) by using collected data from a plant data logger for one year (2018) with a model-based Matlab/Simulink simulation and a hybrid optimization model for electric renewables (HOMER) software. According to the simulation result, the PVGCS with 5 kWp PV array optimized system was recommended, which provides a net present cost (NPC) of 5770 (€/kWh), and a cost of energy (COE) of 0.087 (€/kWh) compared to an existing 10 kWp PV system, which results in a NPC value of 6047 (€/kWh) and COE of 0.098 (€/kWh). Therefore, the resulting 5 kWp PV system connected with a storage battery was found to be more efficient and techno-economically viable as compared to the existing 10 kWp PVGCS plant.

Keywords: optimization; storage battery; photovoltaic; techno-economic; performance analysis; photovoltaic grid-connected system; Matlab

1. Introduction

The need for sustained energy demand and availability of solar resources led countries to establish large distributed energy systems to secure energy requirements. The photovoltaic grid-connected system (PVGCS) under study was the demonstration project in Ethiopia installed in October 2010/11 GC at Bahir Dar University located 578 km northwest of the capital city Addis Ababa. Ethiopia has already implemented a PVGCS at Bahir Dar University and different standalone systems in rural areas,

where it is located in the eastern part of Africa between 3° to 15° north and 33° to 48° east, has abundant solar energy resources.

Since Ethiopia is located near the equator, it has significant potential to use solar energy. The national annual average irradiance is estimated to be 5.2 kWh/m²/day with seasonal variations that range between the minimum of 4.5 kWh/m²/day in July to a maximum of 5.9 kWh/m²/day in March. Though its size is smaller than average, the installed 10kWp PVGCS system under study was the first installed photovoltaic (PV) plant in the country used as a milestone with objectives of establishing a small scale center of excellence in renewable technologies, organizing and providing teaching facilities for undergraduate (UG) and postgraduate (PG) students, and supporting researchers in data registry and system analysis. Besides, this plant aimed to encourage the national strategy for the country to begin the launching and utilization of renewable energy technologies and energy efficiency programs planning for the installation of thousands of megawatt photovoltaic (PV) plants [1]. The country is currently trying to establish a vast system of 100-Megawatt PV plants in one of the regions called "Methehara" with the company group called Enel [2]. The grid-connected photovoltaic system under study was installed and has been functional since October 2010. The PVGCS plant was mounted to supply power for the local load and fed excess energy to the grid, providing 4.5–5 kW of power to the commercial loads, and the remaining 5kW is fed to a nearby university's utility network. The existing PVGCS consists of a total of 56 Webel Solar W1750 PV modules (each representing 180 W) [3], 24 cells connected in series with a total of 48 V of battery storage, and a charge controller. Renewable energy sources connected to the utility network need proper evaluation of their performance, as they impose perturbations on the grid due to their intermittent nature. Researchers mentioned in Section 2 assessed the performance of grid-connected photovoltaic plants and therefore their negative and positive impacts on the grid, while factors which affect their performance were also studied. In addition to the technical performance analysis of the PV system, the plants' economics was also studied. The economic performance evaluation of a building-integrated PV (BIPV) system installed with battery energy storage was conducted in a south Norwegian house for evaluating its contribution to minimizing the annualized energy cost and showed that a BIPV system with energy storage is cost effective with a levelized cost of energy (LCOE) of 0.439 NOK/kWh [4]. A feasibility assessment of PVGCS systems for residential buildings in Saudi Arabia was conducted while considering its techno-economic viability, and found that the systems were feasible with a levelized cost of energy of 0.0382 \$/kWh and a net present value of \$4378 [5]. A techno-economic evaluation of PVGCS for households was performed with a feed-in tariff and time of day tariff technique using a hybrid optimization model for electric renewables (HOMER) [6], and the result indicates that the NPC and COE approach zero for low range household consumption with a BIPV application. In [7], Chiacchio et al. proposed a model-based approach to analyze the techno-economic feasibility of grid-connected PV power plants using ambient variables and stochastic hybrid fault tree automation as input variables and the system was evaluated using the net present value and the payback time. Hoppmann et al. [8] studied the economic viability of integrating battery storage with small scale PV plants for residential applications. Techno-economic based simulation was utilized for evaluating the profitability of battery storage integrated with PV systems. The net present value as a function of storage and PV system size for different electricity scenarios was evaluated, which showed the use of battery energy storage was economically viable. Nge et al. [9] proposed a method for maximizing revenue over a given period. A real-time based energy management system connected with the smart grid was used and focused on a reactive real-time control mechanism. The simulation of the system considered the days and solar irradiance profiles as input variables. Liu et al. [10] conducted an optimization of photovoltaic system connected with battery energy storage and electric vehicle charging stations. The method utilized a cumulative prospect theory and particle swarm optimization algorithm to determine an optimal photovoltaic/battery energy storage/electric vehicle charging stations (PBES) system. Besides the optimization of PV plants, D'Adamo et al. [11] studied the economic viability of PV plants installed in public buildings using a discounted cash flow methodology. With this method, input variables of the insolation level, plant size,

self-consumption share, and electricity purchase price were identified and accordingly the net present value and payback time periods were estimated. In addition to these variables, the grid-connected PV systems operation performance also depended on the climatic condition, orientation, and inclination of the installed PV array, load profile, and inverter efficiency [12–14] where these factors were considered in the current study.

In this paper, the performance and techno-economic of the PVGCS integrated with the battery storage system were assessed. The main contribution of this paper includes use of the techno-economic model for evaluating the performance status of the existing PVGCS plant and performing a comparative analysis of this plant with the result of the proposed 5 kWp PV plant in terms of their respective net present cost and cost of energy values. This, in turn, enables the identification of the optimal and economical sizing of entire plant components and efficient utilization of the storage battery to minimize excess electricity. Using the available solar irradiance and dynamic load profiles as an input to the model, the optimization and sensitivity analysis results give the most optimal combination of battery storage, PV array, converter, and grid network usage. To conduct the existing operation performance analysis of the plant, different performance indicators related to energy yield of the entire plant and the performance ratio (Pr) were used. The techno-economic analysis of the PVGCS plant was conducted using a model-based simulation with a hybrid optimization model for electric renewables (HOMER Pro) software. This software is a professional micro-grid analysis tool having Pro edition features, HOMER Pro 3.10.6499.25914 version, and manufactured by HOMER Energy LLC, Denver Colorado, United States of America. In addition to the techno-economic study, the entire PVGCS system was modeled using the Matlab simulation environment to analyze the dynamic response of the plant to the grid network. The results found from this study can be used as valuable input for other photovoltaic plants to be installed and connect with the grid system and hence, enables efficient utilization of PV plants in Ethiopia.

The rest of the sections in the paper are organized as follows: Section 2 discusses a state-of-the-art review on techno-economic assessments of grid-connected PV plants. Section 3 describes the proposed model-based simulation methodology for techno-economic analysis and optimization. An overview of the existing infrastructure of the PVGCS is also discussed. Section 4 describes the existing performance status and techno-economic result of the existing 10 kWp plant compared with the proposed 5 kWp PVGCS system. Section 5 presents the discussion section. Finally, the conclusion, limitations, and recommendations are offered in Section 6.

2. State of the Art Review on Techno-Economic Studies of Grid-Connected Photovoltaic Systems

Photovoltaic based renewable energy systems can be found in two ways: as standalone and grid-connected systems. The PV systems are the primary source of energy for the load, while PV grid-connected systems are utilized when a shortage of energy occurs in the grid network [15]. However, PV energy systems connected to the grid can impose instability problems due to their intermittent nature and high penetration [16]. Therefore, technical and economic aspects need to be studied before connection of PV systems to the grid network and after they are connected to the grid and on their operational period. So far, scholars mentioned in this section studied the performance assessment, modeling, and techno-economics advantage of photovoltaic plants and their impacts on the grid network. Zhou et al. [17] developed a hybrid optimization model for electric renewables (HOMER) based simulation and optimization technique for evaluating the techno-economic aspects of a rooftop solar PV system in different climate zone conditions. Based on the analysis made, the result showed that grid-connected PV systems are technically and economically feasible for all climate zones considered. The excess electricity, net present cost, and cost of energy values of the grid/PV systems increased with an increase of PV penetration. This paper lacks an evaluation the plant performance in terms of energy production and impact assessment to the grid, and this was identified as a gap. In addition to the techno-economic study, Lau et al. [18] analyzed the effects of individual component costs and feed-in tariffs on grid-connected PV systems in a Malaysian residential application. Based on the analysis

made, the results indicate that grid-connected PV systems were feasible for a PV system with costs of \$1120/kW or lower. Though the authors provide details of the PV plant's economic aspects, analysis of the storage battery and its impact on reducing grid dependency is not well addressed. In contrast to the focus of the above authors, Emmanuel et al. [19] presented a performance and economic analysis of a 10 kWp PVGCS system installed in Wellington, New Zealand. The economic analysis of the PV system was performed by considering the net present cost (NPC), cost of energy (COE), and payback period and this gives promising values for the plant. In line with the techno-economic study of PV plants, Irwan et al. [20] conducted optimization of a photovoltaic grid-connected system, which was performed by considering two scenarios. The first one was considered by investigating the maximum yield factor as a technical matter, and the second involved maximizing the net present cost value for the economic case. For solving the sizing and optimization issues, a method called the evolutionary programming sizing algorithm (EPSA) was applied. This algorithm mainly uses the PV module and inverter model as the decision variables with an objective function of maximizing the technical or economic performance of the system. In addition, the operational optimization of grid-connected PV plants and the evaluation of small scale PVGCS was studied (Table 1). Sidrach et al. [21] assessed the performance of a 2 kWp grid-connected PV system without an energy storage system in Spain in 1998. A single phase-based inverter is used to convert the DC output to AC and connect with the grid network, which is also used for maximum power point tracking (MPPT) purposes. Based on the study made, the system supplied 2678 kWh to the grid within one year, and 7.4 kWh of average daily energy with a monthly average value of daily system efficiency between 6.1% and 8% was attained. For an annual final yield of 1361 kWh/kWp, the daily final yield ranged between 2.2 kWh/kWp in January to 4.8 kWh/kWp in March. The annual performance ratio of these systems was 64.5%. A lack of evaluation on battery storage's contribution to the system is the gap observed in this paper. Sabounchi et al. [22] investigated the performance evaluation of a 36 kWp installed capacity photovoltaic based distributed generation system connected with a 400 V low voltage side of a distribution network based on the actual weather conditions of temperature and solar radiation availability. Considering the plant's one-year performance data, it was concluded that the system performance and efficiency were affected by dust particles deposition on PV modules' surfaces. Therefore, to attain a reasonable power production, it was recommended that a monthly cleaning of the PV modules surface on regular bases is deduced as a solution. Though the power system performance status and the factors affecting it were presented in detail, the grid's positive and negative impacts were not mentioned. Common performance evaluation indices were used by Sharma et al. [23], who also conducted a performance assessment of a 190 kWp grid integrated solar photovoltaic power plant installed at Khatkar-Kalan, India. Based on the study, the final yield, reference yield, and performance ratio vary from 1.45 to 2.84 kWh/kWp/day, 2.29 to 3.53 kWh/kWp/day, and 55% to 83%, respectively. The average annual energy yield of the plant was found to be 812.76 kWh/kWp with a system efficiency of 8.3%. The study also showed that March, September, and October are the months where the maximum energy is generated, and minimum energy is attained in January. Besides, the study suggested that installing solar panels at an optimized tilt angle is very important in providing economic benefits, but the dynamic response of the plant related to transient effect to the grid was not included in the paper.

Kymakis et al. [24] conducted a performance analysis of the grid-connected photovoltaic park found at Crete, Greece. The photovoltaic park has a peak power of 171.36 kWp. It considers a one-year operation data of the plant for estimation of the performance ratio and the various causes of power losses including due to temperature, soiling, internal network, and power electronics. The PV park injected energy of 229 MWh to the grid during 2007, ranging from 335.48 to 869.68 kWh throughout the year. The final yield (Y_F) ranged from 1.96 to 5.07 h/d and provided an annual performance ratio of 67.36%. Similarly, the dynamic response of the plant was not included in the paper. Edalati et al. [25] performed a comparative analysis between mono and polycrystal based PV modules performance under semi moderate and dry climate conditions. The study was conducted on an existing 11.04 kWp PVGCS system. Besides, an experimental based investigation of this plant was done using one year meteorological and performance data of the plant. Accordingly, the average daily final yield (Y_F) of 5.24 kWh/kWp/day and Performance ratio (Pr) of 80.81% was found. Ayompe et al. [26] conducted a performance assessment of 1.72 kWp building integrated system and the temperature and solar radiation data used for analysis of the final yield, array yield and performance ratio results. Based on the results found, the average daily final yield and performance ratio were found to be 2.41 kWh/kWp/day and 81.5%, respectively. The annual total energy generated was also found to be 885.1 kWh/kWp. The author utilized experimental and metrological data for analysis purposes but lacked verification of the result by comparing it with the standard or previous studies. Province [27] analyzed a photovoltaic grid-connected system with 500 kWp capacity that was investigated for its actual performance. Based on the assessment done, 383,274 kWh of system energy was generated for the first eight months and the daily average energy production was 1695.9 kWh. The final yield was found to be in the range of 2.91 to 3.98 h/d, and the performance ratio (Pr) ranged from 70% to 90%. Mondol et al. [28] assessed a 13 kWp roof mounted grid-connected photovoltaic system performance found in north Ireland that was analyzed on an hourly, daily, and monthly basis using parameters of yield and loss indices. Based on the analysis result, the monthly average performance ratio was consistent which is found to be 70% for DC and 61% for AC system. Comparative analysis between two different PVGCS plants was performed by Micheli et al. [29]. Different module technologies consideration and their actual performance assessment were done using temperature and irradiance as an effect. The two types of plants investigated confirmed a good performance with a value of 89.1% CTB (Centrale Tecnologica di Basovizza) found in campus of Basovizza, northern Italy and Q2 building of 82.7% performance ratio. Accordingly, the best technology type was recommended but which type external factors can affect each technology type were not explicitly stated. The combination of module technologies provides an array used in the PV plants, and the significance of different PV arrays was compared and investigated by El et al. [30] for 15 MWp grid-connected installed PV system found in Nouakchott, Mauritania. Analysis and monitoring of results between arrays was compared with PV systems installed in other locations. Besides, performance indices were used for evaluation purposes and a mean value of 67.96% performance ratio was achieved. Drif et al. [31] analyzed a 200 kWp PVGCS system using production data at the plant monitored through 2000–2003. According to the study, the annual average energy production was 168.12 MWh per year, representing 6.40% of the university campus's total consumption. An average daily annual performance value of 65% and an average energy yield of 3.91 was found. Shukla et al. [32] conducted a feasibility study of 110 kWp grid-connected photovoltaic plant to be applied for water pumping, lightening, and other electrical appliances of the selected hospital building. Its feasibility was mainly proved with the help of energy production and performance ratio outputs. The PV modules have been modeled and simulated to determine performance ratios and Energy yield and it was found that the performance ratio (PR) of the PV systems varied from 70% to 88% and their energy yields ranged from 2.67 kWh/kWp to 3.36 kWh/kWp. The authors tried to address the feasibility and performance of the plant in terms of yield factors. But, the economic viability of the system was not addressed for the dedicated application.

In addition to the technical aspects summarized above, the economics of the PV hybrid energy supply systems was assessed by different authors. Some of the studies conducted are briefly presented as follows.

Location	Year	PV Size (kWp)	Final Yield (kWh/kWp/Day)	Performance Ratio, Pr (%)	Reference
Spain	1998	2.0	4.8	64.5	[21]
Greece	2002	171.36	1.96 - 5.07	67.36	[24]
India	2003	190	2.23	74	[23]
Son Province, Thailand	2004	500	2.91-3.98	70–90	[27]
Spain	2005	2.5	1.6	49	[31]
Dublin, Ireland	2008	1.72	2.4	81.5	[26]
Bahir Dar, Ethiopia	2010	10	2.02-3.45	74	Present Study
UAE	2013	36	5.6	-	[22]
Kerman, Iran	2013	5.52	5.24	81	[25]
Nouakchott, Mauritania	2013	954.72	4.94	73.56	[30]
Ballymena, Northern Ireland	-	13	1.61–1.76	60–62	[28]
Trieste, Italy	-	17.94	3.84	89.1	[29]
India	-	110	2.67-3.36	71.6–79.5	[32]

Table 1. Summary of the state-of-the-art review.

Peerapong [33] analyzed the increased utilization of photovoltaic resources on diesel-based hybrid energy systems to reduce the cost of electricity generation and decrease the harmful emissions from fossil fuels. The study used a method of net present cost (NPC) estimation to evaluate the optimum hybrid system. The result shows that the hybrid system reduces NPC and COE. The hybrid system can also reduce all air pollutants for sustainable electricity in rural islands. COE decreases from \$0.429/kWh to \$0.374/kWh compared to the existing diesel-based system and can decrease the emissions of both carbon dioxide by 796.61 tons/year and other gasses by 21.47 tons/year. The hybrid PV/diesel system also reduces the diesel fuel consumption of 302,510 L per year due to an optimal 41% PV resource sharing in this system. The authors describe the significance of using a hybrid system compared to diesel. But the contribution of each component, including the storage battery, was not mentioned. Mamaghani et al. [34] presented an evaluation of an off-grid energy supply system that consisted of a diesel generator, solar panels, and wind turbine units. A dynamic model of the plant was developed with HOMER software to perform a complete parametric analysis of the system configurations and select the most convenient one based on the economic perspectives. Accordingly, the net present cost (NPC), initial capital cost, and cost of energy (COE) were used as economic indicators to define the techno-economic feasibility of the hybrid energy supply system. The gap observed in this paper is that the lack of verification of grid extension distance results compared with standards or references was not included. A comparative study of the hybrid energy system with standalone diesel was conducted by Dursun et al. [35] considering the techno-economic feasibility of a hybrid renewable energy sources with a battery over that of a standalone diesel system to supply a load at a remote location in Turkey. HOMER software was used for the analysis by considering solar and wind data sources of the hybrid system over the diesel system utilizing different solar global irradiances, wind speeds, and diesel prices. The result suggested that the hybrid system reduces the total NPC and COE and the diesel system's dependency. Using this hybrid system, the COE decreased by almost 25%. Though the authors presented the advantage of using the hybrid system to reduce diesel dependency, it lacks the result of the contribution of the storage battery system and payback period of the system.

From the literature reviewed above, the following points were summarized:

- The use of numerical analysis and simulation is essential to optimize the techno-economic benefits
 of the PVGCS system, which in turn reduces costs.
- The utilization of external factors like temperature, GHI, and tilt angle helps to determine the correct simulation output of the system.
- This hybrid system provides a better output based on the net present cost and cost of energy.

Different researchers studied the techno-economic analysis of grid-connected photovoltaic plants under different weather conditions in different countries. But the performance evaluation parameters and indices utilized in the above reviewed papers were not all-inclusive.

In this paper, all primary performance evaluation indices mentioned as a gap in some of the above reviewed papers was considered to conduct a performance assessment and study the techno-economic optimization of the PVGCS system.

Conducting the techno-economic optimization of the PVGCS integrated with a storage battery system provides major significance in terms of:

- Evaluating the techno-economic aspect and performance status of the existing 10 kWp grid-connected PV system.
- Proposing a techno-economically viable combination for the new PVGCS system.
- Identifying the contribution of the PV plant to the grid network.
- Using it further as an input for PV plants connected with the country's grid network in the future.

This paper considers the features of the above-reviewed articles and proposes an analytical and model-based techno-economic evaluation method for the PVGCS plant under study.

3. Methodology and Overview of the Study

The PVGCS system installed on a 160 m² area near to postgraduate laboratory rooms is shown in Figure 1. The PV system is composed of 56 Webel Solar W1750 PV modules. The PV array is installed at an optimal inclination angle of 16° and an azimuth angle of 0°. Each electrical module provides a short circuit current of 5.35 A, open circuit voltage of 44.5 V, a current of maximum power point (IMPP) of 4.96 A, and a voltage of maximum power point (VMPP) of 36.3 V [3]. Under these conditions, the nominal power of the PV array is approximately 10 kW at its peak.



Figure 1. Existing photovoltaic (PV) Array layout [36].

The PV plant was connected to the grid and the electrical energy produced by the PV system is fed to the nearby load and the remaining 4.8 to 5 kW is injected into the grid. The storage battery connected to the plant has a voltage of 48 V with 24 cells series connected with a capacity of 800 Ah. From the overall datasheet shown below, a Hoppecke OPzS 800 lead-acid battery is installed at the plant with a nominal discharge capacity of 800 Ah (Appendix B, Table A3). The discharge capacity with a 10 h discharge is considered as a maximum of 915 Ah with a respective voltage of 2 V. The cycling capability of 1500 cycles with 80% depth of discharge (DOD) and 20 years of life expectancy is provided. As shown in Figure 2, there are two arrays each provides a 5 kWp capacity and when the array outputs exceed the

local load, the excess energy will be dedicated to charging the battery. However, excess energy is fed to the grid after satisfying the local load and battery charging condition. The second array always gives priority to charging the battery whenever it is fully discharged. The battery was used to be discharged whenever there is no power from the PV system. The solar radiation availability and potential of different cities of the country was presented in Figure 3. The plant is installed at a geographic location of 11°35′46″ N, 37°23′39″ E at an elevation of 1789 m above sea level. A map and global horizontal irradiation of the installed plant is presented below.



Figure 2. Overall array installation with surrounding areas [36].





In addition to the above map, the data presented in Appendix A (Table A1) shows the average daily global radiation on the horizontal surface of different cities, including Bahir Dar, which is the site under study. The daily sun hour data of Bahir Dar was found to be around 5.8 kWh/m² as indicated. For the sake of comparative analysis, the percentage difference of radiation data between data centers is also provided. The data shown in Appendix A (Table A2) was also collected for the city of Bahir dar at a latitude of 11°35′46″ (11.60°) north and longitude of 37°23′39″ (37.40°) east. This includes the sunlight potential of the city and the clearness index, which shows the clearness of the respective ambient temperature.

3.1. Performance Parameters Formulation

The characterization of the PV plant production and entire yield was evaluated using performance indices defined by the IEC61724-3 standards [38] for evaluating the plant performance status. This was achieved through analysis of the energy produced by the PV plant, the energy output of the battery, and energy injected into the grid with the help of the performance evaluation parameters. Accordingly, a daily basis and monthly mean values are considered and then results are provided in terms of the evaluation parameters summarized in Table 2.

Parameter	Description	Mathematical Expression	Unit	Reference
PV Array Yield (Y_a)	Represents the time, measured in h/day where the PV array must operate with its nominal power to generate required energy	$Y_a = \frac{E_a}{P_o} = \frac{E_{pv}}{P_{nom}}$ E_a is energy output from PV array and P_o is nominal power of PV array.	h/day	[39]
Reference Yield (Yr)	The ratio between horizontal inclined irradiance (G_{inc}) or H to irradiance at a nominal condition (G_o).	$Y_r = rac{G_{inc}}{G_o}$	h/day	[39]
Final Yield (Y_F)	Defined as the ratio of energy output injected to the grid E_{inj} or E_{ac} to Nominal power of the PV array	$Y_F = rac{E_{inj}}{P_o} = rac{E_{ac}}{P_{nom}}$	h/day	[40]
Capture Losses (Lc)	Represents losses occurred during the operation of PV modules and indicates the amount of time the array is required to operate at its nominal power to provide the losses.	$L_c = Y_r - Y_a$	h/day	[41]
System Losses (Ls)	Obtained by the difference between PV array productivity and the overall productivity	$L_s = Y_a - Y_F$	h/day	[42]
Performance Ratio (P_r)	Ratio of generated energy versus the energy which should be generated by a lossless PV plant and shows the performance status of PV plant.	$P_r = \frac{Y_F}{Y_r} \times 100$	%	[41]

Table 2. Summary of the performance evaluation parameters.

3.2. Modeling of Grid-Connected PV System

In order to model the PVGCS using Matlab, a PV Module datasheet and model parameters at the plant were considered at standard temperature conditions 1000 W/m² and 25 °C and necessary parameters are defined. The daily radiation and load profile data have been considered as an input for

the PV and nearby load for modeling the overall system. The main purpose of modeling the existing PVGCS system using the Matlab software is to study the plant's dynamics response and characteristics. The datasheet of the PV module used for system modeling is presented in Table 3.

Maximum Power	P _{max} (W _p)	170	175	180	185
Short circuit current	Isc (Amp)	5.2	5.3	5.35	5.4
Open circuit voltage	Voc (volt)	44	44.3	44.5	44.8
Current at maximum power	Imax (Amp)	4.79	4.86	4.96	5.06
Voltage at maximum power	Vmax (volt)	35.5	36	36.3	36.6
Maximum System voltage	1000 Volt	-	-	-	-
Module efficiency	14.5% (0.145)	-	-	-	-
Life Span	25 Years	-	-	-	-

Table 3. Manufacturer datasheet for Webel solar module installed at the plant [3].

PV Array Performances

Before analyzing the production aspect of the PV plant, it is recommended to analyze the dynamics characteristics of PV array in terms of its current, voltage, and power output. Together with the production and manufacturer data of modules provided, important parameters of the module's outputs were estimated which in turn were used to evaluate the plant performance together with the performance indices formulated. Accordingly, the array voltage, current, and power output were checked for two different scenarios. The first case is when the temperature is fixed at 25 °C, while irradiance is varied at 1000 W/m², 500 W/m², and 100 W/m². The second case is when the irradiance is fixed at 1000 W/m² and temperature is varied by 25 °C, 45 °C, and 50 °C.

As shown from Figure 4, the output current (varied from 19 to 150 A) is more affected by irradiance than by temperature. In contrast, the voltage is slightly affected by temperature and has an inverse relation. The higher the temperature, the lower the voltage will be and vice versa. The current versus voltage (I-V) and the power versus voltage (P-V) output curves of the PV array are shown in Figures 4 and 5.



Figure 4. I-V curve of the PV array.

Figure 5 shows that the power output (which varies from 1100 to 10,000 W) is affected by both irradiance and temperature and the voltage is slightly affected by temperature and has an inverse relation. The higher the temperature, the lower the voltage will be and vice versa. Hence, the I-V and P-V simulation output of the PV array is coherent with the manufacturer datasheet curve.



Figure 5. P-V curve of the PV array.

3.3. Methodological Steps for the Proposed Study

A summary of the methodology utilized for conducting the overall performance analysis of the PVGCS is shown in Figure 6. Modeling, simulation, optimization, and sensitivity analysis of the PVGCS for the selected site was done using Matlab and HOMER Pro, providing the typical data as input variables.



Figure 6. Flowchart for a performance assessment of a photovoltaic grid-connected system (PVGCS).

The grid-connected photovoltaic system was modeled using HOMER software, which consists of a 10 kWp PV system, a grid-connected converter of 5 kW capacity with Hoppecke 8OPzS800 lead-acid battery storage, and approximately 5 kWp of load.

The microgrid system consisting of load, a PV array, grid, battery, and converter components modeled with their respective actual ratings as installed at the plant are stated below. The schematic representation of the overall PVGCS system is shown in Figure 7.



Figure 7. Schematic diagram of the PVGCS system.

3.4.1. Daily Load Profile

The area under study's daily electrical load profile is based on the consumption of nearby computer laboratory installed for the students' facility. According to the collected data at the plant, the load demand of the selected primary load has a maximum of 16 kWh/day energy consumption with 4.97 kW of peak demand. Based on the input data of the site under study's daily load profile, the average load profile data found from HOMER is shown in Figure 8.



Figure 8. Daily average load profile.

3.4.2. Solar PV Modules

As was described in the above sections, the solar radiation data were taken from the plant and NASA [43]. Based on the data collected from the plant and analysis made, the average solar radiation of 5.8 kWh/m²/day and clearness index of 0.6 was obtained as shown in Figure 9. The clearness index is a measure of the clearness of the atmosphere, which is expressed by the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth.



Figure 9. The global horizontal radiation HOMER result.

The power output of this photovoltaic plant is dependent on the atmospheric and geographical conditions. The PV array power output (P_{PV}), can be calculated as:

$$P_{PV} = G_{PV} f_{PV} \left(\frac{I_T}{I_{T,STC}}\right) \left(1 + \alpha_P (T_C - T_{C,STC})\right) \tag{1}$$

where I_T is the solar radiation incident on the PV array in kW/m², G_{PV} stands for the PV rated capacity in kW, f_{PV} represents the derating factor of PV, $I_{T,STC}$ represents the solar incident radiation at standard temperature conditions (STC) which is considered as 1 kW/m², T_C is the cell temperature of the PV in °C, α_P is the temperature coefficient of power (%/°C), and $T_{C,STC}$ is the cell temperature under STC (25 °C) of the PV [44].

3.4.3. Grid System

The photovoltaic grid-connected system (PVGCS) under study operates with a grid to increase the reliability of the supply system. Therefore, the load is supposed to get its power whenever necessary. The electricity prices of the grid were considered as being \$0.1/kWh and the grid net excess price considered was \$0.05/kWh in the simulation for the case under study.

3.4.4. Battery

The Hoppecke 8OPzS800 lead-acid battery system existing at the plant is considered to supply the required energy when a power shortage occurs in the system. The excess electricity production in the microgrid is stored with a battery energy storage system and provides power to the load when an energy shortage occurs in the system. The energy stored in the battery is given by [45]

$$B_{bat} = B_{bat.0} + \int_{0}^{t} V_{bat} I_{bat} dt$$
⁽²⁾

where, $B_{bat.0}$ denotes the initial battery charge while V_{bat} and I_{bat} are the voltage and current of the battery, respectively. The number of battery cells connected in series to attain the required voltage [45] is

$$N_{bat} = \frac{V_{bus}}{V_{bat}} \tag{3}$$

where V_{bus} is the bus voltage of the microgrid system and V_{bat} is the voltage rating of a single battery cell. In addition, the maximum charge/discharge power of a single battery is described as:

$$P_{bat}^{max} = \frac{N_{bat} V_{bat} I_{bat}^{max}}{1000} \tag{4}$$

where I_{bat}^{max} represents the maximum charging current of the battery in amperes [46]. The battery consists of 24 strings connected in series, with each having 2 V and a total of 48 V.

3.4.5. Converter

The converter considered in this system is used as a bi-directional converter changing the direct current (DC) to alternating current (AC) electric power and vice versa. Its efficiency was assumed to be 95% for the size considered and the lifetime is up to 15 years. The size of this converter mainly depends on peak load demand (P_I^{max}) [45]. The rating of this converter is given as:

$$P_{inv} = \frac{P_L^{max}}{n_{inv}} \tag{5}$$

where n_{inv} stands for inverter efficiency [46].

3.5. Parameter Formulation of System Economics

The economic viability of batteries and microgrid systems was evaluated based on the levelized cost of energy (LCOE) and the total net present cost (NPC) of the system.

3.5.1. Estimation of Net Present Cost (NPC)

The total sum of initial, replacement, operation, and maintenance costs including fuel cost minus the revenue provides the value of the total net present cost (NPC). The total *NPC* was calculated as

$$NPC = \frac{C_A}{CRF(i,n)} \tag{6}$$

where CRF(i,n) represents the capital recovery factor while *n* and *i* represent the number of years and the real annual interest rate, respectively [45]. The capital recovery factor is also defined as:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$
(7)

where $i = \frac{i_{\text{nom}} - f}{1 + f}$, i_{nom} stands for the nominal interest rate, and f represents the yearly inflation rate.

3.5.2. Estimation of Cost of Energy (COE)

The cost of energy (COE) is among the main parameters used for evaluating the economic effectiveness of a given energy system. The COE is defined as the annual cost of all system components divided by total of generated energy [47]. The *COE* is given by

$$COE = \frac{C_A}{E_s} \tag{8}$$

 E_S is the yearly energy supplied and C_A is the total annual cost [45]. The total annual cost is the sum of operation and maintenance cost, capital cost, and replacement cost.

4. Results

After collecting the necessary radiation, temperature, and energy production data from an existing plant, performance analysis was conducted by considering the yield, performance ratio, and loss indices. This helps to check existing operation status and the contribution to the grid, including both positive and negative impacts. For the performance evaluation of the grid-connected plant, one-year data of 2018 was collected from the plant data logger and the analysis was performed based on monthly average values, as shown in Figures 10–14.





Figure 10. Monthly global inclined radiation and temperature.

Figure 11. PV array energy (Ea) and the energy injected to the grid (Eout).



Figure 12. Variation of Array yields (Y_a) , Reference yield (Y_r) , and Final yield (Y_F) in terms of hours per month.

Final Yield (Yf), system lossess (Ls) & Capture lossess (Lc)





Figure 13. Comparison between final yield and losses.



Figure 14. Performance Ratio of the PV system.

4.1. Meteorological Data at the Site

Relevant data, including the radiation and temperature, were collected and needed to be prepared for interpretation. The result of monthly global inclined radiation (H_Ginc) at an optimal angle of 16 degrees versus mean air temperature (Ta) is presented in Figure 10.

During the summer season (usually from June to September), the radiation is higher and the air quality are worse compared to the other months. It is also often very cloudy and rainy during this time in Ethiopia. In this time, the cell temperature rises above 60 °C and the average inclined radiation also reaches 1000 W/m², with an annual average ambient temperature of around 25 °C. In addition to the inclined radiation and temperature relationship presented in Figure 10, the measure of clearness index and radiation relationship are also shown in Figure 9 and were used to analyze the effect of the atmosphere on the distribution of radiation.

4.2. Performance Analysis Result of the PV Plant

The energy delivered by the PV array (Ea) is the monthly PV array energy. E_{inj} is the energy injected into the grid. These two energies in Figure 11 vary with the seasons proportionally to the monthly global radiation.

The difference between the two columns in Figure 11 gives an approximation of the energy consumed by the load, which ranges from 236 kWh per month in August to 616 kWh per month in March.

4.2.1. Array Yield (Y_a), Reference Yield (Y_r), and Final Yield (Y_F) of PV Plant

Illustration of the plant output was presented using common yield factors. The variation of annual yield is also shown in line with respective radiation availability at the site (Figure 12).

In order to find the maximum and optimal output from the plant, the final yield (Y_F), should be equal to the number of hours that the PV plant must operate at a nominal power of $P_0 = 10 \text{ kWp}$ to produce the daily energy injected into the grid. The number of hours in July was found to be 58 h/month and 96 h/month or (kWh/kWp) in March. The final yield is higher in March and lower in July and August. This was caused by the higher and lower availability of radiation effects for the respective months of the year 2018.

4.2.2. Capture Loss and System Losses

The type of losses presented in the PVGCS plant is shown in Figure 13 categorized as system loss and capture loss. These parameters enable us to identify the net production of the plant by taking the system losses into account.

The system losses (Ls), which affect the plant's final yield significantly compared to the losses caused by ambient temperature and excessive long wires across the entire plant, are more commonly observed in December, March, and August with a loss of 60, 61, and 67 h/month, respectively. The capture losses in August is smaller as compared to other months due to very low ambient temperature effect that occurs.

4.2.3. Performance Ratio (P_r) of the PV System

Among different performance evaluation indices, the performance ratio is the determinant factor in monitoring the plant's operational status (Figure 14).

The result of the performance ratio (P_r) was further interpreted and related to the PV system efficiency using the efficiency of the PV module considered at standard temperature conditions of 25 °C. The efficiency of the PV system is the product of the performance ratio (P_r) and efficiency of the PV module at standard temperature conditions (STC), as indicated in Table 3.

From the performance assessment of the plant conducted, it was found that the performance ratio value is 74%, which is of promising value compared to the result of other countries' experiences indicated in Table 1.

4.3. Simulation Result of the Entire PVGCS Using Matlab

Using a simulink model of the entire grid-connected PV system under study, the dynamic characteristics and simulation output of the overall micro-grid system (the PV plant, the grid network, the battery power, the state of charge (SOC), and the load profile) are illustrated in Figure 15.



Figure 15. Power output curve of the PV, grid, load, battery, and battery SOC.

Figure 15 shows that, within 24 h of the day, the solar PV power generation is 0 W from 0 h to 6 h and from 20 h to 24 h and then reaches its peak power production of approximately 10,000 W (10 kW) from 14 h to 15 h. The maximum power output of the PV plant was found at the knee point where the current and voltage values reach their maximum value. From the total power production, around 5 kW of power is fed to the load/battery and the rest (5 kW) is fed to the grid network. The storage battery, that involves an 800 Ah capacity lead-acid battery, supplies power when the power of the PV plant is insufficient, and it absorbs surplus power from the micro-grid when its power is surpassing the electric load. With the provision of power to the loads, the battery is intended to be used as energy storage and as a peak shaving application. The load consumption gets its maximum capacity of 5 kW at around 20 h, supplied by the battery storage system. From 0 h to 12 h and from 18 h to 24 h, battery control is performed by the battery controller. The battery control performs tracking control of the current. From 12 h to 18 h, battery control is not performed, as during this time the State of Charge (SOC) of the storage battery is fixed to a constant. Between 12 h and 18 h, the battery power is 0 W and therefore, the load should get its power from the PV array or from the grid (power_secondary) system, as indicated on the relevant curves in Figure 15. At 12 h, the battery controller shifts the battery SOC value to a constant and the battery power becomes zero. Therefore, the grid (Power_secondary) output curve should rise in line with the battery output curve, and the load consumption should increase as well. The battery output shows that the SOC of the battery decreased down to 75% as it discharged power to the load. The battery supplied power to the load peak hour consumption of 5000 W around 20 h and was decreased to 230 W at around 2 h. The last chart in the figure below represents the time period of 24 h of a day. The analytical and simulation results presented above cover the technical results of the existing 10 kWp grid-connected photovoltaic system. However, to evaluate the economic

effectiveness and optimization of the plant, HOMER software based economic analysis was performed in the following sections.

4.4. Techno-Economic Optimization and Sensitivity Analysis Result

From the optimization result, the best optimal system configuration type was identified with the plant components including a 5 kW PV, a 5 kW converter, and a battery with 24 strings of cells and a total of 48 V. The result shows that in the case of an energy shortage, the battery bank provides necessary backup. The simulation results for both the existing plant with the 10 kWp PV system and the optimized 5 kWp PV system are summarized in Tables 4 and 5. HOMER Pro software provides the optimized results of the microgrid system assuming that when there is a shortage of power from the PV and the battery, the load gets its power from the grid (power_secondary). From the sensitivity analysis result, the most optimal system type is identified and ranked on the bases of the total net present cost (NPC) and the levelized cost of energy (LCOE). The load demand, grid sales and purchase output, PV array power output and grid annual power generation, and state of charge (SOC) of the battery of the existing PVGCS system are shown in Figure 16. To identify the maximum and minimum energy production of the system, the months of maximum energy production (March) and minimum energy production (August) of the year with a sample of one-week profiles are presented.

Table 4. Optimization result summary of a PVGCS with a 10 kWp PV System.

Components	PV	Battery	Grid	Converter	Total
NPC (€/kWh)	4971.03	3296.33	-3649.19	1429.10	6047.27
LCOE (€/kWh)	0.04	0.01	-	0.048	0.098
Production (kWh/Year)	11,812	-	-	-	11,812
Energy Purchased from grid (kWh/Year)	-	-	521	-	521
Energy Sold to grid (kWh/Year)	-	-	5292	-	5292
Component Size (kW)	10	5	1000	6.24	1021.58

Components	PV	Battery	Grid	Converter	Total
NPC (€/kWh)	2485.51	3296.33	-745.20	733.36	5770
LCOE (€/kWh)	0.04	0.01	-	0.037	0.087
Production (kWh/Year)	5906	-	-	-	5906
Energy Purchased from grid (kWh/Year)	-	-	976	-	976
Energy Sold to grid (kWh/Year)	-	-	1012	-	1012
Component Size (kW)	5	5	1000	3.29	1013.29

Table 5. Optimization result summary of a PVGCS with a 5 kWp PV System.



Figure 16. PV Power Generation and SOC of the battery for load during: (**a**) The first week of August, (**b**) The third week of March.

4.4.1. Optimization Results

PV Power Generation and State of Charge (SOC) of the Battery

The power output of the PV array, grid sales and purchases, and demand requirements are shown in Figure 16. In addition, the storage battery state of charge conditions are presented.

Photovoltaic and Grid Electricity Production

A comparison between the PV and grid energy contribution to meeting the load's demand is presented in Figure 17. Accordingly, it is shown that the PV system provides the highest share of electricity production.





Figure 17. Monthly average electricity generation of the PV and the grid.

Battery State of Charge

As it can be seen in Figure 18, the battery state of charge status is illustrated interms of hour of the day, day of the year and month of the year. The results show that the SOC is kept within the specified limit of 20–100%. The maximum utilization of the battery storage is also observed in the month of August



Figure 18. State of charge (SOC) output of a Lead-acid battery (**a**) Hours of the day vs. day of the year, (**b**) SOC vs. month of the year.

4.4.2. Sensitivity Analysis Results

The effect of changing multiple variables, such as solar radiation, load demand, PV capital costs, grid outages, and related parameters that affect the economic output of the optimized PVGCS system can be identified through the result of sensitivity analysis. The effect of these variables can be observed in terms of the NPC and COE values variation of the PVGCS system.

Effect of Solar Radiation Variations

A sensitivity analysis of the PVGCS system was performed with consideration of solar radiation variation, which ranges from 5.02 kWh/m²/day to 6.59 kWh/m²/day for the respective load demand variation of 9.2 kWh/day to 23 kWh/day and an average of 16 kWh/day with grid power price of \$0.05/kWh. From Figure 19 it is observed that the NPC value decreased as the solar radiation increased. On the other hand, the renewable fraction (RF) value increased while the solar radiation increased.



Figure 19. Effect of solar radiation variation on the NPC and RF of the PVGCS.

Effect of Load Change

As shown in Figure 20, the NPC and COE values were measured for the respective daily average load demand variations. The load demand variation ranged from 9.2 kWh/day to 23 kWh/day. From the result it was found that, as the load demand increased, the NPC values also increased, whereas the COE decreased as the demand increased.



Figure 20. Effect of load demand variation on the NPC and COE of PVGCS.

5. Discussion

In this paper, a techno-economic optimization study of the PVGCS system was conducted based on the data collected at the existing plant, together with meteorology sources and software-based simulation outputs. The dynamic response of the plant was studied using the Matlab/Simulink environment and furthermore, the techno-economic aspects were analyzed using hybrid optimization model for electric renewables (HOMER) software. As indicated in Figure 10, the performance assessment of the existing plant was analyzed using the radiation, temperature data, and corresponding performance evaluation indices. Accordingly, the meteorological data gathered were found to be coherent with that of the plant data acquisition system and this made the performance evaluation of the PV plant more effective. Figure 11 illustrates that the total annual energy produced by the PV array is 11,805 kWh, which varies from a minimum production of 561.8 kWh in July to a maximum of 1283 kWh in March. From the

total energy produced, the yearly average energy fed into the grid in one year was approximately 5277 kWh and the rest was supplied to the load. The difference between the two columns in Figure 11 gives an approximation of the energy consumed by the load, which ranges from 236 kWh to 616 kWh per month.

After analysis of the energy production by the source and respective load consumptions, the months of highest and lowest operating hours of energy production were identified as illustrated in Figure 12. Hence, it was found that the PV array yield (Y_a) operated for 56 h/month or kWh/kWp in June and about 128 h/month during March, when the temperature average was around 25 °C. For the reference yield (Yr), the maximum hours of operation at standard conditions were observed during the months of December, January, and March with 142, 140, and 144 h, respectively. The final yield (Y_F) should be equal to the number of hours that the PV plant must operate at a nominal power of $P_0 = 10$ kWp in order to produce the daily energy quantity injected into the grid. The number of hours of operation in the month of July was 58 h/month and the equivalent was 96 h/month (kWh/kWp) in March.

In addition to the production aspects, the system's losses were investigated as indicated in Figure 13. For the capture losses (Lc), it can be observed that May, June, and July were found to be the months where the highest losses were attained with values of 46, 54, and 49 h/month, respectively. This was commonly caused by the ambient temperature and excessively long wires across the entire plant. On the other hand, system losses (Ls) were more commonly observed in December, March, and August with losses of 60, 61, and 67 h/month, respectively. Such losses mainly occurred due to the higher overheating of inverters.

Evaluation of the PV plant performance ratio was also performed to identify the plant's operational efficiency; the ratio was found to be between 64% in June and 74% in the month of March, as indicated in Figure 14. This shows that the system is energy efficient with a system efficiency range of 9.3% to 10.7%. The results of the performance ratio and efficiency indicate that the PVGCS plant can be categorized as a well performing plant, as its overall performance ratio values were in the range of permissible limits as compared to the values observed in other countries that are summarized in Table 1. The plant dynamics response was also evaluated using Matlab software, as indicated in Figure 15. It showed the results of power production and battery response to be coherent with the plant output data. Hence, it showed that the plant dynamic response is good enough. In addition to charging the battery, the excess power from the PV plant is also sold to the grid based on an annual net metering system, which in turn reduces the average cost of electricity. The demand and output power delivered by the PV is shown in Figure 16 for typical months. In addition, the power supplied by the PV and the battery state of charge are also illustrated. The PV power generation, the grid purchases and sales, demand profile, and battery state of charge were assessed for the months of August and March to see the minimum and maximum production in line with the effect of resource availability. The energy production of the PV and grid components considered in the PVGCS are also presented at Figure 17. Due to the high irradiance availability at the site where the plant is installed, the PV array took the lead for electricity production throughout the year compared to the grid. The average state of charge (SOC) output of the lead-acid battery is illustrated in Figure 18. In addition to the technical scenario, the economic aspect of the PVGCS system was analyzed using hybrid optimization model for electric renewables (HOMER) software. As observed from Table 4, for the existing 10 kWp PV system, the yearly electricity production of 11,812 kWh/Year from PV and 521 kWh/Year from grid (power_secondary) purchases provides a total supply of 12,333 kWh/Year. On the other hand, the electricity consumption of 5840 kWh/Year from AC primary load and 5292 kWh/Year of consumption from grid sales provides a total consumption of 11,132 kWh/Year.

Furthermore, for the case of an optimized 5 kWp PV System, yearly electricity production of 5906 kWh/Year from PV and 976 kWh/Year from grid purchase provides a total supply of 6882 kWh/Year. On the other hand, the electricity consumption of 5840 kWh/Year from AC primary load and 1012 kWh/Year from grid sales provides a total consumption of 6852 kWh/Year, as indicated in Table 5. Here it is found that the production and consumption of energy is more balanced for the case

of a 5 kWp PV array compared to a 10 kWp PV array system. Therefore, excess electricity is reduced from 14.47% to 1.04%, which is almost negligible for the optimized 5 kWp system. Based on the results, the total electricity production and consumption are more balanced and adequately optimized for the 5 kWp PV system than that of the 10 kWp PV for the same load condition. In addition to the plant's optimization output, sensitivity analysis was also performed to indicate the effect of changing multiple values for input variables on the optimal system design. These variables can be the solar radiation, load demand, PV capital cost, and related parameters that might affect the optimal system's economic output. As shown from Figure 19, the effect of solar radiation variation was noticed on the NPC and RF value changes. The net present cost found to be decreased as the solar radiation increased. On the other hand, the effect of load demand changes was presented in Figure 20, which in turn resulted in the NPC and COE value changes of the optimized system. As the load increased, the NPC value increased but the COE decreased. The PVGCS system with a 5 kWp PV array provides an average NPC value of 5770 (€/kWh) and COE of 0.087 (€/kWh) compared to a 10 kWp PV system, which results in a NPC of 6047 (\notin /kWh) and COE of 0.098 (\notin /kWh). Moreover, the utilization time and production of the storage battery was also increased from 36.8 kWh to 76.5 kWh with the new optimized system. Therefore, from the study result, the entire plant was found to be more efficient and optimal both technically and economically with an optimized 5 kWp PV system compared to the existing 10 kWp PV system. According to the HOMER result, the optimal 5 kWp PV array configuration provides a system with efficient energy production satisfying the local load, providing a balanced system, negligible losses of electricity, and hence an economically viable system with better NPC and COE values. The methods of techno-economic analysis used in this paper can further be used for commercial sectors while considering the respective resource and demand profiles available at the site to be investigated.

6. Conclusions and Recommendation

In this paper, a techno-economics and operational performance assessment of the PVGCS plant was conducted using collected data, simulation, and optimization of the entire plant. From the measured data at the plant, it was found that, for a yearly average radiation rate of 2378 kWh/m²/year, the PV plant produces an average energy rate of 11,805 kWh/year with consideration of losses. The results from the analytical performance evaluation technique show that the performance ratio value was found to be in the range of a minimum value of 64% and a maximum value of 74%. Accordingly, the system efficiency was found to be in the range of 9.3% to 10.7%. In addition, December, January, and March were the months where the PV system became most efficient and produced the highest amount of energy. The performance status of the plant under study was compared with previous studies and verified as shown in Table 1, resulting in promising output levels. To evaluate the dynamic characteristics and response, the plant was modeled using Matlab, provided that each component's output was within permissible limits and met the demand requirement as needed. Though technically the plant is performing well, according to the optimization and sensitivity results found from HOMER Pro, in terms of economic aspects, the existing 10 kWp PV plant was not well optimized, leading to idle periods for the battery storage and resulting excess electricity. Therefore, based on the simulation output, a 5 kWp PV system was found to be economically more optimal than the existing 10kWp PVGCS system. Accordingly, the system with a 5 kWp PV array provides a net present cost (NPC) value of 5770 (€/kWh) and cost of energy (COE) of 0.087 (€/kWh) compared to the 10 kWp PV system, which results in a NPC of 6047 (\notin /kWh) and COE of 0.098 (\notin /kWh). The energy production of the storage battery also increased from 37 kWh to 77 kWh with a 5 kWp PV array system. Therefore, the entire plant was found to be more efficient and optimal both technically and economically with an optimized 5 kWp PV array system, demonstrating that the PV together with the battery storage unit needs to be properly sized for an efficient operation of the system satisfying the variable load demand. In general, the results found from the plant performance assessment and techno-economic analysis could be used as an input for intensive installation and effective utilization of PVGCS systems in Ethiopia.

In the future, the plant's overall dynamic property and stability impact on the grid can be further investigated by directly collecting solar radiation data at the plant for a couple of years and therefore, the plant performance and economics can be evaluated more efficiently using a feed in tariff estimation mechanism of electricity prices. In addition, the second-life battery energy storage system's impact on reducing the levelized cost of energy for a grid-connected photovoltaic system could be investigated by comparing it with a fresh battery storage system.

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Abbreviations

AC	Alternating current
B _{bat.0}	Initial battery charge
BIPV	Building integrated photovoltaic
C _A	Total annual cost
COE	Cost of energy
CRF	Capital recovery factor
DC	Direct current
DOD	Depth of discharge
Ea	Energy output
E _{inj}	Energy injected to grid
Es	Yearly energy supplied
f_{PV}	Derating factor of PV
G _{inc}	Inclined Irradiance
G_o	Irradiance at nominal condition
G_{PV}	PV rated capacity
HOMER	Hybrid optimization model for electric renewables
Ibat	Current of the battery
I ^{max} bat	Maximum charging current of the battery in amperes
Imax	Current at maximum power
Isc	Short circuit current
I_T	Solar radiation incident
I _{T,STC}	Solar incident radiation at standard temperature conditions
IMPP	Current at maximum power point
L_c	Capture loss
L_s	System loss
MPPT	Maximum power point tracking
NASA	National aeronautics and space administration
NOK	Norwegian Krone
NPC	Net present cost
PBES	Photovoltaic/battery energy storage/electric vehicle charging stations
P _{inv}	Converter power rating
P_{L}^{max}	Peak load demand
P_o	Nominal power

P_r	Performance Ratio
PR	Performance ratio
PV	Photovoltaic
PVGCS	Photovoltaic grid-connected system
RF	Renewable fraction
SOC	State of charge
STC	Standard temperature conditions
T_C	Cell temperature of PV in °C
$T_{C,STC}$	Cell temperature under STC
V _{bat}	Voltage rating of a single battery cell
V _{bus}	Bus voltage
V_{max}	Voltage at maximum power
Voc	Open circuit voltage
VMPP	Voltage at maximum power point
Ya	PV array yield
Y_F	Final yield
Y _r	Reference yield
α_P	Temperature coefficient
η_{inv}	Inverter Efficiency

Appendix A

Location	Lat./Long.	Average D on Ho (k	aily Global orizontal Su Wh/m ² /day	Radiation urface y)		% Difference
	C C	SWERA	NASA	CESEN	SWERAVs NASA	SWERAVs CESEN

Table A1. Radiation data for different cities of Ethiopia [43].

No.	Location	Lat./Long.	(1	kWh/m²/da	y)			
_			SWERA	NASA	CESEN	SWERAVs NASA	SWERAVs CESEN	NASAVs CESEN
1	Addis Ababa	9.03/38.7	2.07	5.94	5.54	187	168	6.7
2	Arba Minch	6.08/37.63	3.521	5.49	5.54	56	57	1.0
3	Awasa	7.07/36.95	2.603	5.02	5.59	93	115	11.5
4	Bahir Dar	11.6/37.4	2.576	5.8	5.39	125	109	7.1
5	Debre Markos	10.03/37.07	2.454	5.69	5.25	132	114	7.6
6	Debirezeit	8.73/38.95	2.615	5.47	5.82	109	123	6.5
7	Dire Dawa	9.6/41.87	3.214	6.01	5.71	87	78	4.9
8	Gode	8.15/35.53	2.274	5.75	5.55	153	144	3.5
9	Gondar	12.55/37.38	2.145	5.92	5.74	176	167	3.1
10	Gore	8.15/35.53	2.193	5.31	5.22	142	138	1.6
11	Jimma	7.67/36.83	2.6	5.02	5.12	93	97	2.2
12	Kombolcha	11.12/39.73	2.209	5.88	5.38	166	144	8.5
13	Mekele	13.5/39.42	2.27	5.86	6.59	158	190	12.4
14	Metehara	8.87/39.9	3.652	5.83	5.77	60	58	1.0
15	Negele	5.03/39.57	3.393	5.30	5.30	56	56	0.0
16	Nekemit	9.08/36.45	2.303	5.83	5.18	153	125	11.2
17	Robe	7.12/40.0	1.977	5.7	5.58	188	182	2.2

The Boldly highlighted values at number 4 of Table A1 corresponds to the radiation data of the site under study.

Table A2. Surface meteorologica	l data of the site under study [43].
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Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Insulation, kWh/m²/day	5.76	6.20	6.48	6.59	6.26	5.74	5.02	5.04	5.67	5.87	6.01	5.67
Clear ness, 0–1	0.68	0.67	0.64	0.63	0.60	0.55	0.48	0.48	0.56	0.62	0.69	0.69
Temperature, °C	21.1	22.43	23.45	22.46	21.39	19.00	17.92	17.90	18.81	20.29	20.56	20.56

Appendix **B**

Туре	C _{nom} /1.80 V Ah *	C ₁₀ /1.80 V Ah **	C ₅ /1.77 V Ah	C ₃ /1.75 V Ah	C1/1.67 V Ah	Weight Kg	Weight Electrolyte Kg (1.24 Kg/L)	Length L mm	Width W mm	Height H mm
4 OPzS 200	200	213	182	161	118	17.2	4.9	105	208	420
5 OPzS 250	250	266	227	201	147	20.8	6.1	126	208	420
6 OPzS 300	300	320	272	241	177	24.3	7.2	147	208	420
5 OPzS 350	350	390	345	304	217	26.9	7.9	126	208	535
6 OPzS 420	420	468	414	364	261	31.5	9.4	147	208	535
7 OPzS 490	490	546	483	425	304	36.1	10.9	168	208	535
6 OPzS 600	600	686	592	511	353	44.8	12.9	147	208	710
8 OPzS 800	800	915	789	681	470	61.3	16.9	215	193	710
10 OPzS 1000	1000	1143	986	852	588	74.6	21.1	215	235	710
12 OPzS 1200	1200	1372	1184	1022	706	88.0	25.5	215	277	710
12 OPzS 1500	1500	1609	1398	1197	784	114.3	34.2	215	277	855
16 OPzS 2000	2000	2146	1864	1596	1045	151.5	48.0	215	400	815
20 OPzS 2500	2500	2682	2330	1995	1307	193.0	68.0	215	490	815
24 OPzS 3000	3000	3219	2796	2394	1568	246.0	76.0	215	580	815

Table A3. Manufacturer datasheet for Hoppecke OPzS 800 lead-acid battery [48].

* C_{nom} = Nominal capacity according to DIN 40736-1 ** C_{10} = Capacity at 10 h discharge.

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