Hybrid Renewable Energy Integration Framework for Smart Grid Stability, Energy Storage Management and Sustainable Power Delivery

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***Abstract*—The growing share of renewables in the modern power system has introduced fresh issues of generation variability, grid stability, proper coordination in power storage and sustainable power delivery. The proposed hybrid renewable energy integration framework for smart grid operation is based on solar PV generation, wind energy, battery energy storage, and an energy management controller, with the support of the utility grid. A comparative analysis was done between the conventional grid-dependent system and the proposed hybrid renewable integrated smart grid using the simulation method for 24 hours. The results indicate that a reduction in the energy consumption of the grid was achieved, from 1714 MWh per day down to 483 MWh per day, resulting in a 71.82% reduction in dependency on the grid. The peak grid import was reduced from 100 MW to 44 MW, representing a peak reduction of 56.00%. The daily operating cost was decreased from 169,220 USD to 49,222 USD, which leads to a cost reduction of 70.91%. Furthermore, carbon emissions related to the grid reduced from 1199.80 tCO_2 to 338.10 tCO_2, which is a reduction of 71.82%. The contribution of the renewable energy source and the contribution from battery energy storage was 1231 MWh/day, which accounted for 71.82% of the total load demand. The results indicated that coordinated hybrid renewable energy integration with battery energy storage can provide a significant benefit in terms of smart grid stability, conventional grid supply reduction and operation of sustainable power systems.**

Keywords— Hybrid renewable energy, smart grid, solar PV, wind energy, battery energy storage system, energy management, grid stability, sustainable power delivery

I. INTRODUCTION

The world's power generation industry is in a state of significant change, as renewable energy sources gain market share, demand for reliable power increases, and carbon emissions from traditional fossil fuel-based power generation are being cut. Clean, modular, and scalable power generation has made PV and wind energy systems a common sight in today's power networks. Their unpredictable and sporadic delivery poses difficulties for grid stability, voltage control, frequency management, and power balancing, however. Therefore, integrating RE sources with smart grid systems requires effective energy management, flexible energy storage, and smart control systems [1] [2]. Recent advancements in renewable energy technologies and smart-grid-supporting infrastructure have further enhanced system efficiency, reliability, and sustainable power delivery capabilities [3] [4].

Conventional power systems were predominantly designed to have a well-defined direction of power flow and to generate power at a centralized location and deliver it to the consumers. Modern smart grids, on the other hand, feature distributed generation, two-way power flow, advanced metering infrastructure, energy storage, communication networks, and real-time monitoring. These features allow the grid to integrate variable renewable generation and ensure stability and efficiency. Recently, smart grids, microgrids, advanced energy storage systems, and artificial intelligence-based control have been identified as enabling technologies for the integration of renewable energy into the future power systems [1] [5].

Hybrid renewable energy systems are a group of two or more renewable energy sources, such as solar PV and wind generation, that are integrated to enhance energy availability and flexibility of systems so they do not rely on a single energy source. Solar PV generation is usually highest during the day, but wind generation can happen at any time of day or night, depending on the weather. This complementary behaviour

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increases the availability of renewable energy sources and reduces the generation-demand mismatch, but not to the extent of completely solving the problem. Advanced energy storage technologies have emerged as key enablers for improving renewable energy utilization and supporting sustainable energy system operation under variable generation conditions [6] [7].

BISG (battery energy storage) is an important component of an integrated smart grid with renewable energy. It enables load shifting, peak-load reduction, frequency regulation, voltage support, power quality improvement, grid flexibility, renewable smoothing, and power quality improvement. Energy storage can minimize renewable energy curtailment and maximize the use of locally produced clean energy. Battery operation should be closely monitored to prevent shortening battery life, increasing operating costs, and compromising reliability due to overcharging or discharging. Hence, the management of the battery state of charge and energy management are important factors in ensuring the stable and sustainable operation of the smart grid [7] [8].

Intelligent energy management approaches have demonstrated significant potential for optimizing energy utilization, reducing operational costs, and improving system reliability in distributed energy networks [9]. They manage solar PV generation, wind generation, battery charging/discharging, utility grid import, and load demand. The implementation of an efficient energy management system can help reduce dependence on the grid, peak grid imports, operating expenses, and carbon emissions from the grid and better use renewable energy. Recent studies about hybrid microgrids and utility-scale renewable hybrid power plants have demonstrated that coordinated energy management can enhance power dispatch, renewable utilization, and power plant reliability [10] [11].

In this context, the present study introduces a hybrid renewable energy integration framework for stability in smart grids, energy storage system management, and delivery of sustainable power. The proposed framework includes integration of solar photovoltaic generation, wind generation, battery energy storage, support for the utility grid, load demand, and an energy management controller. A comparative analysis is carried out between a conventional grid-dependent system and a hybrid renewable-integrated smart grid through simulation for 24 hours. Load demand, renewable generation, grid import, battery SoC, energy contribution, daily operating cost, and grid-related carbon emissions are used to assess the performance of the system. This study primarily aims to show how the integration of hybrid renewable energy and battery storage management can help to minimize dependency on the grid, increase the utilization of renewable energy resources, decrease operating costs, decrease emissions, and ensure stable smart grid operation.

II. METHODOLOGY

The methodology used in this study was a comparative approach based on simulations to assess the stability of smart grids, the management of energy storage, and the delivery of sustainable power in the context of hybrid renewable energy integration. The proposed system was modelled as a renewable integrated smart grid, which contained solar photovoltaic (PV) generation, wind generation, a battery energy storage system (BESS), utility grid support, load demand, and an energy management controller. The performance of the proposed hybrid renewable integrated smart grid has been compared to a conventional grid-dependent system.

The traditional system was thought to provide the full load requirement of the power utility. The proposed smart grid, however, provided the demand through a co-ordinated mix of solar PV, wind generation, battery storage and a modest import from the grid. The analysis was carried out for 24 hours of operation with hourly load demand, renewable generation, battery state of charge, electricity tariff, electricity imported from the grid, cost and emission-related indicators.

The proposed scheme combined several renewables, energy storage, and energy grid support. PV generation was primarily used as the daytime renewable energy source, and wind generation was used to supplement PV generation throughout the day and night. Excess renewable energy was stored in the BESS when there was an abundance of renewable energy and released when demand was high or renewable energy was low. When renewables and batteries were not enough, the utility grid was a standby and balancing power source.

The energy management controller coordinated all the system components. It is primarily used for renewable energy utilisation, control of battery charging and discharging, minimisation of grid import, reduction of peak load and cost-aware operation. The framework has been designed to keep the balance between power generation and consumption and to minimise dependence on the grid and guarantee a stable power supply.

A 24-hour simulation data set was prepared to simulate the hybrid renewable integrated smart grid. The loading was between 42 MW and 100 MW per hour. The maximum solar PV generation was 72 MW at midday, and the minimum generation was 0 MW during night hours. The wind generation plant was available all day and had a capacity of 22MW—44MW. Charging and discharging operations resulted in different battery SOC changes, and the electricity tariff changed hourly to simulate time-varying costs for energy from the electricity grid.

The scheduling period was defined as:

$$T = 1,2,3,\dots,24 \quad (1)$$

where (T) represents the 24-hour simulation horizon.

The main variables used in the study were defined as follows:

$P_L(t)$ = load demand at hour t

$P_{PV}(t)$ = solar PV generation at hour t
$P_W(t)$ = wind generation at hour t
$P_R(t)$ = total hybrid renewable generation at hour t
$P_G(t)$ = utility grid import at hour t
$P_B(t)$ = battery charging or discharging power at hour t
$SOC(t)$ = battery state of charge at hour t
C_t = electricity tariff at hour t

The total hybrid renewable generation was calculated as:

$$P_R(t) = P_{PV}(t) + P_W(t) \quad (2)$$

In the conventional grid-dependent system, the total load demand was assumed to be supplied entirely by the utility grid. Therefore, the grid import was equal to the load demand at each hour:

$$P_{G,conv}(t) = P_L(t) \quad (3)$$

where $P_{G,conv}(t)$ represents grid import under conventional grid operation. This case was used as the baseline for evaluating the benefits of the proposed hybrid renewable integrated smart grid.

In the proposed hybrid renewable smart grid, load demand was supplied by solar PV generation, wind generation, battery storage, and utility grid import. The hourly power balance was expressed as:

$$P_L(t) = P_{PV,used}(t) + P_{W,used}(t) + P_{B,dis}(t) + P_{G,smart}(t) \quad (4)$$

Where $P_{PV,used}(t)$ and $P_{W,used}(t)$ represent renewable power used to supply the load, $P_{B,dis}(t)$ represents battery discharge power, and $P_{G,smart}(t)$ represents grid import under smart grid operation.

When renewable generation exceeded load demand, the surplus renewable power was used to charge the battery:

$$P_{B,ch}(t) = P_R(t) - P_L(t) \quad (5)$$

subject to available battery capacity and SOC constraints. When renewable generation was insufficient, the battery discharged to support the load and reduce grid import.

The BESS was included to improve renewable energy utilization, reduce grid import, and support stable power delivery. The battery charged during renewable-rich periods and discharged during high-demand or low-renewable periods. The battery SOC update was represented as:

$$SOC(t+1) = SOC(t) + \eta_c P_{B,ch}(t) - \frac{P_{B,dis}(t)}{\eta_d} \quad (6)$$

where η_c is the battery charging efficiency, η_d is the battery discharging efficiency, $P_{B,ch}(t)$ is the battery charging power, and $P_{B,dis}(t)$ is the battery discharging power.

The battery was operated within safe limits:

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (7)$$

This constraint ensured that the BESS did not overcharge or over-discharge during the 24-hour operation.

The proposed energy management strategy followed a priority-based control approach. Renewable generation was given the first priority to maximize clean energy utilization. Battery storage was used as the second priority to shift renewable energy from surplus periods to high-demand periods. Utility grid import was used only when renewable generation and battery support were insufficient.

The control sequence was defined as follows:

- Solar PV and wind generation were used first to supply the load demand.
- Surplus renewable generation was used to charge the battery.
- During low-renewable or high-demand periods, the battery discharged to support the load.
- The utility grid supplied only the remaining unmet load.
- Grid import was minimized during peak-demand and high-tariff periods.
- Battery operation was controlled within SOC limits.

The smart grid import was therefore minimized as:

$$P_{G,smart}(t) = P_L(t) - P_{PV,used}(t) - P_{W,used}(t) - P_{B,dis}(t) \quad (8)$$

The daily operating cost was calculated using hourly grid import and time-varying electricity tariff. For the conventional system, the cost was calculated as:

$$Cost_{conv} = \sum_{t=1}^{24} P_{G,conv}(t) \times C_t \quad (9)$$

For the hybrid renewable integrated smart grid, the cost was calculated as:

$$Cost_{smart} = \sum_{t=1}^{24} P_{G,smart}(t) \times C_t \quad (10)$$

The cost reduction was calculated as:

$$Cost\ Reduction = fracCost_{conv} - Cost_{smart} Cost_{conv} \times 100 \quad (11)$$

Grid-related carbon emissions were calculated using the grid emission factor:

$$E_{CO2} = E_G \times EF \quad (12)$$

where (E_G) is the daily grid energy use and $(EF)$is the grid emission factor. In this study, an emission factor of 0.70 $tCO(2)$/MWh was assumed for simulation purposes.

Emission reduction was calculated as:

$$Emission\ Reduction = \frac{E_{CO2,conv} - E_{CO2,smart}}{E_{CO2,conv}} \times 100 \quad (13)$$

The proposed framework was evaluated using technical, economic, and environmental performance indicators.

Daily grid energy use was calculated as:

$$E_G = \sum_{t=1}^{24} P_G(t) \quad (14)$$

Peak grid import was calculated as:

$$P_{peak} = max\big(P_G(t)\big) \quad (15)$$

Grid dependency reduction was calculated as:

$$Grid\ Dependency\ Reduction = \frac{E_{G,conv} - E_{G,smart}}{E_{G,conv}} \times 100 \quad (16)$$

Peak grid import reduction was calculated as:

$$\text{Peak Reduction} = \frac{P_{peak,conv} - P_{peak,smart}}{P_{peak,conv}} \times 100 \quad (17)$$

The renewable and BESS contribution to load demand was calculated as:

$$E_{R+BESS} = E_L - E_{G,smart} \quad (18)$$

where $(E_L)$is the total daily load demand. The percentage contribution was calculated as:

$$Renewable/BESS\ Contribution = \frac{E_{R+BESS}}{E_L} \times 100 \quad (19)$$

The simulation was performed in a step-by-step manner. First, the hourly load demand, solar PV generation, wind generation, electricity tariff, and initial battery SOC were specified for a 24-hour period. Second, a traditional grid operating scenario was simulated by assuming that the entire load requirement was provided to the utility grid. Thirdly, a hybrid renewable integrated smart grid model was created with solar PV generation, wind generation, BESS, and grid import. The 4th, the energy management strategy, was employed to manage the allocation of renewable energy, charge or discharge the battery, and minimize the grid import. Fifth, the battery SOC was updated every hour while operating within safe limits. Lastly, the performance of the conventional system and the proposed framework were compared based on grid energy consumption, peak grid import, contribution of renewable energy, daily cost, and carbon emissions. The methodology offered a structured approach to the evaluation of the integration of hybrid renewables in the smart grid operation. The study compared the traditional grid-dependent operation with the proposed hybrid renewable integrated smart grid, quantifying the advantages of solar PV, wind generation, battery storage, and energy management. The selected performance metrics allowed for the evaluation of smart grid stability, energy storage management, renewable energy use, cost reduction, emission reduction, and sustainable power delivery.

III. Results and Discussion

A 24-hour simulation-based smart grid model was used to evaluate the proposed hybrid renewable energy integration framework. It was a system comprised of solar PV generation, wind generation, a battery energy storage system (BESS), utility grid support, and an energy management controller. The proposed hybrid renewable integrated smart grid was compared with a conventional grid-dependent system in terms of performance. Evaluated items included hourly load demand, renewable generation, import of electricity from the grid, state of charge of the batteries, energy contribution, operating cost, and carbon emissions from the grid.

The smart grid system, Fig. 1, displays the hourly load demand profile for the 24-hour operating period. The load demand value was quite low during late night and early morning hours, from 42 MW to 50 MW from 00:00 to 05:00. Demand slowly picked up after the morning hours until 82 MW at 09:00. The demand level was found to increase in the afternoon and evening, peaking at 100 MW at 18:00.

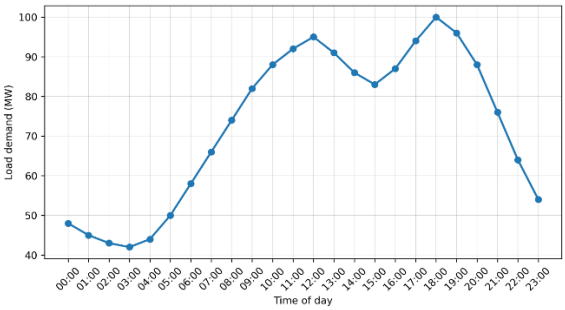

Fig. 1. Hourly load demand profile of the smart grid system

This demand profile represents a typical daily electric load profile, with rising demand during the daytime when activities are taking place and a maximum during the evening peak hours. The difference in the load demands demonstrates the importance of accommodating renewable variability and battery energy storage control. If energy management is not employed, the full load requirement would have to be met by the grid, leading to increased peak grid imports and operating costs.

Fig. 2 shows the hourly generation profiles of solar PV, wind, and total hybrid renewables generation. PV solar generation increased during the day and decreased at night. It was not available at night, was higher after sunrise, and peaked at 72 MW at 12:00. Solar generation began to decline slowly thereafter and would be unavailable at the end of the day and during the night. Wind generation, however, was available all day long and ranged from 22 MW to 44 MW.

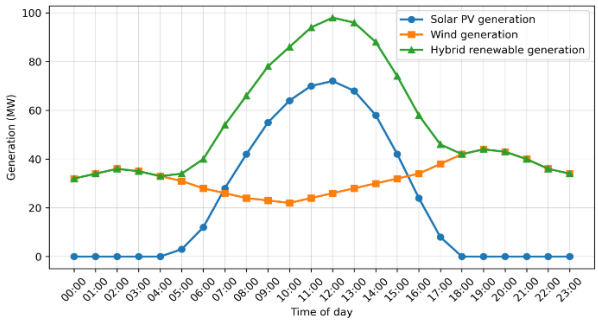

Fig. 2. Solar PV, wind, and hybrid renewable generation profiles

The PV and wind generation complement each other and increase the availability of renewable energy over the entire 24-hour period. The hybrid renewable generation is highest during midday hours when solar generation is at its peak. During the night and evening hours, wind generation continued to serve as load support when solar PV was not available. The complementary nature of the generation resources enhances the availability of renewable energy and decreases overall reliance on the power grid.

Figure 3 displays the hourly load demand alongside the available hybrid renewable generation. The result indicates that there was some relatively high renewable generation in the day, especially between 09:00 and 14:00, when solar PV generation reached its peak. During these hours, the hybrid renewable generation was able to supply a major portion of the load demand and reduce grid import.

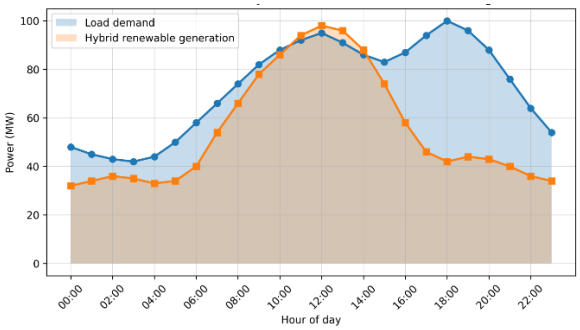

Fig. 3. Load demand and hybrid renewable generation matching

However, the evening peak period revealed a mismatch. The load demand reached its maximum value of 100 MW at 18:00, while solar PV generation was no longer available. During this time, wind generation was also available, but it was not enough to cover the total demand. This discrepancy shows the significance of battery energy storage and grid support in a smart grid with hybrid renewable energy. The BESS can shift renewable energy from periods of high energy availability to periods of high energy demand, which helps stabilize the power supply.

Fig. 4 compares the grid import of the conventional grid system with that of the hybrid renewable integrated smart grid. In the traditional scenario, the grid import was exactly the same as the load demand, as all the load was provided by the utility grid. Because of this comparison, the peak import during the evening peaks was 100 MW.

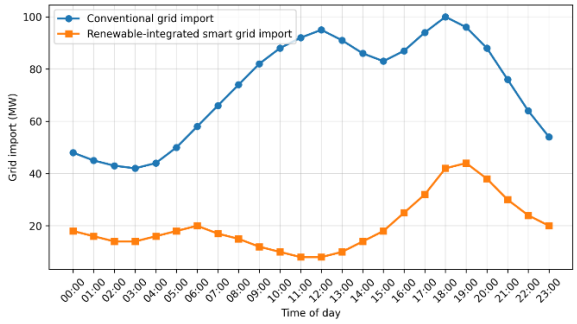

Fig. 4. Grid import before and after hybrid renewable integration

Hybrid renewable integration resulted in a reduced grid import for all operating hours, after which the grid import levels were significantly lower. The smart grid import dropped to extremely low levels during high renewable generation periods, as it was reduced to 8 MW for a 1-hour period between 11:00 and 12:00. Grid import rose in the evening peak hours when solar generation was lower and demand was higher but was still low compared to the conventional grid case. The peak import reduction was also lowered from 100 MW to 44 MW, which is a 56.00% reduction in peak imports. This finding proves that energy storage management and coordinated integration of renewable energy sources can help mitigate grid stress and enhance the stability of smart grids.

Fig. 5 displays the battery state of charge (SOC) profile for 24 hours during smart grid operation. Battery SOC dropped from 54% at 00:00 to 32% at 06:00, which represents battery discharge in low-renewable and early-morning hours. The PV generation has risen since the morning. The SOC level increased after sunrise due to the rise in PV generation, reaching 90% at 13:00.

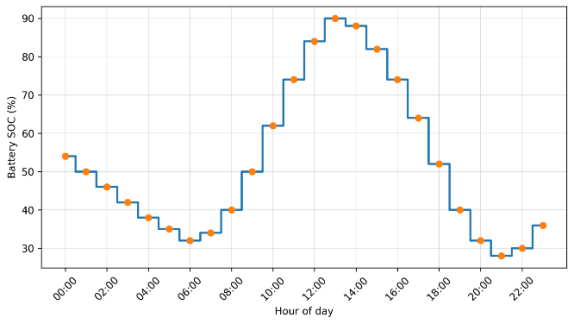

Fig. 5. Battery state of charge during hybrid renewable smart grid operation

Since the solar-rich period, the SOC in the battery has been gradually reduced as the battery discharges to compensate for the afternoon and evening peak demand. The SOC dipped to 28% at 21:00 and then improved slightly during the late-night wind-supported operation. This charging and discharging performance prove that the BESS contributed significantly to energy shifting, peak load management, and import reduction from the grid. The SOC profile also shows that energy storage is needed to ensure that power is delivered during periods when renewable power and loads do not match.

Fig. 6 illustrates the stacked energy contribution of the utility grid supply and renewable-plus-BESS support to the total load demand. Based on the result, it has been observed that the smart grid with a renewable integrated hybrid system provided a significant amount of renewable energy generation and battery storage to meet the demands. The utility grid balanced the remaining load, relying solely on renewable generation and storage.

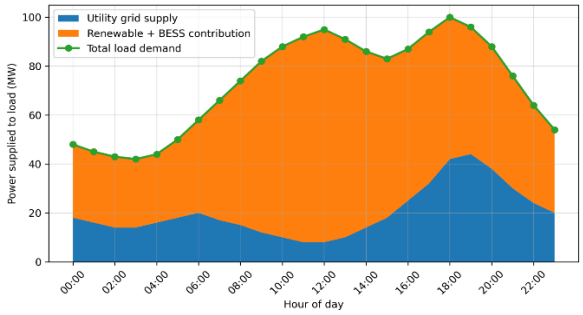

Fig. 6. Energy contribution in the hybrid renewable integrated smart grid

The total load demand for the 24-hour period was 1714 MWh. The electricity grid supplied 1714 MWh during normal use. The total energy consumed by the utility grid was decreased to 483 MWh/day, while renewable resources and BESS provided 1231 MWh/day to the load demand in the proposed hybrid renewable smart grid. The system is 71.82% renewable/BESS. The findings validate the ability to significantly improve renewable energy consumption and, therefore, the reliance on traditional grid supply, with the proposed framework.

The comparison between the daily operating cost and the carbon emissions due to the grid usage of the conventional grid system and the hybrid renewable integrated smart grid is shown in Fig. 7. The daily operating cost of the conventional grid system was 169,220 USD. With the hybrid renewable integration, the operating cost for the day was reduced to 49222 USD. This is a 70.91% cost saving.

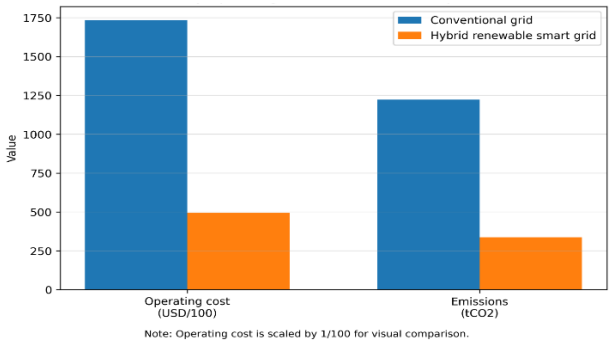

Fig. 7. Daily operating cost and emission comparison

Likewise, the emissions related to the grid were reduced from 1199.80tCO_2 in the conventional system to 338.10 tCO_2 in the hybrid renewable integrated smart grid. This is equivalent to a 71.82% reduction in emissions. The reduction in operating expenses and emissions was possible because the proposed framework reduced the import of energy into the utility grid by maximizing the use of energy from renewables and stored energy. These results demonstrate that using hybrid renewable energy integration is beneficial for both economic and ecological goals while operating a smart grid.

Fig. 8 summarizes the major performance indicators of a conventional grid and a hybrid renewable-integrated smart grid. The results demonstrate that with the integration of solar PV, wind generation, BESS, and energy management, daily grid energy consumption dropped from 1714 MWh to 483 MWh. The peak grid import went down from 100 MW to 44 MW, and the daily operating cost went down from 169,220 USD to 49,222 USD. The emissions related to the grid also fell, from 1199.80 $tCO_2$to 338.10 tCO_2.

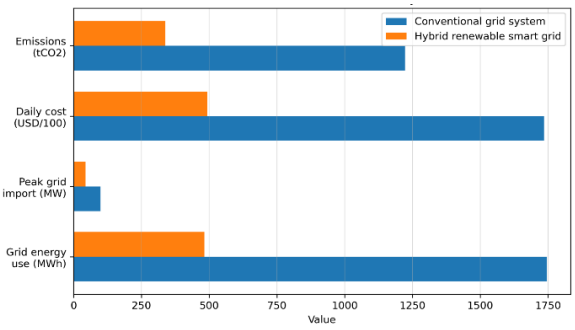

Fig. 8. Overall performance summary of the conventional and hybrid renewable integrated smart grid systems

.The results of the simulation show that the proposed hybrid renewable energy integration framework is better in terms of performance than the conventional operation of the grid. The system achieved a 71.82% reduction in energy consumption from the grid, a 56.00% reduction in peak energy consumption from the grid, a 70.91% reduction in operating expenses, and a 71.82% reduction in carbon emissions from the grid. The obtained outcomes confirm the effectiveness of the hybrid integration of renewable energies and the management of battery energy storage to obtain smart grid stability, sustainable power delivery, and increased energy efficiency.

IV. Conclusion

This paper presents a hybrid renewable energy integration framework designed to enhance smart grid stability, manage energy storage, and ensure sustainable power delivery. The proposed framework consisted of solar photovoltaic generation, wind energy, battery energy storage, support service to the utility grid, and an energy management controller so as to enhance the operational performance of a smart grid with renewable energy integration. The primary goal was to lower grid dependency, peak grid import, increase use of renewables, decrease operating cost, and decrease carbon emissions of the grid. A comparative analysis of the proposed hybrid renewable integrated smart grid system with the conventional grid-dependent system has been done by conducting a simulation analysis for 24 hours. Results indicated that the proposed framework had a significant improvement in the performance of the smart grid. This decrease in energy consumption in the grid resulted in a grid dependency reduction of 71.82% (1714MWh to 483MWh). The peak grid import reduced from 100 MW to 44 MW (-56.00%). The daily operating cost was lowered from 169,220 USD to 49,222 USD, which is 70.91% less. Furthermore, the emissions related to the grid declined by 71.82% from 1,199.80 tCO_2 to 338.10 tCO_2. The contribution of renewable and battery energy storage was 1231 MWh/day or 71.82% of the total load demand. is an effective solution for the future operation of the smart grid under high renewable penetration in general.

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