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Techno-Economic Operation and Environmental Life-Cycle Assessment of a Solar PV-Driven Islanded Microgrid

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ABSTRACT Microgrids (MGs) are playing an important role in the maximum utilization of distributed energy resources. The optimal economic operation and low-carbon electricity generation can enhance MGs effectiveness. This paper presents the results of a solar-photovoltaic (PV)-driven islanded MG's techno-economic optimization analysis and environmental life-cycle assessment (LCA) to achieve economical and environmentally superior performance. A net present cost (NPC)-based simulation for optimal sizing of the MG is proposed. A novel life-cycle inventory (LCI) is developed to evaluate the impacts of the MG under 21 midpoint indicators and three endpoint indicators by the ReCiPe 2016 method, metal particle releases by the Ecopoints approach, and the greenhouse-gas emissions by the IPCC method. The sensitivity analysis is carried out to verify the effects for three different batteries and five different PV modules for all of the considered impact indicators. The results reveal that the proposed MG offers a revenue of 29,520 US$/yr by routing excess energy to neighbors after fulfilling the prosumers' demand at an optimal net present cost of 364,906 US$. Furthermore, the outcomes obtained from the LCA analysis show that, among the MG components, batteries have the highest impact on human health (74%) and the ecosystem (78%) due to greater greenhouse-gas emissions (CO_2-48%, CH_4-37%, and N_20-48%).

INDEX TERMS Microgrid, optimal design, life-cycle assessment, environmental impact, greenhouse-gas.

I. INTRODUCTION

In recent years, microgrids (MGs), have been getting considerable attention worldwide for maximum utilization of distributed energy resources (DERs) [1]. MGs, are small-scale power system consisting of distributed generators, loads, energy storage and control unit, can be employed in a grid connected and/or isolated mode for facilitating power supply and/or for maintaining standard service in a distinct locality. An assembly of local energy sources, storages, and loads builds a typical MG system [2]. These MGs play a pivotal role in fulfilling the local load demands of islands and rural villages by power sharing through economic operation [3]. In addition, using these MGs the excess energy of the prosumers (with PV facility) can be shifted to the nearby consumers (without PV facility). Therefore, MGs are becoming popular from both an economical and a necessity perspective [4]. A solar-PV-driven islanded MGs offers both profit for the prosumers and much-desired energy for the consumers [5]. However, the optimal use of such MGs can be achieved through minimization of the net present cost (NPC) and the levelized cost of energy (COE). Moreover, the cleaner electricity generations are pivotal to abating global warming to 2^oC by 2030, which is the aim of the 21^{st} conference of parties (COP21) of the UNFCCC (United Nations Framework Convention on Climate Change) [6]. Previous literature highlighted that energy-sharing microgrid frameworks operate cost-effectively at higher demands, but a productive utilization of resources has not been ensured [7], [8]. Previous studies also depicted that renewable power plants are responsible for greenhouse-gas emissions due to fossil-fuel consumption in various stages of their lifetimes [9], [10], which can be identified by life-cycle assessment (LCA), a method of quantifying the environmental impacts related to all the steps of a system/product. Therefore, this research aims to optimize cost-economic operation, and performs the

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environmental impact identification of the MG's elements using a newly created life-cycle inventory (LCI), a tracking of all the input and output flows such as energy, materials and emissions by the system/product,to produce low carbon electricity.

The techno-economic analysis of an MG is critical due to the changing nature of its performance with real-time weather data. The modeling of a solar-PV driven MG in an off-grid islanded situation depends on a few factors, such as: the size of the PV modules, the load demand, the size of the converters and inverters, the capacity of storages, the economics of the elements, energy transmission distances, amount of excess energy etc. A number of research groups have used HOMER (Hybrid Optimization Model for Electric Renewables) for cost-benefit analysis, invented by NREL (National Renewable Energy Laboratory, USA) [11], [12]. It can handle a wide range of energy sources such as PV, wind, hydro, fuel cells, boilers etc., consumptions such as AC, DC, thermal, hydrogen etc. Mizani et al. [13] developed a model using HOMER and recognized a best case for the production mix through optimization, which gives lower costs and emissions for the optimal choice of resources. However, they considered a national grid in their model, which is inappropriate for an islanded off-grid community. A standalone MG system is proposed by Thiam et al. considering an island of Senegal, which provides a smaller cost of energy for the community than national grid [14]. Another standalone MG system is proposed by Lee et al. that offers a feasible application of renewable resources for a village community [15]. Kabir et al. developed an MG system using different renewable resources for electricity production and showed that the proposed system is capable of fulfilling the electric demands of an off-grid rural community [16]. Four different cases are modeled and optimized for analyzing the challenges of MG systems using resources from the NREL [17]. A comparative economic assessment of different islanded MG systems considering diesel, hydro-diesel, and PV-diesel is depicted in [18] and analyzes their performance. A heuristic algorithm is developed in [19] for modeling an MG system consisting of wind, PV, and battery, and the outcome shows that a proper use of storages can minimize the system's running costs. A case study for a hypothetical locality with daily load demand of 5000 kWh/day is depicted in [20], but it is not feasible in reality for the unrealistic assumptions. A hybrid source-based system is modeled by Nayar et al. [21] and Anyi et al. [22], in which remote islands of the Maldives and Malaysia are considered, which gives high renewable-energy penetration and a solution for remote off-grid application. Givler et al. [7] conducted a research for small power systems in Sri Lanka, and verified the cost-effectiveness of a PV/diesel-based hybrid MG system, and compared it with a standalone system. Similar works are highlighted in various studies, for example Himri et al. [23] considered a case for an Algerian village, whereas Nfah et al. [24] and Bekele et al. [25] accomplished case studies of Cameroon and Ethiopia, respectively. However, they have not considered the productive use of resources for sharing the excess electricity. A recent work by Fernandez et al. offers benefits by cutting down the cost of energy through utilizing battery storage at the peak time without using electricity from the national grid, providing a game-theory-based energy-sharing model for cost optimization [26]. It reveals about a 9.17% cost saving in summer. Another recent work by Akter et al. [27] developed an energy-sharing model using a rule-based approach for energy management, which lacks revenue maximization from an economic aspect. The NPC-based optimization is a favored method over previously used methods as it optimizes the net present value of the MG system by considering the total annualized cost and the levelized cost. The first main focus of this work is to bridge the research gap by developing an MG system for an islanded locality in Bangladesh, optimizing the system by HOMER's fulfilling the constraints. The optimization and sensitivity analysis are carried out by a systematic priority formation through the optimization technique.

On the other hand, the life-cycle-based environmental-impact assessment of an MG is not an easy task as it is required to consider the effects from the lifespan of all elements. Therefore, it is necessary to collect the industrial datasets for each MG element to identify the dangerous releases in their lifetime. The evaluation of various emissions to air, water and land, and the energy consumption at each life stage of the elements is crucial for LCA analysis. An appropriate strategy is mandatory for assessing and comparing the impacts through LCA. Prior research provides the environmental impacts by each element separately, for example Liang et al. [28] and Lang et al. [29] examined the effects of the lithium-ion batteries, Innocenzi et al. [30] and Meng et al. [31] depicted impacts by the NiMH batteries, Espinosa et al. [32] and Latunussa et al. [33] highlighted the impacts from PV modules. Mizani et al. [13] and Prasai et al. [34] assessed the CO_2 emissions and estimated the amount of CO_2 release reduction, but they did not consider a systematic life-cycle assessment approach. Moreover, until now none has assessed the environmental impacts of an MG for mid-point, end-point indicators and greenhouse-gas emissions considering the raw-material extraction to end-of-life waste-management stages. The parameter of an environmental mechanism for a specific impact category between the inventory data and the category endpoints are defined as a mid-point indicator, whereas an end-point indicator reflects the final effect in a cause-effect chain or in an environmental mechanism [35]. Therefore, the second main focus of this research is to identify the impacts of the proposed MG system using the life-cycle assessment approach. LCA is a practical method of evaluating the environmental effects of any product, as it identifies the impacts for a broad range of environmental categories such as resource scarcity, human carcinogenic toxicity, human non-carcinogenic toxicity, ecotoxicity, freshwater eutrophication, terrestrial acidification, ozone formation, global warming, stratospheric ozone depletion, ionizing radiation, water consumption, fine particulate matter formation, land use etc. [36], [37]. LCA analysis deals with the total inputs and outputs, material flows, and emissions at each stage of a product. It also analyzes the lifetime of a product, from the raw material extraction to manufacturing, usage and end-of-life waste disposal [38]. The LCI is developed to assemble the material flows over the lifetime of the system elements. The Ecoinvent database [39] is used in building the LCI. The LCA is accomplished by SimaPro software version 8.5 [40] using ReCiPe 2016 [41], Intergovernmental Panel on Climate Change (IPCC) [42], and Ecopoints [43] methods. The ReCiPe 2016 method is used to assess the impacts by 18 environmental characterization factors, whereas IPCC approach is used to identify the greenhouse gas emissions (under four categories) of the MG system elements. The Ecopoints methods is utilized to quantify the metal particles-based releases to the environment by each of the MG elements throughout their lifetime.

Overall, the key contributions of this research to fulfill the main focus, cost optimization and negative-impact reduction by the proposed MG, can be outlined as follows:

1) A smart MG system is proposed for an islanded remote community, which provides cost-efficient performance by routing excess electricity to neighboring traditional houses without wasting it in an off-grid condition.
2) An NPC-based optimization is carried out for the highest profit of prosumers through optimal sizing of elements using real-time physical, operating and economic inputs in the proposed MG system.
3) A novel LCI is developed that assesses and compares the environmental impacts by each element of the MG using ReCiPe 2016, Ecopoints and IPCC methods of LCA.
4) Sensitivity analysis is undertaken to identify the best cases among various PV modules such as amorphous silicon (a-Si), copper indium selenide (CIS), multi-Si, ribbon Si and single-Si, and various community storages such as lithium-ion (Li-ion), sodium chloride (NaCl) and nickel metal hydride (NiMH), for lower impact and cost-efficient operation of the MG.

This work is unique in developing an LCI for the LCA analysis of the proposed MG system, and minimizing the system cost by optimal sizing of the elements. Given the above purpose, the rest of the paper is organized as follows. The MG system is introduced in Section II. The methods of techno-economic analysis and LCA analysis are discussed in Section III. Section IV highlights the optimal economic operation outcome and life-cycle environmental impact assessment outcome. The sensitivity analysis outcome considering different cases for PV modules and community storages are presented in Section V. Finally, Section VI makes concluding remarks for this research.

II. MICROGRID SYSTEM OVERVIEW

In the proposed MG system, a small array of houses within a short periphery are connected to share energy by an islanded off-grid setup. A few of the houses (smart houses) have a solar-PV electricity-production facility, and by this MG system the excess electricity is routed to nearby powerless houses (traditional houses) after fulfilling the prosumers' electricity demands. Figure 1 presents a schematic diagram of the microgrid system. Overall, in the MG system the PV panels of smart houses, breakers, energy meters, inverters, converters, controller, and community storages are interconnected through cables with a dc bus and an AC bus. The electricity generated by the PV panels is regulated by the dc/dc converters and then directed toward the dc bus. The energy meters record the power flow, community storage stores the generated energy, inverter converts dc currents to ac, and controllers control the system.

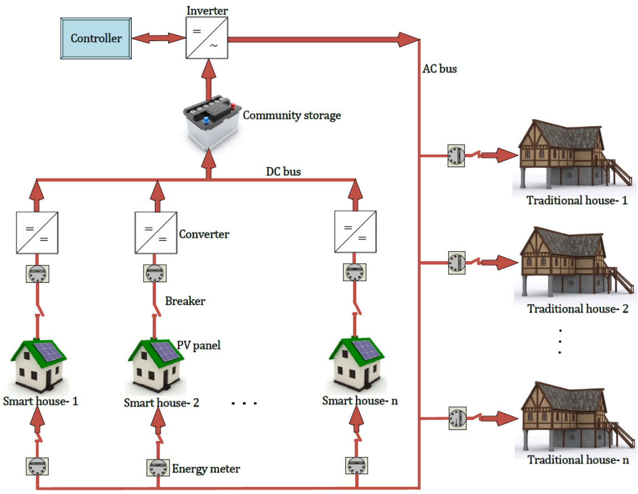


FIGURE 1. The MG-framework structure.

In the model design, the overall electricity generation by the prosumers in normal times is maintained high enough to meet the load demand in an emergency situation in unfavorable weather. Generators are not considered in the model as the system is developed for an islanded situation, with economic constraints for the remote houses. Considering renewable energy, when there exist some energy deficiency in unfavorable weather, the demand would be supplied by their own generators. On the other hand, when there exists surplus in some hours, prosumers make some profit by routing those [3], [44], [45]. The central storage is used instead of decentralized ones for convenient sharing of energy among the smart houses, for routing the overall extra power to the traditional houses, and for lowering the net present cost [46].

The NPC-based optimization model provides the optimal case of PV module numbers and community storage sizes for the considered load demands of the prosumers, and calculates the amount of excess energy for routing to the traditional houses, as described in Section III-A. A novel LCI is developed for assessing the lifetime environmental impacts of the considered MG system using life-cycle assessment, as discussed in Section III-B.

III. METHODS

Two different methods are used in this research: one for optimal economic operation and another for environmental-impact assessment of the MG system. These methods are discussed in the following subsections.

A. OPTIMAL ECONOMIC OPERATION METHOD

The chosen remote village for this research is Kutubdia, a small island in the Bay of Bengal in the Cox's Bazar district of Bangladesh. The MG provides off-grid electricity to the inhabitants of this village, as it has no national grid facility.

The total net present cost (NPC) and the levelized cost of energy (COE) are dependent on the total yearly expense of the MG system. The overall yearly expense of the MG is the sum of its elements' expenses minus miscellaneous expenses. Equation 1 is used to calculate the NPC of the MG [11].

$$NPC = \frac{C_{Total}}{CRF_{(\eta,n)}} \tag{1}$$

where C_{Total} is the overall yearly expenses of the MG, η is interest rate per year, n is the year numbers, and $CRF_{(\eta,n)}$ is the capital recovery, which is calculated using equation 2. Equation 3 is used for calculating the COE [11].

$$CRF_{(\eta,n)} = \frac{\eta(1+\eta)^n}{(1+\eta)^n - 1} \tag{2}$$

$$COE = \frac{C_{Total}}{E_P + E_C} \tag{3}$$

where E_P and E_C are the annual load demands of prosumers and consumers respectively met by the MG system. The optimization is carried out for a minimal NPC of the MG system using HOMER following the method described in [11], [12].

The installed PV capacity is defined by Equations 4 to 6 [47]:

$$P_{PV} = V_{PV} \times I_{PV} \tag{4}$$

$$V_{PV} = \frac{mkT}{q} ln(1 + \frac{I_{SC}}{I_0}) \tag{5}$$

$$I_{PV} = I_{SC} - I_0(e^{\frac{qV_{PV}}{mkT}} - 1) \tag{6}$$

where V_{PV} is the output voltage of each PV cell; I_{PV} is the PV current of each cell; m is the ideality factor; k is the Boltzmann's constant; T is the PV cell temperature; I_{SC} is the short circuit current; I_0 is the saturation current; and q is the charge of electron.

The community storage energy is estimated using Equation 7 [47]:

$$E_x = \frac{V \times D \times SOC}{Y_{converter} \times Y_{storage}} \tag{7}$$

where, E_x is the stored energy and x is the discharge time in hour; V is the voltage in offload condition; D is the zero charging days at the disfavored weather condition; $Y_{converter}$ and $Y_{storage}$ are converter and storage yield value; and SOC is the State of Charge. The SOC range is kept between 30% to 80% for better lifetime of the storage.

TABLE 1. Simulation parameters.

Parameters	Values
Solar scaled average	4.5 kWh/m^2/day
Nominal capacity of Community storage	1820 kWh
Each PV panel capacity	60 kW
Inverter and converter capacity	72 kW
Prosumers load demand	370 kWh/day
Each PV panel cost	6,956 US$
Community storage cost	1,006 US$
Inverter/converter cost	1,671 US$
Community storage replacement cost	533 US$
Inverter/converter Replacement cost	472 US$
Each PV panel capacity factor	18%
Interest rate	0.5%
Project lifetime	25 years

The key assumptions for the simulation of the MG system using HOMER are as follows.

1) MODEL PARAMETERS

The proposed MG system has a total of 12 houses, out of which four are considered as smart houses with a PV facility, while the others are traditional houses that depend on smart houses for electricity, as there is no national grid available. The considered model parameters for NPC-based optimization are presented in Table 1. The consumers' loads are not considered as the main aim is to fulfill prosumers' demand first, and check the remaining electricity for consumers after optimization, which will earn revenue for the prosumers through energy routing. The solar radiation profile of Cox's Bazar, Bangladesh, is used for this work, which is collected from the NASA Surface Meteorology website [48]. The average solar radiation is found to be 4.5 kWh/m^2/day. All expenses associated with the capital, operation, maintenance, replacement, fuel, miscellaneous are included in the NPC. All expenses of the MG system are considered in constant dollars [11], [12].

2) SIMULATION

HOMER simulation identifies the lifetime cost feasibility and the operation strategy for the MG system. It runs simulation on an hourly basis and it considers the sustainable operation capacity of the grid.

3) OPTIMIZATION

HOMER provides the optimal sizing of the PV panels and battery strings through optimization maintaining the constraints. It considers minimum NPC for the system and gives an optimal configuration after optimization.

4) SENSITIVITY ANALYSIS

Sensitivity analysis helps to identify the influences of changing various parameters of the system. In this research, various lifetimes of batteries such as 5, 10, 15 and 20 years and

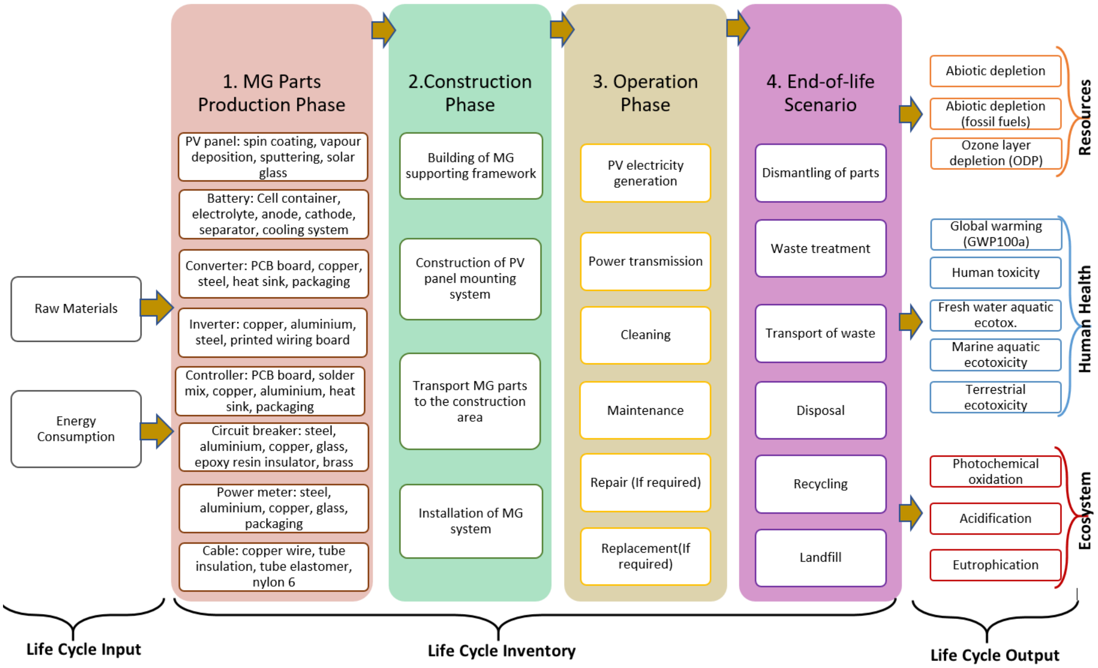


FIGURE 2. The system boundary of the MG-framework for LCA analysis.

various solar scale capacities such as 4.5, 5 and 5.58 are considered for sensitivity analysis. Many optimization outcomes are achieved for these assumptions and are guided to identify the best case.

B. LIFE-CYCLE ENVIRONMENTAL IMPACT ASSESSMENT METHOD

Life-cycle assessment is a systematic approach to environmental-impact evaluation to identify and categorize the effects caused by a product or process throughout its entire lifetime [49], [50]. This approach consists of four basic steps: i) goal and scope definition, ii) life-cycle inventory, iii) life-cycle impact estimation, and iv) life-cycle impact interpretation. For LCA analysis maintaining these steps, ISO (International Organization for Standards) standard 14040:2006 is followed [51], [52]. In the below subsections, the LCA steps are briefly described to highlight the LCA methodology which is maintained in this study.

1) GOAL AND SCOPE DEFINITION

The first LCA step is goal and scope definition, where the objective is defined and the LCA system boundaries are established. The goal of this LCA is to identify and compare the negative environmental impacts of the MG system. The scope of this LCA analysis is cradle-to-grave aspects [53], [54] for mid-point and end-point environmental impact indicators for the system. Therefore, the comprehensive LCA considers the lifetime of the system including raw-material extraction, key parts manufacturing, transportation, MG system installation, and end-of-life waste disposal. The functional unit [49], [50] of this LCA is chosen as 1 kWh of electricity supply by the MG system.

2) LIFE-CYCLE INVENTORY

The second LCA step is the development of the life-cycle inventory, where all inputs (material and energy) and outputs (emissions) at each stage of the element's lifetime are added. The formation of the LCA boundary of the MG system as shown in Figure 2 is the unique contribution of this work. The boundary is modeled with mandatory equipment, following their lifetime stages such as raw-material extraction from mines, transportation of these materials, production of MG parts, transportation of the parts to the MG location, MG construction, MG operation, and the end-of-life waste disposal. The schematic intakes and releases at each stage are shown in Figure 3. Energy and material intakes took place in the raw materials extraction, micro-grid elements production and microgrid installation stage, whereas only energy intakes happened in the transportation and waste management stage. The solid material and gaseous emissions are released during several stages such as waste management, MG installation, MG elements production and raw materials extraction stage. The energy output is only found in the micro-grid operation stage. Figure 4 shows the stage-by-stage energy and material flows for the considered MG system. Blue indicates the MG assembly which is formed by adding all unit processes, white indicates the unit processes that contributes to reuse and disassembly, light yellow indicates the unit processes that concerned to energy flow, and light green indicates the unit processes that related to materials processing, transport

TABLE 2. Data collection for the LCA of MG-framework.

Unit process	Process source
PV panel	Photovoltaic panel,CIS, at plant/GLO U/I U/AusSD U
Battery	Battery, Li-ion,rechargeable, prismatic {GLO}/ market for / Alloc Def, U
Energy meter	Electric meter,unspecified {GLO}/ production / Conseq, U
Breaker	Switch, toggle,type, at plant/GLO U/AusSD U
Cable	Cable, unspecified,{GLO}/ market for / Conseq, U
Converter	Converter, 250W, for electric system {GLO}/ production / Conseq, U
Inverter	Inverter, 250W, at,plant/GLO U/I U/AusSD U

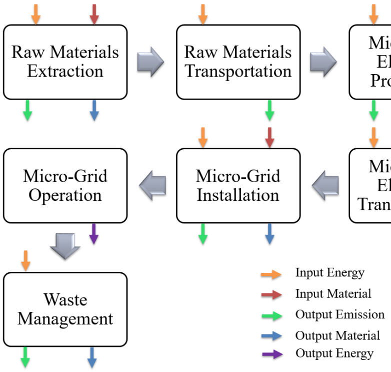


FIGURE 3. The stage-wise material, energy and emission flow.

and waste treatment. The Ecoinvent database [55]–[57] is used to collect the life-cycle inputs and outputs of the MG elements because it has global industrial and commercial datasets for different element manufacturing, transportation, waste management etc. [56]–[58]. From Ecoinvent database, base unit processes are chosen depending on item specifications. Table 2 gives the data source for the MG elements. The considered PV panel, battery (community storage) types are CIS and Li-ion, respectively. Moreover, the global unit processes are considered for other elements such as inverter, converter, cable, breaker, and energy meter. An assembly of these unit processes of the elements are formed for the desired MG system, which is finally used to evaluate the individual effects by every process element. The energy losses and heat releases during the power transmission and distribution stages are not considered in this LCA due to lack of datasets.

3) LIFE-CYCLE IMPACT ESTIMATION

In the third LCA step, life-cycle assessment is carried out based on the ISO 14040:2006 standard following the ReCiPe 2016, IPCC and Ecopoints methods. SimaPro software version 8.5 [40] is used in identifying the effects after developing the LCA system boundary because it is universally used among LCA software [59]. The ReCiPe 2016 approach [41] combines the scientific rigor of the CML2001 and the Ecoindicator-99 approaches for assessing the mid-point impacts under 18 categories (8 more than Ecoindicator-99), which is a maximum among all LCA approaches. The 18 mid-point effects obtained by the ReCiPe 2016 approach are resource scarcity (fossil and mineral), human carcinogenic toxicity, human non-carcinogenic toxicity, ecotoxicity (marine, terrestrial and freshwater), freshwater eutrophication, terrestrial acidification, ozone formation (human health and terrestrial ecosystems), global warming (human health, terrestrial ecosystems and freshwater ecosystems), stratospheric ozone depletion, ionizing radiation, water consumption (human health, terrestrial ecosystems and aquatic ecosystems), fine particulate matter formation, and land use. This method also estimates the end-point impacts under three aggregated categories: human health, ecosystems, and resources (Figure 5).

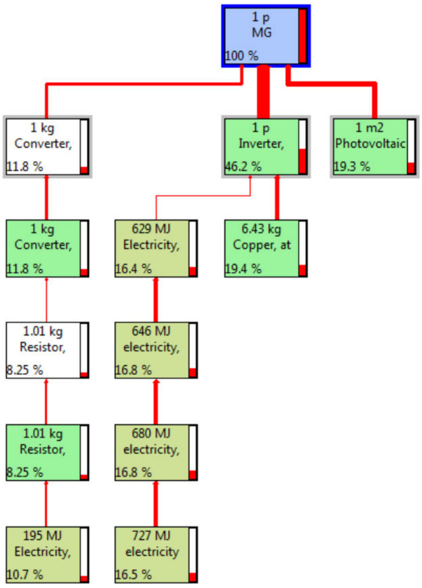


FIGURE 4. The material flow of the MG-framework.

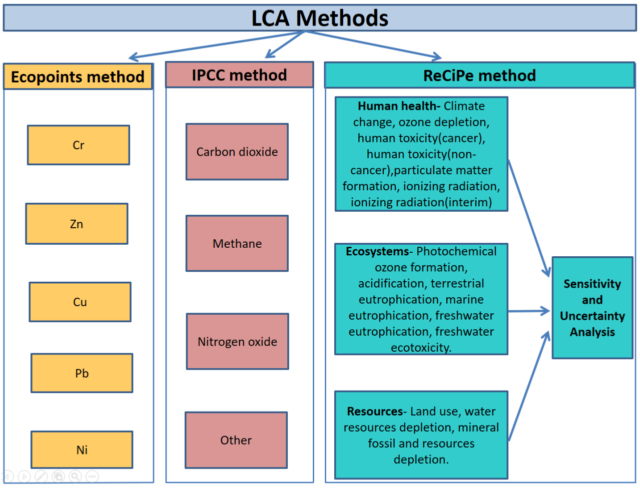
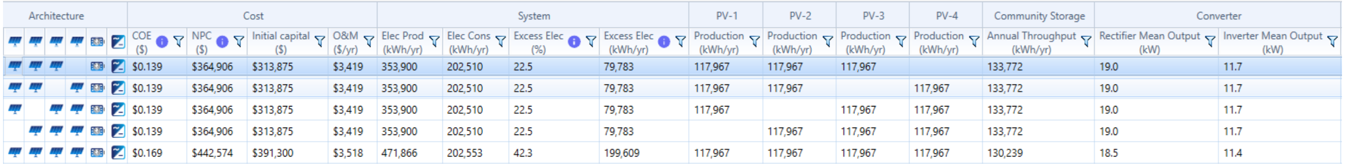


FIGURE 5. The LCA methods used in this analysis.

Additionally, the IPCC approach estimates the greenhouse-gas emissions such as carbon dioxide, methane, nitrogen oxide etc. (Figure 5) following a 100-year time-frame [42]. This method provides three advantages in evaluating the greenhouse-gas releases : a) assures optimal utilization of available datasets in a comprehensive way, b) provides accuracy in estimation, and c) gives information for policy

TABLE 3. The NPC-based optimization result of the MG-framework.



Architecture						Cost				System				PV-1	PV-2	PV-3	PV-4	Community Storage	Converter	
						COE ($)	NPC ($)	Initial capital ($)	O&M ($/yr)	Elec Prod (kWh/yr)	Elec Cons (kWh/yr)	Excess Elec (%)	Excess Elec (kWh/yr)	Production (kWh/yr)	Production (kWh/yr)	Production (kWh/yr)	Production (kWh/yr)	Annual Throughput (kWh/yr)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
●	●	●		●	●	$0.139	$364,906	$313,875	$3,419	353,900	202,510	22.5	79,783	117,967	117,967	117,967		133,772	19.0	11.7
●	●		●	●	●	$0.139	$364,906	$313,875	$3,419	353,900	202,510	22.5	79,783	117,967	117,967		117,967	133,772	19.0	11.7
●		●	●	●	●	$0.139	$364,906	$313,875	$3,419	353,900	202,510	22.5	79,783	117,967		117,967	117,967	133,772	19.0	11.7
	●	●	●	●	●	$0.139	$364,906	$313,875	$3,419	353,900	202,510	22.5	79,783		117,967	117,967	117,967	133,772	19.0	11.7
●	●	●	●	●	●	$0.169	$442,574	$391,300	$3,518	471,866	202,553	42.3	199,609	117,967	117,967	117,967	117,967	130,239	18.5	11.4

developers on climate changes. It does not deal with carbon monoxide and radiative emissions in the atmosphere.

Furthermore, the Ecopoints method [43] is utilized to quantify the harmful metal particle releases such as lead (Pb), copper (Cu), cadmium (Cd), chromium (Cr), zinc (Zn), and nickel (Ni) from each elements of the MG (Figure 5). This approach uses 3 steps to assess the impacts such as, classification, normalization and weighting. The datasets collection and cumulative summation for each element for each impact indicator from the whole life cycle of the system includes classification phase. The normalization step determines the environmental degradation magnitude by taking the ratio of impact indicator amount and reference value. The impact indicator value is multiplied with the weighting factor to obtain the single score value for comparative analysis in the last phase of Eco-points method called weighting.

4) LIFE-CYCLE IMPACT INTERPRETATION

In this last LCA step, life-cycle interpretation, impact outcomes are analyzed and interpreted to identify the most significant substances for each of the mid-point and end-point environmental effect indicators over the lifetime of the MG system. These findings correlate with the sustainability factors of the systems to abate the impacts on human health, ecosystem and resources.

Finally, sensitivity analysis has been carried out by the ReCiPe 2016 method, considering various PV panels (single-Si, multi-Si, ribbon-Si, copper indium selenium (CIS), and amorphous-Si) and community storages (nickel-metal hydride, sodium chloride, and lithium-ion) to check the changes in effects for the cases. It helps to track the optimal option with regard to the environment-impact aspects.

IV. RESULTS AND DISCUSSION

A. OPTIMAL ECONOMIC OPERATION OUTCOME

The obtained optimal operation is presented in Table 3. It is found that having three PV panels along with the community storage and converters is the optimal case for the least net present cost of the MG system. The optimal NPC and COE rates are 364,906 US$ and 0.139 US$, whereas, the MG system with four PV panels is the worst case with an NPC of 442,574 US$ and a COE of 0.169 US$. It is also found that about 79,783 kWh/yr (22.5 %) of excess electricity is produced, giving a profit of 29,520 US$/yr (considering 0.37 US$/kWh) through routing to nearby consumers. The weekly scenario of the total renewable power output and the excess electrical production is depicted in Figure 6.

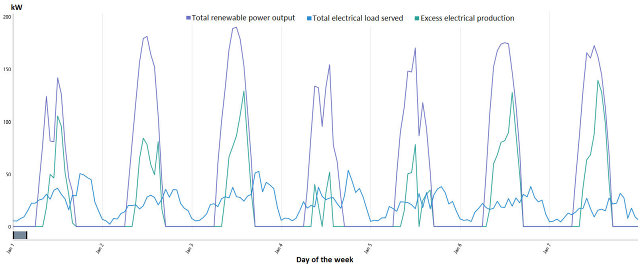


FIGURE 6. The weekly excess power rate of the MG-framework.

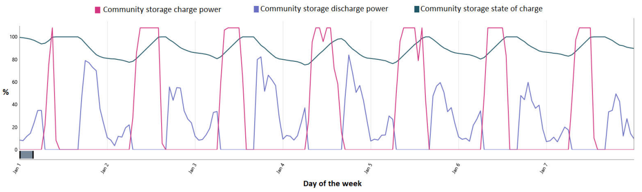


FIGURE 7. The weekly SoC profile of the community storage.

The outcome shows that there is a significant amount of excess energy in each day of the week, which can be routed to more traditional houses to make a revenue by the prosumers.

The results are compared with the existing studies of standalone MG systems and reveal that a range of design parameters such as PV module size, community storage capacity, solar irradiation rate, converter/inverter capacity, storage strings number etc. are responsible for different COEs ranging between 0.1 US$ and 2 US$ [14], [15], [23]–[25]. The obtained COE in [14] is 0.18 US$/kWh for Senegal, in [15] is 0.49 US$/kWh for China, in [24] is 0.34 US$/kWh for Cameroon, in [25] is 0.94 US$/kWh for Ethiopia, while in this study the COE is 0.13 US$/kWh for Bangladesh, which is very small. On the other hand, the obtained NPC in [23] is 2,982,825 US$ for Algeria, in [24] is 376,856 US$ for Cameroon, in [25] is 464,600 US$ for Ethiopia, whereas in this study it is 364,906 US$ for Bangladesh.

The weekly SoC profile of the central storage is shown in Figure 7.The lowest and highest charge limits of the storage are maintained as 10 and 90%. The charge level was about 60-80%for most of the days, which ensures that there is an extra energy and PV owners make some revenue by routing it to fulfill nearby neighbors load demands.

B. LIFE-CYCLE ENVIRONMENTAL IMPACT ASSESSMENT RESULTS

1) ENVIRONMENTAL IMPACTS OF THE MICROGRID

The midpoint impact outcome of MG parts obtained by the ReCiPe 2016 method using a cradle-to-grave analysis

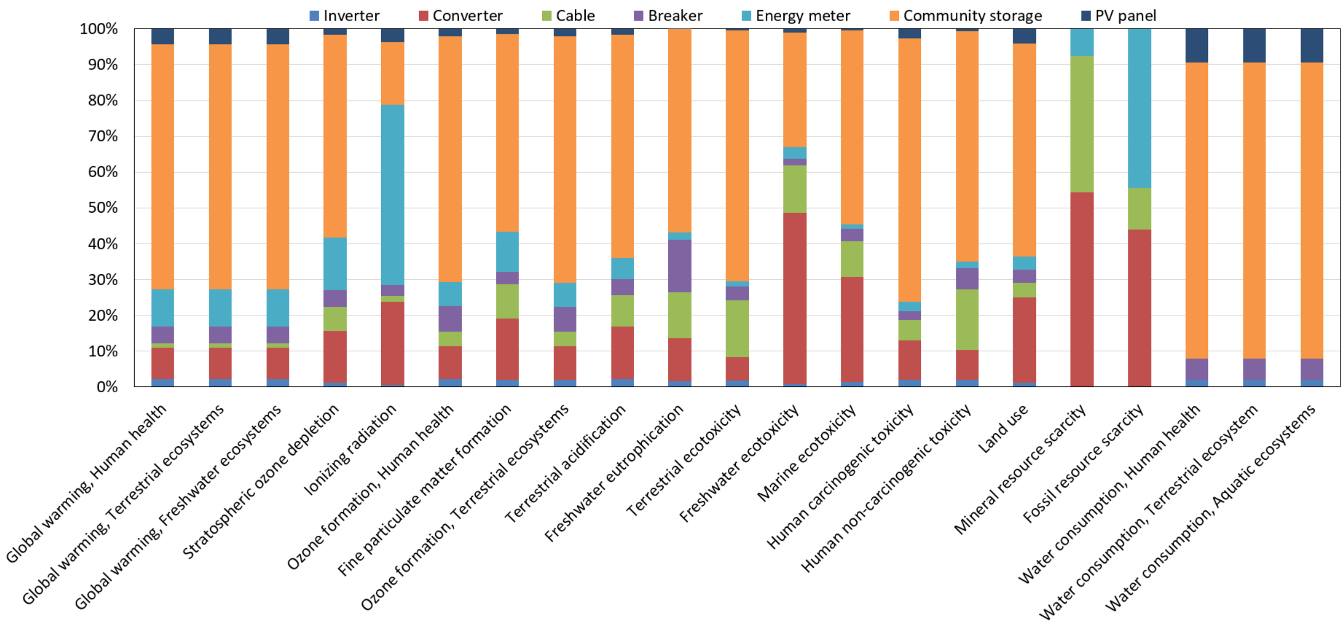


FIGURE 8. The life-cycle environmental profiles of the framework using ReCiPe 2016 method.

TABLE 4. The key hazardous substances of the MG elements that mostly affect the end-point environmental indicators.

Impact Category	Main dangerous Substance for the MG elements						
	Community storage	Converter	Cable	Switch	Meter	Inverter	PV panel
Human health (DALY/kWh)	Carbon dioxide (3.18E-05)	Zinc (1.31E-04)	Copper (4.09E-05)	Chromium (9.63E-05)	Particulates (5.14E-05)	Sulfur dioxide (2.32E-04)	Sulfur oxides (3.58E-04)
Ecosystems (Species.yr/kWh)	Phosphate (7.94E-07)	Ammonia (8.16E-08)	Zinc (6.25E-08)	Nitrogen (7.84E-07)	Sulfur hexafluoride (2.53E-08)	Phosphate (2.74E-07)	Carbon dioxide (4.64E-06)
Resources (kg/kWh)	Zirconium (4.97E-06)	Silver (1.39E-04)	Natural gas (6.39E-07)	Xylene (1.94E-08)	Copper (2.16E-08)	Aluminium (4.05E-07)	Hard coal (9.54E-06)

is presented in Figure 8. It is found that the community storage provide maximum impact for most of the indicators such as water consumptions (82.68%), terrestrial ecotoxicity (70.05%), ozone formation (68.87%), global warming (68.51%), whereas the inverter impacts very little for maximum indicators such as ionizing radiation (0.47%), freshwater ecotoxicity (0.80%), stratospheric ozone depletion (1.15%), and land use (1.25%). The cable is harmful maximum for mineral resource scarcity (54.40%) and minimum for water consumptions (0.01%). The breaker impacts highest for freshwater eutrophication (14.77%) and second greatest for ozone formation (6.97%). The energy meter is significantly dangerous for the impact categories of ionizing radiation (50.37%) and fossil resource scarcity (44.35%). The converter affects least for water consumptions (0.04%) and is optimal for mineral resource scarcity (54.40%). The PV panels impact is about 9.32% for water consumptions (human health, terrestrial ecosystem and aquatic ecosystem). About 4.23% global warming (human health, terrestrial ecosystem and aquatic ecosystem) impacts was incurred by the PV panel. Overall, the PV modules provided smaller effects for most of the midpoint categories such as mineral and fossil resource scarcity (0.001%), freshwater eutrophication (0.09%), marine ecotoxicity (0.40%), and human non-carcinogenic toxicity (0.65%).

The comparative endpoint impacts of the MG elements obtained by the ReCiPe 2016 method are highlighted in Figure 9, which shows that the converter, energy meter and cables impact resources mostly with a rate of 45%, 39% and 15%, respectively. Community storage affects the ecosystems and human health greatly with respective rates of 79% and 74% due to their large size and dangerous chemicals. The PV panels incurred maximum effect to ecosystems due to significant amounts of fossil-fuel consumption, mostly in the raw material extraction and processing, and high end-of-life pollution. Therefore, following the endpoint outcome, future research should be undertaken to utilize renewable resources in all stages of the MG components' lifetime from raw-material extraction to end-of-life recycling and disposal.

The most impactful substances for the end-point indicators by each MG element are depicted in Table 4, which shows that carbon dioxide is released from the community storage, affecting greatly human health (3.18E-05 DALY/kWh). DALY (Disability Adjusted Life Year) is concerned to human

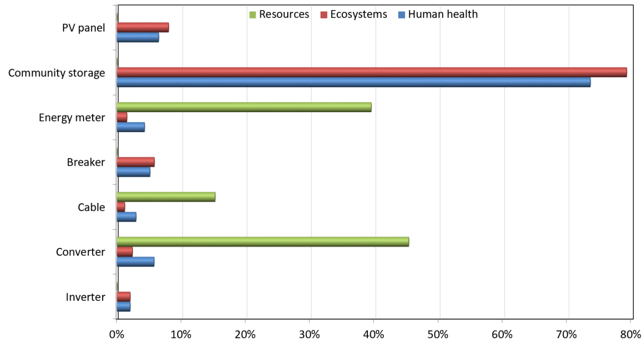


FIGURE 9. The end-point damage assessment of the framework using the ReCiPe 2016 method.

health damage, which indicates the years that lead to risk of a person to become disabled due to an accident/disease. The representation for ecosystem quality is the measure of species extinction integrated over time (species year). Zinc is most dangerous for human health due to the converter (1.31E-04 DALY/kWh) and copper from cable affects mostly human health (4.09E-05 DALY/kWh). Hard coal is responsible for the impacts to resources by the PV panels (9.54E-06 kg/kWh) and natural gas is for cable (6.39E-07 kg/kWh). Overall, the maximum harmful substances that released from the MG over its lifetime to affect human health, resources and ecosystems are sulfur dioxide, carbon dioxide and silver, respectively. Sulfur dioxide and carbon dioxide mostly emits from PV panel, while silver greatly releases from converter. It is required to concentrate on designing a new type of PV panel/converter by an alternative sustainable material to limit these harmful emissions.

2) GREENHOUSE-GAS EMISSIONS BY THE MICROGRID

The comparative life-cycle GHG emissions from the MG components, obtained by the IPCC method, are depicted in Figure 10. It is found that carbon dioxide is mostly emitted for the community storage and PV panels, with rates of about 48% and 34%, respectively. Moreover, the release of methane and nitrous oxide are also high for the community storage, with amounts of 38% and 48%, respectively. The converter and energy meter release a maximum to the land during end-of-life recycling with rates of 43% and 42.5%, respectively. Overall, community storage is highly dangerous due to the maximum release of greenhouse-gases for all three categories of carbon dioxide, methane and nitrous oxide due to the chemicals used. Therefore, researchers should pay considerable attention to enhance the environmental profiles of the community storages.

3) METAL PARTICLE RELEASES BY THE MICROGRID

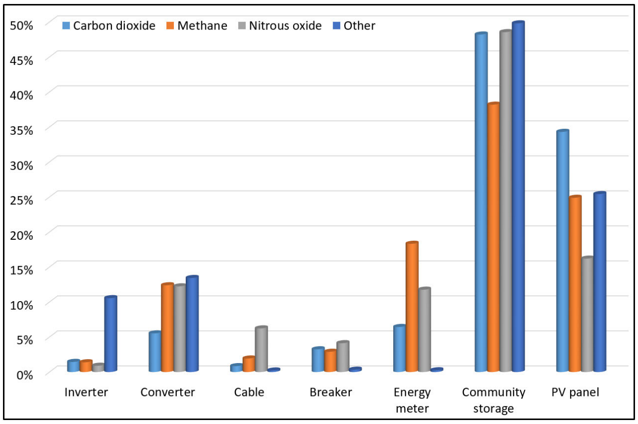


FIGURE 10. The GHG emission evaluation outcome using the IPCC method.

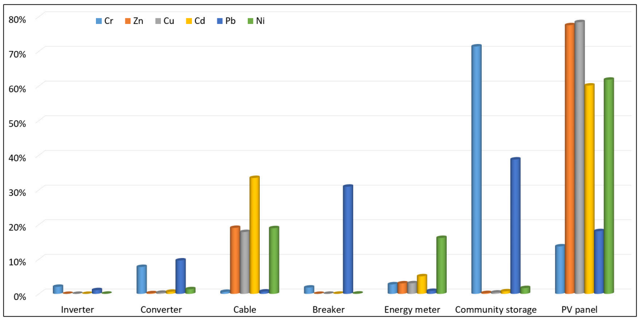


FIGURE 11. The metal-based emissions quantification outcome using the Ecopoints 97 method.

The metal particle releases obtained by the Eco-points 97 method depicted in Figure 11 highlight that solar panel is contributed to the highest amount of metal particle emissions for the categories of Zn, Cu, Cd and Ni. In contrast, inverter is the lowest impactful based on metal particle releases to the environment. Pb and Cr are released maximum by the community storage with a rate of 38% and 71%, respectively. However, converter, cable, breaker and energy meter shows a medium risk to the environment for metal particle releases with respect to other elements.

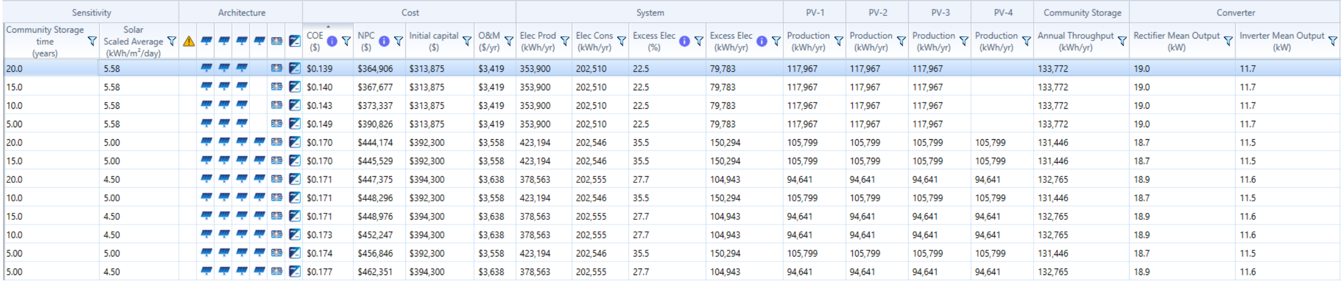
V. SENSITIVITY ANALYSIS

Several sensitivity analyses have been carried out to test the techno-economic operation and the environmental profiles of the proposed MG system for various battery lifetimes, solar scales, PV modules and community storages, which helped to identify the best case.

A. EFFECTS FOR VARIOUS COMMUNITY-STORAGE LIFE AND SOLAR SCALE RATES

The effect of changing the community storage's lifetime and the solar scales is shown in Table 5, which reveals that the smallest NPC (364,906 US$) and COE (0.139 US$) is found for the case of 20 years' life and 5.58 kWh/m^2/day solar irradiation, which is the optimized case among the 12 options. On the other hand, a community storage with 5 years' life and 4.50 kWh/m^2/day solar irradiation provided the maximum NPC of 462,351 US$ and the highest COE of 0.177 US$. Moreover, the same COE of 0.171 US$ is obtained for the three cases with various combinations of community storage

TABLE 5. Sensitivity analysis outcomes for various battery lifetimes and solar scaled factors in NPC-based optimization of the MG.



Sensitivity		Architecture							Cost				System					PV-1	PV-2	PV-3	PV-4	Community Storage	Converter	
Community Storage time (years)	Solar Scaled Average (kWh/m²/day)	⚠							COE ($)	NPC ($)	Initial capital ($)	O&M ($/yr)	Elec Prod (kWh/yr)	Elec Cons (kWh/yr)	Excess Elec (%)	Excess Elec (kWh/yr)		Production (kWh/yr)	Production (kWh/yr)	Production (kWh/yr)	Production (kWh/yr)	Annual Throughput (kWh/yr)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
20.0	5.58		■	■	■		■	■	$0.139	$364,906	$313,875	$3,419	353,900	202,510	22.5	79,783		117,967	117,967	117,967		133,772	19.0	11.7
15.0	5.58		■	■	■		■	■	$0.140	$367,677	$313,875	$3,419	353,900	202,510	22.5	79,783		117,967	117,967	117,967		133,772	19.0	11.7
10.0	5.58		■	■	■		■	■	$0.143	$373,337	$313,875	$3,419	353,900	202,510	22.5	79,783		117,967	117,967	117,967		133,772	19.0	11.7
5.00	5.58		■	■	■		■	■	$0.149	$390,826	$313,875	$3,419	353,900	202,510	22.5	79,783		117,967	117,967	117,967		133,772	19.0	11.7
20.0	5.00		■	■	■	■	■	■	$0.170	$444,174	$392,300	$3,558	423,194	202,546	35.5	150,294		105,799	105,799	105,799	105,799	131,446	18.7	11.5
15.0	5.00		■	■	■	■	■	■	$0.170	$445,529	$392,300	$3,558	423,194	202,546	35.5	150,294		105,799	105,799	105,799	105,799	131,446	18.7	11.5
20.0	4.50		■	■	■	■	■	■	$0.171	$447,375	$394,300	$3,638	378,563	202,555	27.7	104,943		94,641	94,641	94,641	94,641	132,765	18.9	11.6
10.0	5.00		■	■	■	■	■	■	$0.171	$448,296	$392,300	$3,558	423,194	202,546	35.5	150,294		105,799	105,799	105,799	105,799	131,446	18.7	11.5
15.0	4.50		■	■	■	■	■	■	$0.171	$448,976	$394,300	$3,638	378,563	202,555	27.7	104,943		94,641	94,641	94,641	94,641	132,765	18.9	11.6
10.0	4.50		■	■	■	■	■	■	$0.173	$452,247	$394,300	$3,638	378,563	202,555	27.7	104,943		94,641	94,641	94,641	94,641	132,765	18.9	11.6
5.00	5.00		■	■	■	■	■	■	$0.174	$456,846	$392,300	$3,558	423,194	202,546	35.5	150,294		105,799	105,799	105,799	105,799	131,446	18.7	11.5
5.00	4.50		■	■	■	■	■	■	$0.177	$462,351	$394,300	$3,638	378,563	202,555	27.7	104,943		94,641	94,641	94,641	94,641	132,765	18.9	11.6

TABLE 6. Sensitivity analysis outcome for various PV modules of the MG.

Impact Category	Single-Si [mPt]	Multi-Si [mPt]	Ribbon-Si [mPt]	a-Si [mPt]	CIS [mPt]
Global warming, Human health	45.14	37.75	34.51	19.99	33.91
Global warming, Terrestrial ecosystems	45.14	37.75	34.51	19.99	33.91
Global warming, Freshwater ecosystems	45.14	37.75	34.50	19.99	33.91
Stratospheric ozone depletion	41.46	37.58	32.61	11.18	15.97
Ionizing radiation	14.30	14.89	11.79	37.85	4.16
Ozone formation, Human health	37.92	31.19	28.88	12.55	29.19
Fine particulate matter formation	23.14	17.14	16.22	9.38	18.68
Ozone formation, Terrestrial ecosystems	38.01	31.51	29.24	12.35	28.65
Terrestrial acidification	28.54	21.37	20.52	11.11	23.61
Freshwater eutrophication	3.73	3.44	3.35	0.86	1.91
Terrestrial ecotoxicity	33.81	33.27	33.15	2.13	4.05
Freshwater ecotoxicity	14.65	10.96	9.32	6.74	5.87
Marine ecotoxicity	18.52	18.24	17.99	2.23	2.97
Human carcinogenic toxicity	26.55	21.54	16.66	20.14	16.75
Human non-carcinogenic toxicity	22.19	21.87	21.58	3.57	5.66
Land use	47.57	42.95	38.52	16.18	31.62
Water consumption, Human health	84.73	85.98	78.53	35.09	21.47
Water consumption, Terrestrial ecosystem	84.73	85.98	78.53	35.09	21.47
Water consumption, Aquatic ecosystems	84.73	85.98	78.53	35.09	21.47

TABLE 7. Sensitivity analysis outcome for various batteries of the MG.

Impact category	NiMH [mPt]	NaCl [mPt]	Li-ion [mPt]
Global warming, Human health	3.65	1.19	2.13
Global warming, Terrestrial ecosystems	3.65	1.19	2.13
Global warming, Freshwater ecosystems	3.65	1.19	2.13
Stratospheric ozone depletion	32.07	2.48	1.15
Ionizing radiation	18.05	13.42	0.47
Ozone formation, Human health	3.20	1.39	2.10
Fine particulate matter formation	14.25	11.26	1.95
Ozone formation, Terrestrial ecosystems	3.17	1.39	2.08
Terrestrial acidification	15.12	11.64	2.16
Freshwater eutrophication	1.98	1.47	1.62
Terrestrial ecotoxicity	2.60	1.89	1.85
Freshwater ecotoxicity	1.11	5.91	0.80
Marine ecotoxicity	2.18	1.90	1.46
Human carcinogenic toxicity	2.17	3.31	1.99
Human non-carcinogenic toxicity	0.64	1.70	1.89
Land use	1.28	1.01	1.25
Mineral resource scarcity	0	25.33	0
Fossil resource scarcity	0	9.12	0
Water consumption, Human health	21.11	0.01	2.02
Water consumption, Terrestrial ecosystem	21.11	0.01	2.02
Water consumption, Aquatic ecosystems	21.11	0.01	2.02

lifetime and solar scales. Overall, the optimal sizing of the MG is obtained for the increased rate of community storage life and solar scale as it provided better sensitivity outcomes with lower COE and NPC.

B. IMPACTS FOR VARIOUS TYPES OF PV MODULES

The sensitivity analysis outcome using five different PV modules such as single-Si, multi-Si, ribbon-Si, a-Si and CIS for the considered MG system is depicted in Table 6. It is found that multi-Si is notably responsible for water consumption (85.98 mPt), whereas CIS given the smallest impact for water consumption (21.47 mPt). The a-Si PV modules are highly accountable for ionizing radiation (37.87 mPt) and the single-Si PV modules are mostly liable for water consumption (84.73 mPt) and global warming (45.14 mPt). Overall, the CIS-based PV modules given a better environmental performance for most of the impact indicators. Therefore, investors should use CIS solar modules in building an MG system for its superior environmental profiles rather than the alternatives, to escape from the dangerous impacts.

C. IMPACTS FOR VARIOUS TYPES OF COMMUNITY STORAGES

The sensitivity analysis outcome using various community storages for the MG system, shown in Table 7, highlights that an NiMH-based system given higher effects for most of the categories such as stratospheric ozone depletion (32.07 mPt), water consumption (21.11 mPt), ionizing radiation (18.05 mPt), terrestrial acidification (15.12 mPt), fine particulate matter formation (14.25 mPt) and global warming (3.65 mPt). The NaCl community storage-based MG system provided a maximum impact for three categories among 21, mineral resource scarcity (25.33 mPt), fossil resource scarcity (9.12 mPt), and freshwater ecotoxicity (5.91 mPt). Overall, the Li-ion community storage-based MG system depicted the best environmental performance at the sensitivity analysis. Therefore, prosumers should use Li-ion-type community storage in constructing MG systems. The key implication of the sensitivity outcome is in smart grids, in which shareholders should use environment-friendly community storages to avoid the environmental dangers.

VI. CONCLUSION

In this paper, a net-present-cost-based optimization analysis and a life-cycle assessment-based environmental-impact assessment of a solar-PV driven off-grid microgrid framework is undertaken. To ensure the validity of this research, we i) developed a off-grid microgrid system, ii) optimized based on net-present-cost minimization, iii) analyzed life-cycle material flow, iv) built a life-cycle inventory, v) assessed environmental profiles by multiple methods, and

vi) conducted sensitivity analyses that examine the optimal design and superior environmental performance of the MG. The well-known HOMER Pro and SimaPro softwares, and the renowned Ecoinvent global database are used for the cost optimization and impact assessment. This research is unique in developing an LCI and assessing the impacts of an MG by multiple methods such as ReCiPe 2016 for midpoint and endpoint effects analysis, Ecopoints for metal particles releases quantification, and IPCC for GHG emissions estimation. Results reveal that the NPC-based techno-economic optimization offers a profit of 29,520 US$/yr to the prosumers at an optimal net present cost of 364,906 US$ and an levelized cost of energy 0.139 $. Furthermore, the LCA outcome shows that the battery is the highest affecting element of the MG for most of the midpoint impact indicators such as global warming (68.51%), land use (59.45%), ecotoxicity (32.12%), eutrophication (56.79%), acidification (62.25%). The sensitivity analysis outcome highlights that an increased lifetime of the community storage and solar scale provides minimal net present cost, and that CIS-PV modules and Li-ion batteries are environmentally superior to others, for an MG. The incorporation of a national grid and other renewable sources in the MG framework and finding an environment-friendly replacement of the dangerous elements is the future direction of this research for broad application and cleaner operation.

REFERENCES

[1] J.-M. Clairand, M. Arriaga, C. A. Canizares, and C. Alvarez, "Power generation planning of Galapagos' microgrid considering electric vehicles and induction stoves," *IEEE Trans. Energy*, to be published.

[2] Y. Karimi, H. Oraee, M. S. Golsorkhi, and J. M. Guerrero, "Decentralized method for load sharing and power management in a PV/battery hybrid source islanded microgrid," *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3525–3535, May 2017.

[3] M. A. P. Mahmud, M. J. Hossain, M. S. H. Nizami, M. S. Rahman, S. H. Farjana, N. Huda, and C. Lang , "Advanced power routing framework for optimal economic operation and control of solar photovoltaic-based islanded microgrid," *IET Smart Grid*, vol. 2, no. 2, pp. 242–249, Jun. 2019.

[4] M. A. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "Environmental life-cycle assessment and techno-economic analysis of photovoltaic (PV) and photovoltaic/thermal (PV/T) systems," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. (EEEIC)*, vol. 1, Jun. 2018, pp. 1–5.

[5] N. Liu, M. Cheng, X. Yu, J. Zhong, and J. Lei, "Energy-sharing provider for PV prosumer clusters: A hybrid approach using stochastic programming and stackelberg game," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6740–6750, Aug. 2018.

[6] *Adoption of the Paris Agreement*, Documents FCCC/Cp/2015/L.9/Rev.1, UNFCCC, 2015.

[7] T. Givler and P. Lilienthal, "Using HOMER software, NREL's micro power optimization model, to explore the role of gen-sets in small solar power systems case study: Sri Lanka," Dept. Energy, Nat. Renew. Energy Lab. U.S., Golden, CO, USA, Tech. Rep. NREL/TP-710-36774, 2005. [Online]. Available: http://www.osti.gov/bridge

[8] K. Y. Lau, M. F. M. Yousof, S. N. M. Arshad, M. Anwari, and A. H. M. Yatim, "Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions," *Energy*, vol. 35, no. 8, pp. 3245–3255, Aug. 2010.

[9] N. Y. Amponsah, M. Troldborg, B. Kington, I. Aalders, and R. L. Hough, "Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 461–475, Nov. 2014.

[10] Z. Li, H. Du, Y. Xiao, and J. Guo, "Carbon footprints of two large hydro-projects in China: Life-cycle assessment according to ISO/TS 14067," *Renew. Energy*, vol. 114, pp. 534–546, Dec. 2017.

[11] *HOMER Analysis*. Accessed: Mar. 3, 2019. [Online]. Available: https://analysis.nrel.gov/homer/

[12] T. lambert, P. Gilman, and P. Lilienthal, "Micropower system modeling with HOMER," *Nat. Renew. Energy Lab.*, vol. 1, no. 1, pp. 379–385, Apr. 2006.

[13] S. Mizani and A. Yazdani, "Optimal design and operation of a grid-connected microgrid," in *Proc. IEEE Elect. Power Energy Conf. (EPEC)*, Oct. 2009, pp. 1–6.

[14] D.-R. Thiam, "Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal," *Renew. Energy*, vol. 35, no. 8, pp. 1615–1623, Aug. 2010.

[15] M. Lee, G. C. Shaw, and V. Modi, "Battery storage: Comparing shared to individually owned storage given rural demand profiles of a cluster of customers," in *Proc. IEEE Global Humanitarian Technol. Conf. (GHTC)*, vol. 2, Oct. 2014, pp. 200–206.

[16] M. A. Kabir, A. S. M. M. Hasan, T. H. Sakib, and S. J. Hamim, "Challenges of photovoltaic based hybrid minigrid for off-grid rural electrification in Bangladesh," in *Proc. 4th Int. Conf. Adv. Electr. Eng. (ICAEE)*, vol. 2, Sep. 2017, pp. 686–690.

[17] B. Kroposki and G. Martin, "Hybrid renewable energy and microgrid research work at NREL," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–4.

[18] P. Diaz, C. A. Arias, R. Pena, and D. Sandoval, "FAR from the grid: A rural electrification field study," *Renew. Energy*, vol. 35, no. 12, pp. 2829–2834, Dec. 2010.

[19] S. Chakraborty and M. G. Simoes, "PV-microgrid operational cost minimization by neural forecasting and heuristic optimization," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2008, pp. 1–8.

[20] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renew. Energy*, vol. 45, pp. 7–15, Sep. 2012.

[21] C. Nayar, M. Tang, and W. Suponthana, "Wind/PV/diesel micro grid system implemented in remote islands in the Republic of Maldives," in *Proc. IEEE Int. Conf. Sustain. Energy Technol.*, Nov. 2008, pp. 1076–1080.

[22] M. Anyi, B. Kirke, and S. Ali, "Remote community electrification in Sarawak, Malaysia," *Renew. Energy*, vol. 35, no. 7, pp. 1609–1613, Jul. 2010.

[23] Y. Himri, A. B. Stambouli, B. Draoui, and S. Himri, "Techno-economical study of hybrid power system for a remote village in Algeria," *Energy*, vol. 33, no. 7, pp. 1128–1136, Jul. 2008.

[24] E. M. Nfah, J. M. Ngundam, M. Vandenbergh, and J. Schmid, "Simulation of off-grid generation options for remote villages in Cameroon," *Renew. Energy*, vol. 33, no. 5, pp. 1064–1072, May 2008.

[25] G. Bekele and B. Palm, "Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia," *Appl. Energy*, vol. 87, no. 2, pp. 487–495, Feb. 2010.

[26] E. Fernandez, M. J. Hossain, and M. S. H. Nizami, "Game-theoretic approach to demand-side energy management for a smart neighbourhood in Sydney incorporating renewable resources," *Appl. Energy*, vol. 232, pp. 245–257, Dec. 2018.

[27] M. N. Akter, M. A. Mahmud, and A. M. T. Oo, "A hierarchical transactive energy management system for energy sharing in residential microgrids," *Energies*, vol. 10, no. 12, p. 2098, Dec. 2017.

[28] Y. Liang, J. Su, B. Xi, Y. Yu, D. Ji, Y. Sun, C. Cui, and J. Zhu, "Life cycle assessment of lithium-ion batteries for greenhouse gas emissions," *Resour., Conservation Recycling*, vol. 117, pp. 285–293, Feb. 2017.

[29] M. A. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "Comparative life cycle environmental impact analysis of lithium-ion (LiIo) and nickel-metal hydride (NiMH) batteries," *Batteries*, vol. 5, no. 1, p. 22, Feb. 2019.

[30] V. Innocenzi, N. M. Ippolito, I. De Michelis, M. Prisciandaro, F. Medici, and F. Vegliò, "A review of the processes and lab-scale techniques for the treatment of spent rechargeable NiMH batteries," *J. Power Sour.*, vol. 362, pp. 202–218, Sep. 2017.

[31] T. Meng, K.-H. Young, D. F. Wong, and J. Nei, "Ionic liquid-based non-aqueous electrolytes for nickel/metal hydride batteries," *Batteries*, vol. 3, no. 1, p. 4, Feb. 2017.

[32] N. Espinosa, Y.-S. Zimmermann, G. A. dos Reis Benatto, M. Lenz, and F. C. Krebs, "Outdoor fate and environmental impact of polymer solar cells through leaching and emission to rainwater and soil," *Energy Environ. Sci.*, vol. 9, no. 5, pp. 1674–1680, 2016.

[33] C. E. L. Latunussa, F. Ardente, G. A. Blengini, and L. Mancini, "Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels," *Solar Energy Mater. Solar Cells*, vol. 156, pp. 101–111, Nov. 2016.

[34] A. Prasai, A. Paquette, Y. Du, R. Harley, and D. Divan, "Minimizing emissions in microgrids while meeting reliability and power quality objectives," in *Proc. Int. Power Electron. Conf. (IPEC)*, Jun. 2010, pp. 726–733.

[35] J. C. Bare, P. Hofstetter, D. W. Pennington, and H. A. Udo de Haes, "Midpoints versus endpoints: The sacrifices and benefits," *Int. J. Life Cycle Ass.*, vol. 5, pp. 319–326, Nov. 2009.

[36] M. A. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "A strategic impact assessment of hydropower plants in alpine and non-alpine areas of Europe," *Appl. Energy*, vol. 250, pp. 198–214, Sep. 2019.

[37] M. A. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "Environmental sustainability assessment of hydropower plant in europe using life cycle assessment," *IOP Conf.,, Mater. Sci. Eng.*, vol. 351, no. 1, May 2018, Art. no. 012006.

[38] M. A. P. Mahmud, N. Huda, S. H. Farjana, and C. Lang, "Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment," *Energies*, vol. 11, no. 9, p. 2346, Sep. 2018.

[39] N. jungbluth, M. Stucki, R. Frischknecht, S. Buesser, and R. I. Dones, "Ökoinventare von Energiesystemen Grundlagen für den ökologischen Vergleich von Energiesystemen undden Einbezug von Energiesystemen in Ökobilanzen für die Schweiz," ESU-services GmbH, Schaffhausen, Switzerland, Tech. Rep. 6-xii, 2010.

[40] M. Goedkoop, M. Oele, M. Vieira, J. Leijting, T. Ponsioen, and E. Meijer. (2014). *SimaPro Tutorial*, vol. 89. [Online]. Available: https://network.simapro.com/

[41] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, and R. van Zelm, "ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level," *Int. J. Life Cycle Assessment*, vol. 22, no. 2, pp. 138–147, Feb. 2017.

[42] J. C. Minx, M. Callaghan, W. F. Lamb, J. Garard, and O. Edenhofer, "Learning about climate change solutions in the IPCC and beyond," *Environ. Sci. Policy*, vol. 77, pp. 252–259, Nov. 2017.

[43] A. H. Sharaai, N. Z. Mahmood, and A. H. Sulaiman, "Life cycle impact assessment (LCIA) using the ecological scarcity (Ecopoints) method: A potential impact analysis to potable water production," *World Appl. Sci. J.*, vol. 11, no. 6, pp. 1077–1088, 2010.

[44] Z. Shi, H. Liang, S. Huang, and V. Dinavahi, "Distributionally robust chance-constrained energy management for islanded microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2234–2244, Mar. 2019.

[45] V. Sarfi and H. Livani, "An economic-reliability security-constrained optimal dispatch for microgrids," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6777–6786, Nov. 2018.

[46] A. A. Bashir, M. Pourakbari-Kasmaei, J. Contreras, and M. Lehtonen, "A novel energy scheduling framework for reliable and economic operation of islanded and grid-connected microgrids," *Electr. Power Syst. Res.*, vol. 171, pp. 85–96, Jun. 2019.

[47] A. M. Aly, A. M. Kassem, K. Sayed, and I. Aboelhassan, "Design of microgrid with flywheel energy storage system using homer software for case study," in *Proc. Int. Conf. Innov. Trends Comput. Eng. (ITCE)*, Feb. 2019, pp. 485–491.

[48] *NASA Surface Meteorology and Solar Energy*. Accessed: Mar. 3, 2019. [Online]. Available: http://eosweb.larc.nasa.gov/sse/

[49] R. Heijungs and J. B. Guineev, *An Overview of the Life Cycle Assessment Method-Past, Present, and Future*. Hoboken, NJ, USA: Wiley, 2012, ch. 2, pp. 15–41.

[50] A. Lewandowska, A. Matuszak-Flejszman, K. Joachimiak, and A. Ciroth, "Environmental life cycle assessment (LCA) as a tool for identification and assessment of environmental aspects in environmental management systems (EMS)," *Int. J. Life Cycle Assessment*, vol. 16, no. 3, pp. 247–257, Mar. 2011.

[51] J. Pryshlakivsky and C. Searcy, "Fifteen years of ISO 14040: A review," *J. Cleaner Prod.*, vol. 57, pp. 115–123, Oct. 2013.

[52] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H.-J. Klüppel, "The new international standards for life cycle assessment: ISO 14040 and ISO 14044," *Int. J. Life Cycle Assessment*, vol. 11, no. 2, pp. 80–85, Mar. 2006.

[53] P. Stavropoulos, C. Giannoulis, A. Papacharalampopoulos, P. Foteinopoulos, and G. Chryssolouris, "Life cycle analysis: Comparison between different methods and optimization challenges," *Procedia CIRP*, vol. 41, pp. 626–631, Jan. 2016.

[54] H. A. U. de Haes, "Methodology and LCA applications," *J. Cleaner Prod.*, vol. 1, nos. 3–4, pp. 205–206, Dec. 1993.

[55] R. Hischier, M. Classen, M. Lehmann, and W. Scharnhorst, "Life cycle inventories of electric and electronic equipment: Production, use and disposal," Swiss Federal Laboratories Mater. Sci. Technol., Dübendorf, Switzerlan, Tech. Rep. 18, 2017.

[56] J. Pascual-Gonzalez, G. Guillén-Gosálbez, J. M. Mateo-Sanz, and L. Jimenez-Esteller, "Statistical analysis of the ecoinvent database to uncover relationships between life cycle impact assessment metrics," *J. Cleaner Prod.*, vol. 112, pp. 359–368, Jan. 2016.

[57] R. Frischknecht and G. Rebitzer, "The ecoinvent database system: A comprehensive web-based LCA database," *J. Cleaner Prod.*, vol. 13, nos. 13–14, pp. 1337–1343, Nov./Dec. 2005.

[58] I. Boustead, "General principles for life cycle assessment databases," *J. Cleaner Prod.*, vol. 1, nos. 3–4, pp. 167–172, 1993.

[59] M. Marsmann and A. Schiburr, "Databases, software and LCA applications," *J. Cleaner Prod.*, vol. 1, no. 3, pp. 206–207, 1993.

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