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Midpoint Environmental Impact Assessments of Selected Microgrid Systems

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Abstract

This study compares life cycle assessment (LCA) profiles of solar and wind-based microgrid energy systems to assess their environmental performance. To this end, the OpenLCA software used data available in the ELCD 3.2 database. The analysis uses the ReCiPe 2016 Midpoint (E) approach to determine environmental impacts in 18 categories, considering the energy generation stages, upstream processes, raw material extraction, manufacturing, and component transport. The results show that the solar microgrid system outperforms the wind microgrid in most environmental impact categories. The global warming potential (GWP) of the solar microgrid is much less at 0.15311 kg CO_2 equivalent compared to 0.88678 kg CO_2 equivalent for the wind system. Similarly, the wind microgrid is characterized by higher values for categories such as fossil resource scarcity, particulate matter formation, and a variety of toxicity indicators, often 5–6-fold more than those of the solar system. An exception is registered in the category of scarcity of mineral resources, where the increased impact of the solar microgrid is documented, perhaps as a result of using resource-intensive materials in photovoltaic panels. Both systems demonstrate negative water consumption values, which are equivalent to net water savings compared to traditional grid-based generation. Nevertheless, the potential of water saving that is offered by the wind microgrid is only slightly higher. This comparative analysis gives essential insight into the sustainability of renewable microgrids, with a smaller environmental pawprint for solar-based systems. The results enable informed adoption decisions of clean distributed energy systems and confirm upstream material and technology decisions.

Keywords
Life Cycle Assessment (LCA), OpenLCA, ReCiPe 2016 Midpoint (E), Solar microgrid, Wind microgrid

1. Introduction
The rise of sustainable and resilient energy solutions has stimulated increased adoption of microgrids that unite conventional power sources with renewable solutions for nearby power creation needs. Research on microgrids' full-scale environmental and economic effects remains insufficient, although they offer improved energy reliability and efficiency. The assessment of microgrid sustainability requires Life Cycle Analysis (LCA) because it evaluates

environmental impacts, operating expenses, and energy usage throughout the entire system lifetime. Microgrid systems experience various stages from raw material extraction up to component production, followed by installation and maintenance before being disposed of. Multiple stages in microgrid development generate environmental consequences, which include carbon emissions, together with resource scarcity, and waste production. Industrial production of solar panels, along with battery storage units, demands extensive energy consumption during manufacturing, and recycling these systems at the end of life becomes complicated.

The global shift towards low-carbon energy systems has sped up the application of renewable energy technologies, especially decentralized systems such as microgrids. Microgrids provide a robust and scalable solution to electrification by including distributed energy resources such as solar and wind in localized energy infrastructure. Such systems are getting more applications in urban centers and remote communities where the connection to the centralized grids is minimal or erratic (Mill and Wiser 2012). Although renewable energy sources lower operational emissions, the life cycle impacts of those should not be considered insignificant. An LCA has a systematic framework to address these impacts of raw material extraction, manufacturing, and operation through end-of-life disposal or recycling ISO 14040 (2006). Today's studies place much emphasis on the importance of carrying out cradle-to-grave LCA in a bid to inform technology selection as well as policy decisions (Finkbeiner et al. 2006).

Upstream material processing and component manufacturing, as in the case of solar photovoltaic (PV) systems, for instance, can cause both great resource and toxicity impacts (Ardente et al. 2009). Likewise, wind turbines also contain significant embedded energy and material input, especially when it comes to constructing towers and blades (Vestas, 2016). Even though they are increasingly being adopted, there are limited comparisons of solar and wind microgrids' environmental profiles using harmonized datasets and approaches. The current study fills the research gap by performing comparisons of LCA of solar and wind-based microgrids with the use of the ELCD 3.2 database and ReCiPe 2016 Midpoint (E) method in OpenLCA. The goal is to quantify and interpret the environmental trade-offs for each unit of electricity delivered, which in turn shall guide the stakeholders to choose sustainable microgrid technologies.

A comprehensive environmental analysis needs to be completed because the development of the lifecycle of both solar and wind microgrids includes material extraction steps manufacturing emissions, and end-of-life disposal concerns. The research value stems from its implementation of the ReCiPe 2016 Midpoint (E) method through the OpenLCA framework to perform advanced LCAs of solar and wind microgrids. The study delivers essential knowledge to help decision-makers in government and engineering, as well as energy planning authorities, create smarter choices toward sustainable low-carbon infrastructure.

1.1. Objectives

The main goal of this study is to conduct a comparative environmental analysis of two renewable energy-based micro-grid systems, viz, solar photovoltaic (PV) and wind turbine, based on the LCA methodology. Although both technologies are widely used in distributed power (DP) generation, their life cycle environmental burdens differ substantially depending on materials, manufacturing, efficiency, and end-of-life. This study is intended to offer a clear understanding of these impacts as regards several environmental categories.

Specifically, the study seeks to estimate life cycle environmental comparisons between solar and wind microgrids in terms of kWh of power supplied to the end-user. It employs the ELCD 3.2 database in the OpenLCA software environment to simulate energy systems with the help of high-quality European life cycle inventory (LCI) data. Then it uses the ReCiPe 2016 Midpoint impact assessment method to assess 18 impact categories such as the global warming potential, fossil resource scarcity, toxicity, ecotoxicity, acidification, and water consumption. Afterward, it estimates the main impact of contributors and trade-offs between the two types of microgrids. This study offers evidence-based insights to guide policymakers, energy planners, and sustainability analysts in microgrid technologies with environmentally sustainable choices appropriate in different geographic and climatic conditions.

2. Literature Review

2.1. Solar Microgrid Systems

Several studies have been conducted on the environmental effects of solar microgrids that look at some of the phases of the life cycle. Bilich et al. (2017) evaluated solar PV microgrids in off-grid Kenya communities and reported drastic reductions in CO_2 emissions and particulate matter over diesel generators, highlighting the need for system configuration and battery integration. Badza et al. (2024) carried out an LCA of an independent PV system in Burkina Faso, showing that the primary environmental impact resulted from the manufacturing of batteries used in the system and end-of-life disposal, demonstrating the importance of recycling and material efficacy in PV systems. Viole et al. (2024) compared hybrid energy systems such as PV systems and concluded that the environmental effects were highly dependent on the system's spatial location and the quality of the energy storage technologies assimilated into the microgrid. In the context of developing countries, Minas et al. (2024) enlightened the role of solar microgrids towards attaining Sustainable Development Goals (SDGs) through reliable energy access with minimal environmental degradation. Furthermore, Mansour et al. (2024) examined the PV–diesel hybrid systems, finding that PV components account for greater initial manufacturing impacts, but over time, the entire system operates better, environmentally speaking, because of its lower operation emissions. This environmental threat related to the informal disposal of PV systems in Malawi was treated by Kinally et al. (2024), who proposed improved PV systems disposal practices to shrink the ecological impact of solar systems.

2.2. Wind Microgrid Systems

The impacts of wind microgrids have also been studied recently. Carallo et al. (2024) observed the difference between traditional and advanced sustainable wind blades and discovered that the environmental advantages of new materials are enormous in manufacturing and end-of-life stages. On the same note, Yang et al. (2024) reviewed the LCA studies on the production of wind energy and stated that the human impact of wind turbines is most significant at the stage of their production and assembly, especially for materials utilized in constructing towers and producing turbine blades. A comparative analysis of the combined electro-thermo-chemical technologies' performance and that of the traditional battery storage for wind microgrids was carried out by Diskin et al. (2024). Accordingly, innovative energy storage methods may help alleviate the environmental effects of wind energy production. The authors, Ghasemi et al. (2023), utilized a multi-objective optimization approach to assess wind microgrids and proved that the wind systems could create significant environmental impacts once mated to efficient energy storage solutions. What's more, Huber et al. (2023) identified the necessity to integrate wind energy into decentralized energy systems in Belgium, so that wind microgrids can offer clean solutions when connected to efficient, flexible energy management systems. A hybrid PV–battery system was evaluated in Brazilian Indigenous communities by Costa et al. (2023), which demonstrated the prospect of wind microgrids in remote areas with limited access to the grid, arguing for their economic feasibility and sustainability.

2.3. Environmental Impacts of Hybrid Energy Systems

Environmental performance is being examined in hybrid energy systems that combine solar and wind energy. Bai et al. (2023) performed an LCA of a hybrid PV-wind system, pointing out that the environmental gains of such systems can be realized when they are combined with advanced storage units such as lithium-ion batteries. They also identified that the hybrid approach helps to lower emissions compared to conventional diesel generators. In addition, Su et al. (2024) conducted LCA of hybrid systems using solar, wind, and biomass; the study revealed that biomass could help mitigate environmental impacts, especially in areas where energy access is a problem, like in remote areas. Liu et al. (2023) investigated hybrid solar wind microgrids in China, and they determined that both renewable energies have lower emissions compared to fossil fuels; nonetheless, when integrating wind power, there were higher impacts related to land use as well as resource consumption during the manufacturing process. Likewise, Jones et al. (2023) examined the hybrid systems in the U.S. and concluded that the optimization of energy management strategies could reduce the carbon footprint and enhance the sustainability of the systems. Further, a research study by Wang et al. (2024) also revealed that introducing wind turbines to an existing solar microgrid may increase energy reliability, decrease operational costs and environmental effects in specific geographical areas.

2.4. Technological Advancements in Microgrid Design

Technological developments in microgrid control systems are very important in improving the environmental sustainability of hybrid systems. Based on the importance of advanced control strategies, Zhang et al. (2024) noted their ability to reduce the life cycle environmental impacts of wind and solar microgrids, especially in areas with varying weather. In addition, the use of artificial intelligence in optimizing the operation of wind-solar microgrids was studied by Hwang et al. (2024), and it was established that machine-learning techniques can minimize losses of energy and enhance the overall sustainability of the system. Nguyen et al. (2023) have revealed that energy storage systems are vital in the reduction of the life cycle environmental impacts of wind-solar hybrids. According to their findings, the extensive incorporation of long-duration storage solutions can remarkably reduce the carbon footprint during the lifetime of the microgrid.

2.5. Synthesis and Research Gap

- Review how existing studies were done and their shortcomings.
- Understand how to plug those gaps with standard tools and data (OpenLCA, ELCD 3.2, ReCiPe 2016 Midpoint (E), per-kWh unit).
- Introduce the originality of examining the two energies (solar and wind) within microgrids via the same assessment parameters.

3.Methods

The methodology to be used in this study entails a comprehensive LCA for solar and wind microgrids using the OpenLCA software and the ELCD 3.2 database. The sequence of steps below illustrates the method of evaluating the environmental impacts of solar and wind microgrids:

3.1 Goal and Scope Definition:

The scope of this study is to assess the environmental impacts of solar and wind microgrids in terms of their entire lifecycle, from their production and decommissioning. The study is intended to measure the effects on the different categories of the environment, including global warming, freshwater ecotoxicity, human toxicity, and resource scarcity, to compare the two energy generation technologies. The functional unit selected for this study is 1000 kWh of electricity produced by each of the microgrids. The system boundaries that are considered in this LCA include raw material extraction, manufacturing of components (for example, solar panels, wind turbines, inverters, and batteries), installation, operations, and disposal at the end of life. The impact assessment will apply the ReCiPe 2016 midpoint (E) method that classifies the environmental impact of the microgrids into several impact categories.

3.2 Inventory Analysis (Life Cycle Inventory – LCI)

The LCI stage comprises data collection on all inputs (materials, energy, water, etc.) and outputs (emissions, waste, etc.) connected with the microgrid systems. The database used in the study is ELCD 3.2 (ELCD_3_2_Greendelta_v2_18_correction_20220908.zolca) from which information about the materials and processes involved in solar and wind microgrid construction and operation is extracted. This database gives detailed information about energy production, transport, and waste management for both renewable energy technologies.

3.3 Impact Assessment

Following the inventory analysis, the systems' environmental impacts are determined using the ReCiPe 2016 midpoint (E) method. In this approach, we have a set of mid-point indicators for different categories of the environment, as given below:

Global Warming Potential (GWP): Measured in CO_2 equivalents (kg CO_2 eq), the contribution of the system to global warming due to the emission of greenhouse gases (GHGs) is quantified.

Human Toxicity: In 1,4-DCB equivalents (kg 1,4-DCB eq), this category considers the potentially harmful impacts of pollutants on humans.

Freshwater Ecotoxicity: This evaluates the toxicity of pollutants in freshwater ecosystems in terms of 1,4-DCB equivalents (kg 1,4-DCB eq).

Fossil Resource Scarcity: In kg oil eq, this category assesses the depletion of fossil fuel resources from energy generation activities.
Other classes, namely ionizing radiation, marine eutrophication, and terrestrial acidification, are also used to assess the environmental implications of the two forms of energy technologies**.**
Table 1 indicates the primary life stage or event that influences each impact category the most, by using common LCA sources and the ELCD 3.2 and ReCiPe 2016 Midpoint (E) frameworks.

Table 1. Key processes or stages that contribute to each environmental impact category, are referenced from ELCD 3.2 and ReCiPe midpoint indicators.

Impact Category	Dominant Contributor - Solar	Dominant Contributor - Wind
Fine particulate matter formation	Panel manufacturing (high-temp processes)	Concrete and steel production
Fossil resource scarcity	Inverter and transport emissions	Heavy transport of turbine components
Freshwater ecotoxicity	Panel coatings and etching chemicals	Generator oils and lubricant leaks
Freshwater eutrophication	Silicon purification and cell production	Steel fabrication waste
Global warming	PV module production (aluminum, silicon)	Cement, steel, and transport
Human carcinogenic toxicity	Semiconductor processing chemicals	Epoxy resins and rare earth extraction
Human non-carcinogenic toxicity	Battery production (Li-ion)	Generator manufacturing (copper, magnets)
Ionizing radiation	Electricity mix in the manufacturing phase	Grid energy during maintenance
Land use	Negligible	Negligible
Marine ecotoxicity	Disposal of PV materials	Lubricant and composite material leaching
Marine eutrophication	Cell processing effluents	Manufacturing process water discharge
Mineral resource scarcity	Silver and indium in solar cells	Steel and aluminum for towers
Ozone formation (Human Health)	Energy-intensive furnace steps	NOx from concrete production
Ozone formation (Terrestrial)	Chemical vapor deposition (CVD)	Diesel transport and concrete curing
Stratospheric ozone depletion	Use of fluorinated gases in PV	Insulation gases in turbine electronics
Terrestrial acidification	Aluminum and glass production	Steel production and logistics emissions
Terrestrial ecotoxicity	Cadmium and lead traces in panels	Composite materials and heavy metals
Water consumption	Silicon wafer cutting and cleaning	Concrete mixing and cooling needs

3.4 Software and Tools

The OpenLCA software is used to conduct the LCA, and it is a powerful tool for life cycle assessment, which allows highly detailed study and modeling of environmental impacts. The ELCD 3.2 database is also coupled into the software for obtaining correct process data that can be used to model the life cycle stages of both solar and wind microgrid systems.

3.5 Assumptions for Lifetime and Efficiency Loss

Each microgrid system's output was normalized to 1000 kWh, representing the total electricity it can provide during its entire operational period. We collected these values by examining research articles and data provided by manufacturers, concluding that solar panels would last approximately 25 years and wind turbines up to 20 years. These data were used to make sure the system generates power effectively over its long-term life. This means that the environmental impacts reported per 1000 kWh match the regular behavior of each technology, so they can be similarly compared.

4.Data Collection

Data for this life cycle assessment were obtained using the ELCD 3.2 database on the OpenLCA software. The database offers a validated life cycle inventory for energy systems, materials, production, transport, and end-of-life treatment procedures. Some of the specific components represented include solar panels, wind turbines, inverters, batteries, support structures, and terminating grid connections. The scope of the system boundaries stretches a cradle-to-grave view, incorporating the raw material extraction phase, production, installation, operation, maintenance, and disposal phases. All background data were extracted directly from the ELCD datasets, while the estimation of lifetime (20–25 years), efficiency, and capacity were taken from literature and manufacturer specifications. An amount of 1000 kWh of the generated electric power was taken as a function unit to make relevant comparisons of the microgrid systems for solar and wind sources.

5.Results and Discussion

The life cycle assessment results achieved by OpenLCA and the ReCiPe 2016 midpoint €method provide a complete comparison of the impacts on the environment of solar and wind microgrids. The impacts are normalized to a functional unit of 1000 kWh of electricity production, thus providing fair and comparable results. The results indicate a reduced impact on the environment for the solar microgrid relative to the wind microgrid, except for the mineral resource scarcity parameter, which the wind microgrid does better. The primary contributors to additional wind system impacts are (among others) the construction of wind turbines, e.g., in terms of material intensity (steel, concrete, or rare earths for generators) and energy inputs for operational maintenance in remote areas. A summary table of the impact assessment's results is outlined below.

Bar charts representing the disparities between the values of the global warming potential and the level of human toxicity, which are two of the most important impact categories in renewable energy life cycle assessments, have been created, as shown in Figure 1. The global warming potential of the wind microgrid is much higher (0.88678 kg CO_2 eq/kWh) than the solar microgrid (0.15311 kg CO_2 eq/kWh). The major reason for this will be the carbon-intensive materials and methods involved in building and maintaining the wind turbines. Solar microgrids have simpler infrastructure and produce relatively fewer operational emissions, thus making them more climate-friendly in generating units of electricity.

Table 2. Life Cycle Environmental Impacts per kWh of Electricity Generated

Impact categories	**Unit**	**Solar Microgrid Generation**	**Wind Microgrid Generation**
Fine particulate matter formation	kg PM2.5 eq	0.00020	0.00107
Fossil resource scarcity	kg oil eq	0.04073	0.23337
Freshwater ecotoxicity	kg 1,4-DCB	1.70372E-5	9.71541E-5
Freshwater eutrophication	kg P eq	6.23058E-7	3.17762E-6
Global warming	kg CO2 eq	0.15311	0.88678
Human carcinogenic toxicity	kg 1,4-DCB	0.00116	0.00598
Human non-carcinogenic toxicity	kg 1,4-DCB	0.46576	2.53289
Ionizing radiation	kBq Co-60 eq	0.03259	0.17443
Land use	m2a crop eq	0.00000	0.00000
Marine ecotoxicity	kg 1,4-DCB	0.29729	1.68905
Marine eutrophication	kg N eq	3.02463E-6	1.76086E-5
Mineral resource scarcity	kg Cu eq	0.03407	0.02014
Ozone formation, Human health	kg Nox eq	0.00026	0.00138
Ozone formation, Terrestrial ecosystems	kg Nox eq	0.00027	0.00139
Stratospheric ozone depletion	kg CFC11 eq	4.84501E-8	2.96982E-7
Terrestrial acidification	kg SO2 eq	0.00068	0.00365
Terrestrial ecotoxicity	kg 1,4-DCB	0.10096	0.55264
Water consumption	m3	-0.00023	-0.00122

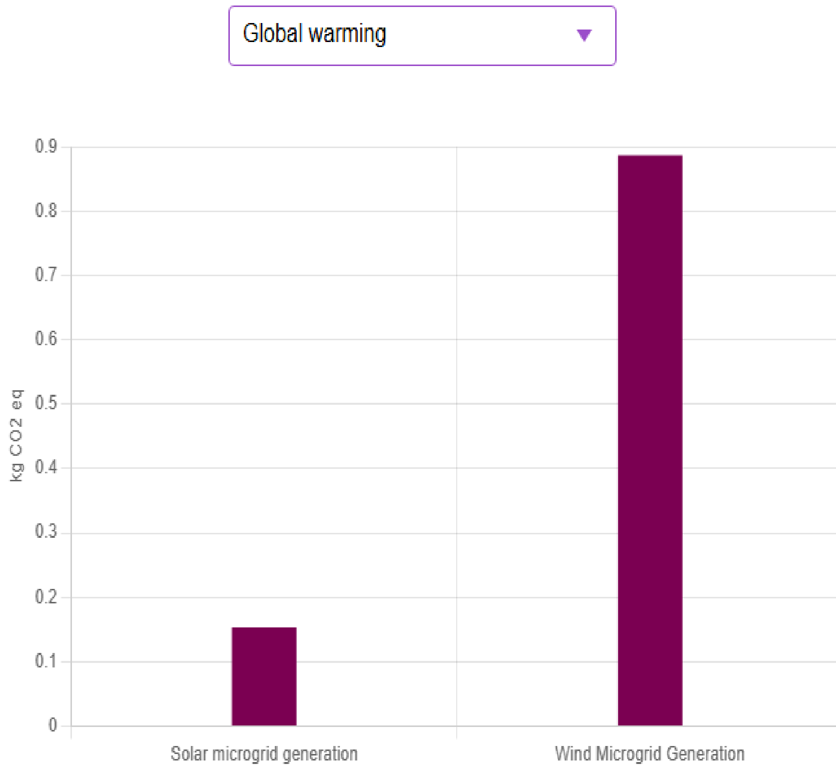

Figure 1. Global Warming Potential (kg CO_2 eq/kWh). The wind microgrid has a greater global warming potential (0.88678 kg CO_2 eq/kWh) than the solar microgrid (0.15311 kg CO_2 eq/kWh), mostly because using turbines involves so much energy and low-grade materials.

Figure 2 shows the comparison of Human non-carcinogenic toxicity between the solar microgrid and the wind microgrid. In this category, the wind microgrid has had considerably more non-carcinogenic toxicity compared to the solar microgrid. For the wind, the microgrid records 2.53289 kg 1,4-DCB eq/kWh, for the solar microgrid it is recorded at 0.46576 kg 1,4-DCB eq/kWh. This means that the contribution of the wind system to the burden on human health is more than fivefold compared to the solar system. Figure 3 shows the comparison of freshwater ecotoxicity between Solar Microgrid and Wind Microgrid. The freshwater ecotoxicity impact of the wind microgrid (9.72105E-5 kg 1,4-DCB eq/kWh) is much higher than the solar microgrid (1.70105E-5 kg 1,4-DCB eq/kWh). This category relates to the possible damage to aquatic organisms due to toxic emissions throughout the life cycle. The high magnitude of impact in wind systems is primarily attributed to the emissions from metal processes, composite materials, and lubricant turbine components.

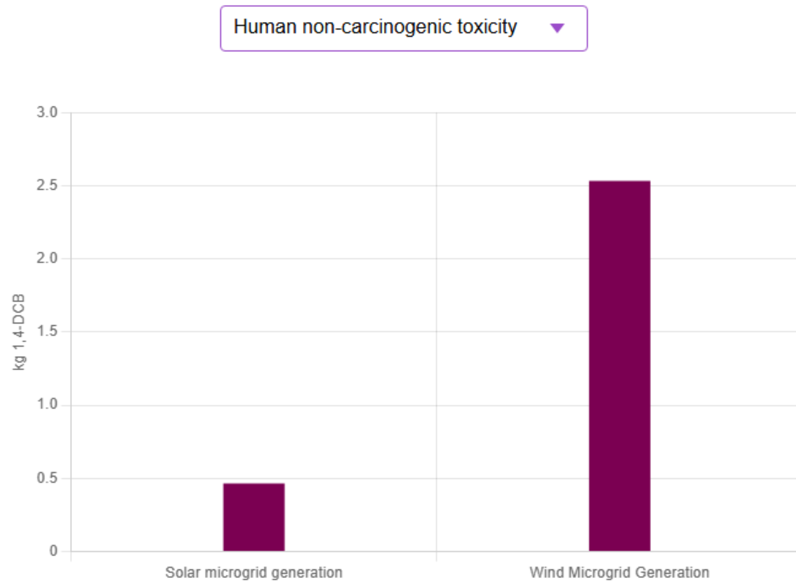

Figure 2. Human Non-Carcinogenic Toxicity (kg 1,4-DCB eq/kWh). Solar microgrids cause less noncarcinogenic toxic effects (0.46576 kg 1,4-DCB eq/kWh) than wind microgrids (2.53289 kg 1,4-DCB eq/kWh).

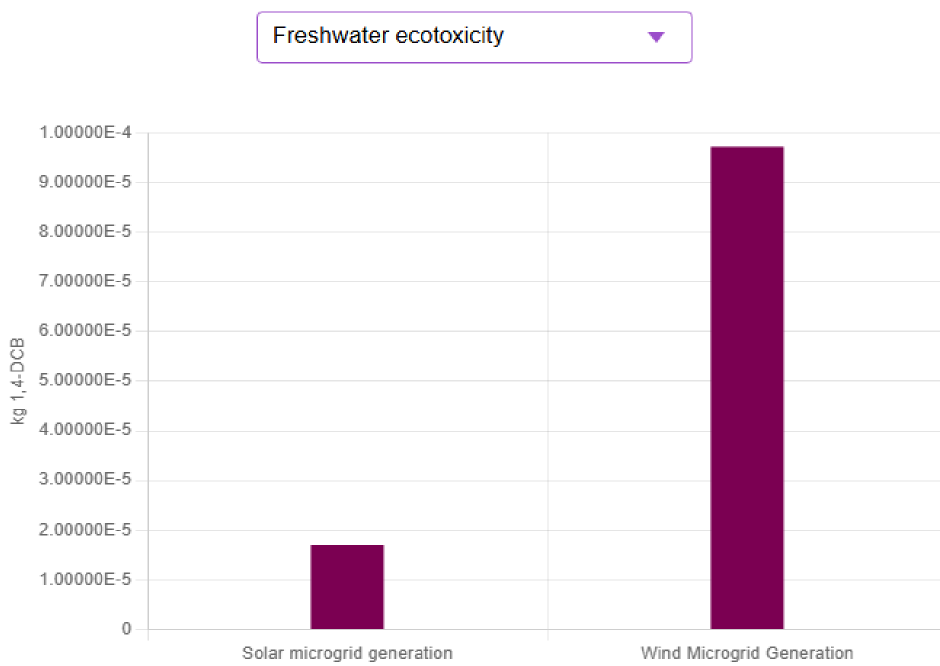

Figure 3. Fresh Water Ecotoxicity (kg 1,4-DCB). Wind systems cause much more freshwater ecotoxicity impacts (9.72105E-5 kg 1,4-DCB eq/kWh) compared to solar systems (1.70105E-5 kg 1,4-DCB eq/kWh), largely due to emissions related to metal processing, composite materials, and lubricating wind turbines.

5.Conclusion

This study reported a comparative LCA of solar and wind microgrid systems with the use of the ELCD 3.2 database within the OpenLCA software framework; the ReCiPe 2016 midpoint (E) impact assessment method was applied. The analysis captured a variety of environmental impact categories that allowed for an all-around assessment of both systems based on a per kWh basis of electricity generation. The results show that the solar microgrid is always superior to the wind microgrid in most environmental indices like global warming potential, human toxicity (carcinogenic and non-carcinogenic), formation of fine particulate matter, freshwater and marine ecotoxicity, and fossil resource scarcity. The wind microgrid reflects significantly more impacts, primarily because of materials-intensive components such as steel, concrete, rare earth elements, or complex maintenance. But, when it comes to mineral resource scarcity, the impact of the wind system is less, meaning that the solar PV modules can have a heavier mark on the material extraction footprint, especially with silicon and silver elements. While both systems are renewable and are less adverse as compared to fossil-powered generation, the solar microgrid shows better environmental performance, thus making it a better sustainable option for small-scale and distributed energy systems. These findings are extremely instructive for policymakers, engineers, and energy planners who intend to implement low-impact energy systems. Future studies may consider dynamic LCA modeling throughout systems' lifecycles, regional variations in the supply chains, and more efficient recycling and circular economy habits. Overall, the incorporation of LCA in design and planning levels can inform the selection of cleaner technologies and the actual transition to sustainable energy. This study did not include a detailed sensitivity analysis. But this issue is recognized as a drawback. Further work will consider how sensitive results are to alternative assumptions on lifespans, materials, and supply chain options.

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Biographies

Aravind Sanikommu is currently pursuing a Master of Science in Electrical Engineering, building on a strong foundation in electronics, embedded systems, and software engineering. Before starting my graduate studies, he gained 1.6 years of industry experience as a Software Engineer specializing in Advanced Driver Assistance Systems (ADAS) testing, where he contributed to the development and validation of safety-critical automotive technologies. Before entering the workforce, Aravind completed a 6-month certification course in Embedded Systems Engineering, which enhanced his practical skills in microcontrollers, embedded C, and real-time operating systems. Aravind's academic journey began with a Bachelor of Technology in Electronics and Communication Engineering (2017–2021), where he developed a solid grounding in circuit design, signal processing, and communication systems. Before Aravind's undergraduate studies, he completed two years of Intermediate education (2015–2017) with a concentration in Mathematics, Physics, and Chemistry (MPC). Aravind completed his Class 10 education in 2015. Aravind's diverse academic and professional experiences have fuelled a passion for intelligent systems and sustainable technology, with current interests in smart grids, control systems, and AI-based energy solutions.

Dr. Hossain joined as a faculty member of Arkansas State University in 2012 and serves as a Professor of Civil Engineering. His research interests include energy conservation, recycling, nano- and bio-modifications, and intelligent system design of geotechnical and transportation materials for pavement applications. He is also a member of an interdisciplinary research team at the Centre for Efficient and Sustainable Use of Resources. Dr. Hossain focuses on the development and characterization of innovative geotechnical (stabilized subgrades and aggregates) and asphalt pavement materials and green technologies that will safeguard the environment and facilitate the building of longer-lasting pavements. Besides mechanistic performance evaluation, Dr. Hossain is interested in surface science and analytical chemistry (i.e., spectroscopy) approaches to evaluate these materials. Furthermore, Dr. Hossain is interested in constitutive modeling, data mining and visualization, neural network modeling, lean construction, and molecular dynamics simulation of pavement materials. Dr. Hossain also holds a "Green Belt" certification in Lean and Six/Sigma from the University of Oklahoma. Dr. Hossain is a recipient of the President's Gold Medal from Khulna University of Engineering and Technology for his outstanding performance in his undergraduate studies.