Life Cycle Carbon Footprint Assessment of Renewable Energy Technologies Across Different Geographic Region

Dr.Shikha Sharma1, Dr.Sunil Kumar Vohra 2

[1] Lincoln University ; Adjunct Research Faculty , Lincoln Global Postdoctoral Researcher Programme [2]

Email ID – pdf.shikhasharma@lincoln.edu.my , sunilvohra2002@yahoo.co.in

Abstract

The shift to renewable energy is key to carbon neutrality and climate change mitigation. While renewable energy sources produce far fewer greenhouse gas (GHG) emissions when generating electricity than fossil fuels, a life-cycle approach is required to fully understand the environmental impact of renewable energy. This study analyzes the life cycle carbon footprint of Solar Photovoltaic (PV), Onshore Wind and Biomass energy systems in various geographical regions, by applying the Life Cycle Assessment (LCA) methodology according to the ISO 14040/44 standards. The assessment follows a cradle-to-grave approach that includes raw material extraction, manufacturing, transportation, installation, operation, maintenance and end-of-life management. The study also investigates how the regional electricity mix, manufacturing processes, supply chain properties, resource access, and recycling facilities impact overall emissions. To assess important regional differences and emission drivers, a comparative statistical tool with descriptive statistics is suggested. The proposed framework offers a science-based tool for policymakers, researchers and industry to optimize renewable energy deployment and minimize life cycle carbon emissions that facilitates sustainable energy transitions.

Keywords: Life Cycle Assessment, Carbon Footprint, Renewable Energy, Solar PV, Wind Energy, Biomass, Sustainability, Geographic Variation.

1. Introduction

Climate change has become one of the great environmental challenges of the 21st century, largely as a result of emissions of greenhouse gasses (GHGs) from fossil fuel energy systems. The global drive towards Net Zero emissions and the Sustainable Development Goals (SDGs) has increased investment in renewable energy technologies, including solar photovoltaic (PV), wind, and biomass. These technologies emit virtually nothing during operation, but they do have environmental impacts during the extraction of raw materials, production, transportation, installation, maintenance, and at the end of the life when disposed of.

Life Cycle Assessment (LCA) is a new tool for assessing environment impacts along the entire life cycle of energy technologies. LCA includes not only the operational emissions, but also the emissions embedded in the manufacture, supply chain and recycling processes. Renewable energy technologies have consistently been found to have significantly lower life cycle GHG emissions than coal and natural gas generation, in previous studies. But there are significant geographical differences, as the carbon intensity of the energy used to make energy sources, the distance of transport and the availability of local resources, electricity grid and recycling infrastructure vary widely across regions.

Although a significant amount of research has been done on renewable energy technologies, very few studies have considered comparative analysis combining geographical factors with statistical analysis. The majority of current research does not systematically consider regional factors to influence carbon performance, but rather focuses on single technologies or single regions. Thus this study aims to create a comparative LCA model for characterizing the Solar PV, Wind and Biomass technologies over different geographical regions and to establish a statistical evaluation model for the identification of the major determinants in the life cycle of carbon emissions. The results will be used for sustainable energy planning, low carbon production, and policy making with evidence.

2. Research Objectives

The study aims to:

1. Calculate carbon footprints of Solar PV, Wind and Biomass energy systems throughout their life cycle.

2.Assess the impact of carbon intensity of the electrical grid, manufacturing process, transportation and resource availability on lifecycle emissions.

3. Literature Review

Life Cycle Assessment Methodology

Life Cycle Assessment (LCA) is considered to be one of the most powerful tools for assessing the environmental impacts of products, processes and technologies throughout their entire life cycle. LCA provides a structured method to consider environmental impacts throughout the entire life cycle, from raw material acquisition to manufacture, transport, use, maintenance and disposal (ISO, 2006). The environmental impacts in an electricity generating system are usually measured per kilowatt-hour (kWh) of electricity generated. Greenhouse gas emissions are usually estimated in terms of grams of CO_2e/kWh for different energy technologies (UNECE, 2021). One of the major benefits of LCA is its ability to capture emissions resulting from the end-of-life phases. Renewable energy technologies produce relatively little or no pollutants as they are used to produce electricity, but they can have significant environmental impacts at the production, installation, transport and waste stages. Thus, LCA offers a more comprehensive perspective on sustainability than assessments that focus solely on operational emissions do (Hampo et al., 2022).The methodological choices, however, such as system boundaries, allocation procedures, data quality and geographic assumptions, have an impact on LCA results. The differences in these parameters can cause differences in calculated carbon footprints, and it is important to standardize these parameters to improve the comparability between studies (Gao et al., 2021). There are many studies that demonstrate that the carbon footprint of renewable energy technologies is much smaller than the carbon footprint of traditional electricity systems based on fossil fuels. The Intergovernmental Panel on Climate Change (IPCC) offers harmonized assessments of the carbon footprints of the main electricity generation technologies, which show that wind energy has the lowest carbon footprint in its life cycle, followed by biomass energy and solar photovoltaic (PV) systems (IPCC, 2014). The typical range of wind energy LCE for wind energy is between 7 and 38 gCO_2e/kWh, with the primary sources of emissions being the steel production, concrete foundations and manufacturing of the wind turbines. The emissions associated with solar PV typically range from 20 to 100 gCO_2e/kWh, with the production activities that involve manufacturing, such as the silicon purification and module assembly, accounting for a significant proportion of the total emission (IPCC, 2014; Hampo et al., 2022).The carbon footprint is more variable for biomass energy as emissions can be significantly affected by the type of biomass, its cultivation method, distance of transport and the technologies employed to produce the energy. Emissions are known to be between approximately 40 gCO_2e/kWh and over 120 gCO_2e/kWh, particularly if land-use change and agricultural inputs are included (Gao Gao et al., 2021).

Despite these differences, renewable energy technologies are still outperforming fossil fuel-based technologies. The emissions from coal fired electricity generation range between 800 and 1200 gCO_2e per kWh, while the emissions from natural gas systems range from 400 to 500 gCO_2e per kWh over the carbon cycle (IPCC, 2014). This results shows the significant climate mitigation potential of renewables technologies.

The impact of Geography and Supply Chains on Carbon Footprints.

New research reveals the geographical and chain of supply dimensions that can have a strong influence on environmental impacts of renewable energy technologies. One of the most key impacts on a technology's embodied carbon footprint is the carbon intensity of the electricity required for the production process. For example, solar panels that are produced in regions where there is a high reliance on coal-fired power would generally have a higher LCO than would be the case if they were produced using a source of low carbon power such as hydropower, wind power, or nuclear power (Montel Energy, 2025).

Resource availability is also a great determinant of environmental performance. The lower emissions per unit of electricity generated by solar PV systems are due to the fact that these systems generate more electricity over their useful life in regions with high solar PV irradiance. Likewise, wind turbines situated in regions with robust and steady wind resources attain greater capacity factors, resulting in reduced life cycle emissions (MDPI Energies, 2025).

Differences in regional carbon footprints are also attributable to transportation and logistics. Renewables equipment is often manufactured in sites away from where it is taken. It has been found that implementing local production and using local value chains has significant impacts to reduce these effects and promote overall sustainability (The Climate Center, 2024).

End-of-life processes are an emerging concern. It is possible to recover valuable materials such as aluminum, silicon, silver and steel from waste by designing a good recycling system, which will help to reduce the need for extracting raw materials and reduce the impact on the environment. However, the infrastructure for recycling solar panels and wind turbine components is still not available in many parts of the world (MDPI Energies, 2025)

Overall, the literature confirmed that sustainability of the renewable energy technologies is not only related to the technology itself but also to the geographical, economic and infrastructural environment in which the technology is produced, installed and operated.

Table 1.1 The carbon footprints can be supported using harmonized Life Cycle Assessment (LCA) values published by the **Intergovernmental Panel on Climate Change (IPCC)** and the **United Nations Economic Commission for Europe (UNECE)**.

Renewable Energy Technology	Median Life Cycle Carbon Footprint (gCO_2e/kWh)	Typical Range (gCO_2e/kWh)	Source
Solar Photovoltaic (PV)	48	18–180	IPCC (2014); UNECE (2021)
Onshore Wind	12	7–38	IPCC (2014); UNECE (2021)
Biomass	230*	35–230+ (technology and feedstock dependent)	IPCC (2014); UNECE (2021)

Table 1.2 Assess the impact of carbon intensity of the electrical grid, manufacturing process, transportation and resource availability on lifecycle emissions.

Variable	Evidence	Source
Electricity Grid Carbon Intensity	Manufacturing PV modules using coal-intensive electricity substantially increases embodied carbon compared with manufacturing in regions with cleaner electricity grids.	UNECE (2021); IPCC (2014)
Manufacturing Process	Silicon purification and wafer production account for approximately **45–70%** of the total life cycle emissions of crystalline silicon PV systems.	Hsu et al. (2012); IEA PVPS (2022)
Transportation	Long-distance transportation contributes approximately **2–10%** of total lifecycle emissions depending on transport mode and distance.	Ecoinvent Database; Gao et al. (2021)
Resource Availability	Higher solar irradiance and higher wind capacity factors reduce lifecycle emissions per unit of electricity because more electricity is generated over the system lifetime.	UNECE (2021); NREL (2021)

4. Benefits and Key Areas of Study

The study adds to the research on Renewable energy by combining LCA and geographical and statistical analysis. The results can help guide policy development towards environmentally friendly renewable energy technologies in various regions, as well as help industry mitigate emissions from production and optimise supply chain sustainability. The study also helps to sustainable development by encouraging practices of circular economy and better recycling.

5. Methodology

A quantitative comparative research design is used, with the secondary data generated from internationally recognized databases such as IPCC, UNECE, IEA, Ecoinvent, GaBi, SimaPro and published peer-reviewed literature. Assessment carried out in accordance with ISO 14040/14044 in a cradle to grave system boundary.

The study compares the three renewable energy technologies in five geographical regions – North America, Europe, Asia-Pacific, Africa and Latin America. It is evaluated in 1 kWh of electricity produced, which enables the comparison of the different technologies.

The following life cycle stages are taken into account:

- Raw material extraction
- Component manufacturing
- Transportation
- Installation
- Operation and maintenance
- Decommissioning
- Recycling and disposal

The main variables are: lifecycle carbon emissions (gCO_2e/kWh), electricity grid carbon intensity, transportation distance, manufacturing emissions, resource availability, capacity factor, and recycling rates.

Methods of data collection and sample size.

A structured secondary dataset is used for the study with three renewable energy technologies (RETs) evaluated for seven lifecycle stages across five geographical regions. Data are sourced from internationally recognized LCA databases, energy agencies and published literature. Data preprocessing involved validation, normalisation, data deduplication and standardisation of the data in carbon emission units (gCO_2e/kWh).

6. Statistical Evaluation Framework

The suggested analytical framework is the integration of Life Cycle Assessment and the use of statistical analysis to assess the regional variations in carbon performance of the renewable energy.

7. Conclusion

A comprehensive life cycle assessments of Solar PV, Wind and Biomass energy system life cycle carbon footprints is presented for different geographical regions. The proposed framework incorporates Life Cycle Assessment and statistical evaluation, which allows for an appropriate comparison of renewable energy technologies that also considers regional differences in resource availability, electricity generation, transportation and manufacturing.

References

1. C. Gao, Y. Zhang, H. Wang, and X. Li, "Comprehensive comparison of multiple renewable power generation methods: A combination analysis of life cycle assessment and ecological footprint," Renewable and Sustainable Energy Reviews, vol. 147, Art. no. 111255, 2021. https://doi.org/10.1016/j.rser.2021.111255

2. C. C. Hampo, M. Rodriguez, and J. Silva, "Life cycle assessment of renewable energy technologies," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2022. (Verify volume, issue, pages, and DOI before submission, as this citation could not be independently verified.)

3. Intergovernmental Panel on Climate Change (IPCC), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, U.K.: Cambridge University Press, 2014.

4. International Organization for Standardization (ISO), ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland: ISO, 2006.

5. International Organization for Standardization (ISO), ISO 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Geneva, Switzerland: ISO, 2006.

6. "Renewable Energy and CO_2 Emissions: Analysis of the Life Cycle and Impact on the Ecosystem in the Context of Energy Mix Changes," Energies, vol. 18, no. 13, Art. no. 3332, 2025. (Add authors and DOI if available before submission.)

7. Montel Energy, "Why Are Life Cycle Assessments Important for Renewables," Mar. 31, 2025. [Online]. Available: https://montel.energy (Use only if journal guidelines permit website references.)

8. The Climate Center, "Carbon Footprint Mapping: A Powerful Tool for Revealing Climate Solutions," 2024. [Online]. Available: https://theclimatecenter.org (Use only if journal guidelines permit website references.)

9. United Nations Economic Commission for Europe (UNECE), Life Cycle Assessment of Electricity Generation Options. Geneva, Switzerland: United Nations, 2021.

10. D. D. Hsu, P. O'Donoughue, V. Fthenakis, G. Heath, H. C. Kim, P. Sawyer, J. K. Choi, and D. E. Turney, "Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation," Journal of Industrial Ecology, vol. 16, no. S1, pp. S122-S135, 2012. https://doi.org/10.1111/j.1530-9290.2011.00439.x