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

Shikha Sharma, Sunil Kumar Vohra
Lincoln University College, Malaysia
Email: pdf.shikhasharma@lincoln.edu.my

Abstract

With the technologies accelerating the shift towards renewable energy in many countries around the world, it is important to understand that the impacts of these technologies are not only during operations. The electricity produced by solar panels, wind turbines, and biomass systems, have relatively small greenhouse gas emissions, but emissions are generated during raw material extraction, manufacturing, transportation, installation, maintenance, and disposal.

The present research evaluates the life cycle carbon footprints of solar PV, wind and biomass energy systems across various geographical locations. The study is done using Life Cycle Assessment (LCA) method that quantifies Green House Gas (GHG) emissions throughout the life cycle of a technology, from its beginning to its end of life. The results show that wind energy has the lowest life cycle emissions (738 gCO_2e/kWh) and solar PV the next lowest (20100 gCO_2e/kWh). Biomass systems tend to have a higher emission level due to varying approaches to the production of biomass feedstock.

The study also highlights the significant impact of factors such as regional energy mix, manufacturing processes, availability of resources, and supply chain characteristics on environmental performance. The results underscore the need of policy makers and industry actors to include geographic and supply chain aspects in renewable energy deployment planning to maximize climate benefits.

The presentation will cover the following topics: Introduction to LCA and CF, Renewable Energy, Solar PV, Wind Energy, Biomass Energy, Geographical variations and Sustainable Energy Transition.

Introduction

Climate change has become one of the biggest global problems of the day and is gaining more attention by governments and industries worldwide to make the transition to cleaner energy sources. Solar, wind, and biomass are considered to be vital to reduce fossil fuel use and greenhouse gas (GHG) emissions.

But just looking at electricity generation emissions is not enough to get a full picture of their broader environmental effects. Renewable energy systems require a significant amount of raw materials and complex manufacturing, transportation and installation processes, maintenance and upkeep, and decommissioning and disposal. The total carbon footprint of the technology is accumulated throughout the stages.

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.The effects on Carbon Footprints of Geography and Supply Chains.

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.

Methodology

Study Scope

This study reviews the carbon footprints for three major renewable energy technologies throughout their lifecycle: Solar PV, Onshore wind and Biomass power generation.

The analysis is carried out in these five key regions, with various renewable resources, manufacturing methods and electricity grid characteristics, and uses a cradle-to -grave approach to examine the technologies' life cycles.

1.The removal of natural resources.

2.Component manufacturing

3.Transportation

4.Installation and construction

5.Operation and Maintenance

6. Discontinuation

7.Disposal or recycling

All these steps are included to provide a more complete picture of the real environmental effects of the renewable energy systems.

Data Collection and Analysis

The analysis is based on emission information from reputable LCA databases, as well as world energy statistics. This study accounts for emissions at the different solar PV manufacturing stages such as polysilicon production, wafer fabrication, cell production and module assembly. For wind energy, this includes emissions from steel towers, turbine components and fiberglass blades.

All results are in grams CO_2 equivalent per kWh electricity generated (gCO_2e/kWh). This is an often used metric, which allows easy comparison between technologies and regions.

Results

Solar Photovoltaic Systems

The carbon footprint of solar PV was the most region dependent. In areas with cleaner electricity grids, and high solar irradiances, the best performing systems were built. The average emissions for both Northern and Southern Europe were between 20 and 35 gCO_2e per kWh. In contrast, panels made in regions in East Asia where the electricity is generated with coal had much higher emissions, up to 100 gCO_2e/kWh.

The results illustrate that the overall sustainability of solar energy is greatly influenced by the manufacturing process used as well as the amount of local sunlight received.

Wind Power Systems

Wind energy had the lowest life cycle emissions of all the technologies studied. In Northern Europe, where wind resources are abundant and manufacturing carbon emissions are relatively low, emissions were as low as 712 gCO_2e/kWh. In areas with less favorable conditions, wind power typically stayed under 38 gCO_2e/kWh.

Most emissions associated with wind turbines are from the fabrication of steel towers and concrete foundations, which are material intensive components.

Biomass Power Generation

Biomass systems produced the greatest and most variable emissions of the renewable technology systems that were examined. The facilities utilizing agricultural waste or forest residues tended to perform better than those relying on special energy crops. Emissions ranged from about 40 to over 120 gCO_2e/ kWh in the different agricultural waste systems and in some energy-crop-based systems.

These results suggest that management practices and feedstock selection are key factors in determining sustainability of biomass.

Discussion

What are the reasons for different emissions in different regions?

The findings are quite obvious that there is a location effect. The main source of variation is the electricity used during the manufacturing. Renewable energy equipment with a carbon-intensive grid would already have a higher carbon footprint from the factory, before it gets to the site. The quality of the resources is another important determinant. The more electricity can be produced by wind turbines and solar panels, the stronger the wind speeds or the greater the solar irradiance. The more energy that is produced over the life of the equipment, the less emissions per kilowatt-hour. Regional disparities are also due to transportation and supply chain logistics. Long-distance transportation is a source of emissions, while local production can reduce such emissions.

The importance of End-of -life Management.

With the increasing adoption of renewable energy, handling of equipment at the end of its useful life becomes increasingly important. Solar panels contain valuable materials such as silicon, aluminum, and silver that can be recovered from the panels through the recycling process. But wind turbine blades are more difficult to recycle because they are made of composites. Strategies to improve recycling facilities and extend equipment lifetimes through refurbishment can significantly reduce the overall carbon footprint of renewable energy systems.

Other Sustainability Factors This research is focused on GHGs, but other environmental factors should also be taken into consideration. Big renewable energy projects can impact land use, biodiversity, water supplies, and the need for essential materials. Therefore, a view broader than just carbon should be taken in energy planning for true sustainability.

Conclusion: This study demonstrates the great climate benefits renewable energy technologies offer over fossil fuels, but also highlights the great variability in their environmental impact depending on the specific technology and the country in which it is produced and installed.

The lowest life cycle emissions (7 – 38 gCO_2e/kWh) were found to be associated with wind energy. Solar PV had a wider range of emissions (20-100 gCO_2e/kWh) due to fluctuations in the manufacturing energy sources as well as variations in the availability of solar resources.

Biomass systems exhibited the widest range of emissions, with the type of feedstock and management significantly influencing emissions. The results underscore that to maximize the climate benefits of renewables, more than simply investing in renewables is needed. It is also imperative for the city and industry players to prioritize decarbonization of industrial activities, optimizing supply chains, locationing, and recycling and circular economy options.

References

1. Gao, C., Zhang, Y., Wang, H., & Li, X. (2021). *Comprehensive comparison of multiple renewable power generation methods: A combination analysis of life cycle assessment and ecological footprint*. Renewable and Sustainable Energy Reviews, 147, 111255.
2. Hampo, C. C., Rodriguez, M., & Silva, J. (2022). *Life cycle assessment of renewable energy technologies*. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects.
3. IPCC. (2014). *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 University Press.
4. ISO. (2006). *ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework*. International Organization for Standardization, Geneva, Switzerland.
5. ISO. (2006). *ISO 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines*. International Organization for Standardization, Geneva, Switzerland.
6. MDPI Energies. (2025). *Renewable Energy and CO_2 Emissions: Analysis of the Life Cycle and Impact on the Ecosystem in the Context of Energy Mix Changes*. Energies, 18(13), 3332.
7. Montel Energy. (2025). *Why Are Life Cycle Assessments Important for Renewables?* March 31, 2025.
8. The Climate Center. (2024). *Carbon Footprint Mapping: A Powerful Tool for Revealing Climate Solutions*.
9. United Nations Economic Commission for Europe (UNECE). (2021). *Life Cycle Assessment of Electricity Generation Options*.