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Lifecycle Assessment of Green Technologies: A Comprehensive Analysis of Environmental Impacts from Production to Disposal

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Abstract

The shift towards a cleaner, low-carbon future relies heavily on the use of green technologies such as solar panels, wind turbines, electric vehicles (EVs), and energy storage systems. These technologies play a crucial role in reducing greenhouse gas (GHG) emissions and lowering our dependence on fossil fuels. However, they are not completely free of environmental impacts. From the mining of raw materials to the manufacturing process, daily operation, and final disposal, each stage of their lifecycle involves energy use, resource consumption, and emissions.

This research explores the environmental impacts of key green technologies through a comprehensive lifecycle assessment (LCA), which examines every stage of their existence — from resource extraction to end-of-life recycling or disposal. The findings show that while these technologies offer major environmental benefits during their operation, especially in terms of reducing GHG emissions, significant impacts occur during the early stages of production and material processing. To make green technologies more sustainable overall, strategies such as improved recycling methods, eco-friendly product design, the use of renewable energy in manufacturing, and the adoption of circular economy principles are essential. By addressing these challenges, green technologies can deliver even greater environmental benefits and contribute more effectively to a truly sustainable future.

Key words: Green Technologies, Environmental Impacts, lifecycle assessment (LCA), sustainable energy, batteries,

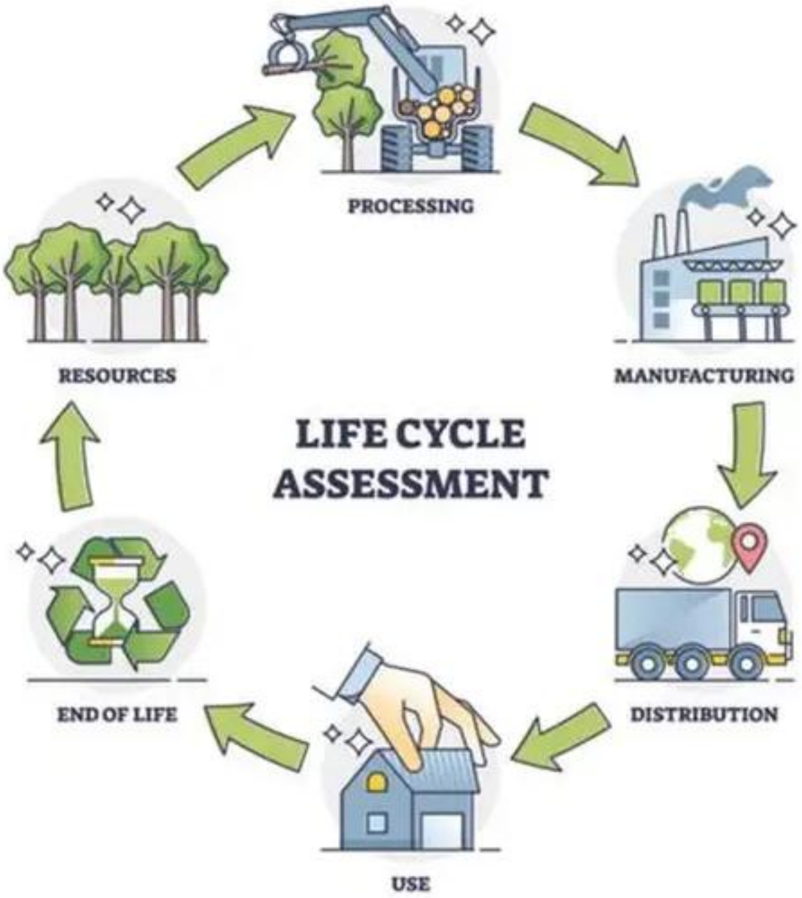
Introduction

The world is facing major challenges like climate change, air pollution, and the need for reliable energy for everyone. To address these issues, countries are moving toward clean and renewable energy sources, such as solar power, wind power, electric vehicles, and battery storage systems. These technologies help reduce greenhouse gas emissions, lower pollution, and make energy systems more sustainable.[1-5]

However, using these technologies is only part of the solution. To truly protect the environment, we need to consider the **entire life of these technologies**. This means looking at everything from the raw materials used to make them, the energy and resources needed during manufacturing, how they are used, and what happens to them at the end of their life, such as recycling or disposal. Each stage can have its own impact on the environment, even if the technology is clean when it is in use.[2]

Lifecycle Assessment (LCA) is a method that helps us understand and measure the total environmental impact of a technology throughout its entire life. It looks at factors like energy use, greenhouse gas emissions, waste generation, and resource consumption. By using LCA, engineers, scientists, policymakers, and companies can make better decisions about which technologies to use, how to improve them, and how to reduce their overall impact on the environment.[3,4]

This approach is important because it shows that even green technologies can have hidden environmental costs. With careful planning, better designs, and sustainable practices like recycling and using renewable energy in manufacturing, these technologies can become much more environmentally friendly. LCA helps guide this process, making sure that the shift to a clean energy future is truly sustainable from start to finish.[5,6]



Lifecycle Assessment (LCA): Concepts and Methodology

Lifecycle Assessment, or **LCA**, is a method used to study the total impact a product or technology has on the environment during its entire life. It looks at every stage, from the very beginning to the end, to see how much energy, resources, and emissions are involved.[1-6]

The main stages include:

1. **Raw Material Extraction:** This is the first step, where materials like silicon for solar panels, rare earth metals for wind turbines, or lithium for batteries are mined, refined, and processed. This stage often uses a lot of energy and can have significant environmental impacts.
2. **Manufacturing and Assembly:** Making the components and putting them together requires energy and can produce emissions. For example, building a solar panel or a wind turbine involves industrial processes that use electricity, heat, and other resources.
3. **Transportation and Installation:** Moving materials and finished products to their destination and installing them also has an environmental impact. This includes fuel use and emissions from trucks, ships, or cranes.

4. **Operation and Maintenance:** This is when the technology is in use. For green technologies, this stage often saves energy and reduces emissions compared to conventional options, but regular maintenance and energy use still matter.
5. **End-of-Life:** Finally, when a product reaches the end of its useful life, it may be recycled, reused, or disposed of. Each option has its own environmental consequences, such as emissions from disposal or benefits from recovering materials through recycling.

3. LCA of Selected Green Technologies

3.1 Solar Photovoltaic (PV) Systems

Solar photovoltaic (PV) systems, commonly known as solar panels, are one of the most popular sources of renewable energy. They convert sunlight directly into electricity without producing harmful greenhouse gases during use. However, to understand how sustainable they really are, we need to look at their entire lifecycle — from how they are made to how they are used and what happens when they are no longer needed.[7-9]

The first stage is raw material extraction. Solar panels are mainly made from silicon, which must be very pure to work well. Producing this high-purity silicon uses a lot of energy, and this energy often comes from fossil fuels. As a result, this stage can release significant amounts of carbon dioxide (CO_2) into the atmosphere.

Next is the manufacturing stage, where the silicon is turned into thin wafers and assembled into complete solar modules. This process also uses a lot of energy and can produce emissions. In fact, making and assembling the solar panels is responsible for about 40% to 50% of their total greenhouse gas emissions over their whole life.[8]

The operation stage is the cleanest part of a solar panel's life. Once installed, solar panels generate electricity directly from sunlight without releasing harmful gases. They usually last 25 to 30 years, providing clean power for a long time. During this period, they also help reduce the need for fossil fuels, which further cuts greenhouse gas emissions.

At the end of their life, solar panels do not become useless. Most of their parts — including glass, aluminum frames, and silicon — can be recycled. Around 85–90% of a solar panel's materials can be reused to make new products, reducing waste and saving resources.[7-9]

When we compare solar panels with fossil fuels, the difference is huge. Solar energy produces about 20 to 60 grams of CO_2 per kilowatt-hour, while coal produces around 900 grams for the same amount of electricity. This shows how much cleaner solar power is. Another important point is energy payback time — the time it takes for a solar panel to generate the same amount of energy that was used to make it. For most panels, this is just 1 to 4 years, which means they produce far more energy over their lifetime than what was used in their production.[10]

In conclusion, solar PV systems are a highly effective and sustainable energy technology. They produce clean electricity, reduce greenhouse gas emissions, and have a positive energy balance over their lifetime. However, there is still room for improvement. Using cleaner energy during manufacturing, improving production efficiency, and expanding recycling programs can make solar panels even more environmentally friendly and sustainable for the future.[7-11]

3.2 Wind Turbines

Wind turbines are machines that use the power of the wind to make electricity. They are one of the cleanest and most common renewable energy technologies in the world. To understand how they affect the environment, we look at their whole life cycle — from building them to using them and finally recycling them.[12]

The first stage is raw materials. Wind turbines are made from materials like steel, fiberglass, concrete, and rare earth metals. Making these materials uses a lot of energy and natural resources, which can create pollution. The next step is manufacturing and transportation, where the turbine parts are built and moved to the site. This stage also produces some greenhouse gases, especially because turbines are large and heavy and need special equipment to move and install them.[13]

Once the turbine is built and starts working, the operation stage is almost pollution-free. Wind turbines make electricity without burning fuel and without producing harmful gases. They usually last about 20 to 25 years and need only small amounts of maintenance. When the turbine reaches the end of its life, most parts — about 80–90% — can be recycled, like the steel and concrete. However, the blades are harder to recycle because they are made from special materials, and many still end up in landfills.[14-15]

Wind turbines are one of the cleanest energy sources when it comes to greenhouse gas emissions. They produce only about 10–20 grams of CO_2 for every kilowatt-hour of electricity, which is much lower than coal or oil. Their energy payback time — the time they need to generate the same amount of energy used to make them — is also very short, usually 6 months to 1 year.[15]

In short, wind turbines are a very clean and sustainable source of electricity. They have one of the lowest carbon footprints of any energy technology. If we can improve blade recycling and design turbines to be more reusable, they will become even more environmentally friendly in the future.[14-16]

3.3 Electric Vehicles (EVs)

Electric vehicles (EVs) are cars that run on electricity instead of petrol or diesel. They are becoming more popular because they help reduce air pollution and greenhouse gas emissions. To understand how they affect the environment, we need to look at their whole life cycle — from making them to using them and finally recycling them.[17]

The first stage is raw materials. EV batteries need materials like lithium, cobalt, and nickel. Mining these materials uses a lot of energy and can harm the environment. It can also cause problems for local communities where the materials are mined.

The second stage is manufacturing. Building an EV, especially its battery, uses a lot of energy. Making the battery can produce up to 40% of the total emissions over the car's life. Using cleaner energy in factories can help reduce this impact.[18]

The third stage is operation - this is when the car is being driven. EVs have a big advantage here because they produce almost no pollution from the exhaust. However, the total emissions depend on how the electricity is made. If the electricity comes from solar, wind, or other renewable sources, EVs are much cleaner than regular cars.[19]

Finally, there is the end-of-life stage. When the battery reaches the end of its use, it can be recycled. About 60–90% of important materials like lithium and cobalt can be recovered and reused. Recycling reduces the need for new mining and helps protect the environment.[20]

Overall, EVs produce about 50–70% less greenhouse gas emissions over their lifetime compared to petrol or diesel cars, especially if they run on renewable electricity. They also have an energy payback period of about 1–2 years, which means they save more energy than was used to make them quite quickly.[20,21]

In short, electric vehicles are a cleaner and more sustainable choice for transportation. They greatly reduce pollution over their lifetime, but we still need to improve battery production, make supply chains cleaner, and build better recycling systems to make them even more environmentally friendly.[21]

3.4 Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) are increasingly recognized as a cornerstone technology for enabling a low-carbon energy future. By providing flexibility, stability, and reliability to power systems, they support the large-scale deployment of renewable energy sources such as solar and wind. However, the environmental performance of BESS must be evaluated across their entire lifecycle—from raw material extraction to end-of-life management—to ensure net sustainability benefits.[22]

4. Lifecycle Stages and Environmental Impacts

4.1 Raw Materials Extraction- The production of lithium-ion batteries relies heavily on critical minerals such as lithium, cobalt, nickel, manganese, graphite, and copper. Mining and processing these materials are resource- and energy-intensive, often associated with land degradation, water use, toxic emissions, and social challenges such as labor conditions in cobalt supply chains. The environmental impact of raw materials can represent up to 40–60% of total battery GHG emissions. Efforts are underway to mitigate these impacts through:[23]

- Transition to low-impact chemistries (e.g., lithium iron phosphate – LFP, and sodium-ion batteries) that avoid cobalt and nickel.
- Increasing the use of secondary materials via recycling and material recovery.
- Developing responsible sourcing standards and transparent supply chains.

4.2. Manufacturing and Assembly- Battery manufacturing is highly energy-intensive, particularly during cell production, electrode coating, and drying processes. Historically, these activities have relied on fossil-based electricity, significantly affecting carbon footprints. However, newer renewable-powered gigafactories and process optimizations are helping reduce emissions. Typical manufacturing energy demand ranges between 50–150 kWh per kWh of battery capacity, translating to substantial emissions if powered by non-renewable sources.[24]
Sustainability gains can be achieved by:

1. Electrifying production with renewable energy sources.
2. Improving energy efficiency in clean room operations and drying steps.
3. Optimizing battery design to minimize material use without compromising performance.

4.3. Operation and Use Phase- During operation, BESS deliver crucial system-level environmental benefits:

Renewable energy integration: BESS smooth out intermittent generation, enabling higher renewable penetration.

Peak shaving and load balancing: Batteries reduce reliance on fossil-fuel-based peaker plants, lowering grid emissions.

Frequency and voltage regulation: Improves grid stability and resilience.
While BESS consume minimal energy during operation, their lifecycle GHG impact depends heavily on how they are used—frequent cycling and alignment with low-carbon grids improve their environmental return on investment.

4.4 End-of-Life and Recycling- As global battery deployment accelerates, end-of-life management is becoming a major sustainability priority. Current recycling technologies—such as pyrometallurgical, hydrometallurgical, and direct recycling—are evolving to recover valuable metals (e.g., lithium, nickel, cobalt) and reduce waste.
However, recycling infrastructure remains underdeveloped in most regions, and collection, logistics, and process economics pose significant challenges. Expanding second-life applications, where used EV batteries are repurposed for stationary storage, offers an intermediate step before full material recovery. Developing a circular battery economy—combining reuse, remanufacturing, and recycling—is key to minimizing resource extraction and waste.[24-25]

Key Environmental Metrics

Metric[26]	**Typical Range / Description**
GHG Emissions (Cradle-to-Gate)	~60–150 kg CO_2-eq per kWh of storage capacity (varies by chemistry and grid mix)
Energy Payback Time	2–5 years, depending on cycle frequency, depth of discharge, and grid carbon intensity
Round-trip Efficiency	85–95%, depending on system design and battery type
Operational Lifetime	10–15 years, with performance degradation typically 1–3% per year

5. Strategies for Reducing Lifecycle Impacts

Circular economy strategies can significantly improve sustainability across product lifecycles by emphasizing design for disassembly, component reuse, and closed-loop recycling of critical materials. These efforts are strengthened by cleaner manufacturing practices that incorporate renewable energy to reduce embedded carbon emissions. At the same time, material innovation—such as developing alternatives to rare or toxic inputs, including cobalt-free battery chemistries—helps reduce environmental and ethical impacts. Effective policy and regulatory frameworks, particularly extended producer responsibility (EPR), play a key role in ensuring that manufacturers support robust recycling and recovery infrastructures. Additionally, digital technologies like artificial intelligence and the Internet of Things enable smarter resource management, predictive maintenance, and longer product lifespans, collectively enhancing overall system efficiency and sustainability.[27]

6. Conclusion

Lifecycle assessment shows that green technologies, despite the environmental burdens associated with their early production stages, ultimately deliver substantial long-term benefits. Solar PV systems, wind turbines, electric vehicles, and battery storage significantly reduce greenhouse gas emissions and air pollution compared to fossil-fuel technologies, particularly during operation when they produce or use energy with minimal direct emissions. However, focusing only on the use phase overlooks key sustainability challenges. The extraction and processing of critical materials such as lithium, cobalt, and rare earth elements can cause ecological impacts, while manufacturing processes for components like solar cells and batteries often remain energy-intensive. End-of-life management also presents growing concerns as increasing volumes of panels, turbine blades, and batteries require effective recycling and recovery systems. By integrating lifecycle assessment into design, policy, and investment decisions, stakeholders can reduce upstream impacts, improve recycling, and ensure that the global transition to clean energy is both environmentally responsible and truly sustainable.

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