Conceptualizing a Life Cycle Assessment (LCA) Model for Cleaning Robots

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Abstract

Robotics has become increasingly prevalent in various sectors, including domestic and industrial cleaning. As their usage grows, so does the need to understand and mitigate their environmental impacts. Life Cycle Assessment (LCA) is a recognized method for assessing the environmental impacts of products and services throughout their life cycle, from production to disposal. It helps in identifying key areas where environmental impacts are significant and in developing strategies for mitigation. Despite its widespread application in various industries, the specific application to cleaning robots remains under-explored. This study introduces a conceptual model for a Life Cycle Assessment (LCA) method for cleaning robots. It identifies key environmental impact indicators across four major stages of a cleaning robot's life cycle: *production, transport, operations, and end-of-life*. The purpose is to provide a comprehensive method for future assessments of the ecological footprint of these robots. In the *production* phase, the proposed model suggests evaluating greenhouse gas (GHG) emissions, carbon intensity, the share of renewable energy used, and the proportion of recycled or renewable materials in manufacturing. These indicators aim to quantify the environmental impacts associated with the manufacturing process of cleaning robots. The *transportation* stage is conceptualized to include assessments of GHG emissions during transit, the carbon intensity of transport methods, and the use of low-carbon and renewable energy in logistics. This aspect of the assessment focuses on the environmental impact of distributing cleaning robots from manufacturers to end-users. For the *operational* phase, the model proposes metrics such as electricity consumption, renewable electricity usage, Power Usage Effectiveness (PUE), and Carbon Usage Effectiveness (CUE). These indicators are designed to measure the energy efficiency and carbon footprint of cleaning robots during their use. The *end-of-life* stage includes metrics like the total electronic waste (E-Waste) generated, recycling rates, Electronics Disposal Efficiency (EDE), and the percentage of e-waste sent to landfills. These indicators evaluate the environmental impact of cleaning robots at the end of their usable life and for guiding sustainable disposal and recycling practices. This research attempts to contribute to the broader field of sustainable robotics by providing a framework to evaluate and improve the environmental performance of cleaning robots.

Indexing terms: Life Cycle Assessment (LCA), Environmental Impact, Cleaning Robots, Sustainability in Robotics, Carbon Footprint, Energy Efficiency, E-Waste Management

Introduction

The rise of cleaning robots in the last decade marks a notable shift in both domestic and commercial cleaning practices. Initially seen as a novelty, these robotic devices have become increasingly mainstream, due to their ability to automate mundane tasks like vacuuming, mopping, and even window cleaning. In domestic settings, cleaning robots have become popular for their convenience and time-saving benefits. They offer homeowners the luxury of maintaining clean living spaces with minimal effort, running scheduled cleaning cycles and even recharging themselves autonomously. In commercial spaces, these robots are valued for their efficiency and consistency, capable of maintaining large areas such as office spaces, hotels, and shopping centers with less manpower and often greater precision than traditional methods. This shift towards automated cleaning solutions reflects a broader trend in embracing smart technology in everyday life, where convenience and efficiency are highly prized.

While cleaning robots offer apparent immediate benefits, their long-term environmental impact remains a subject of growing concern and investigation. The environmental footprint of these devices encompasses their manufacturing, operation, and eventual disposal. The manufacturing process involves the extraction and processing of various materials, including plastics and metals, which has its own environmental implications. Additionally, the energy consumed during their operation, although typically less than that of larger, manual cleaning equipment, still contributes to the overall energy demand and associated carbon emissions. Furthermore, the disposal of these robots poses significant environmental challenges. Their electronic components and batteries are not only difficult to recycle but can also be harmful to the environment if not disposed of properly.

Figure 1. Cleaning robotics' environmental impact by stage

Stage 1.

Manufacturing

Resource-intensive with significant environmental impacts due to materials extraction and global logistics.

Stage 2.

Transportation

Carbon emissions from global logistics and supply chain movement.

Stage 3.

Operation

Energy consumption varies based on the energy source; indirect impacts on employment and resource use.

Stage 4

Disposal

Challenges in recycling hazardous materials and managing waste due to rapid obsolescence.

In light of these concerns, the future of cleaning robots depends on balancing the benefits they offer with their environmental impact. Innovations in sustainable manufacturing, energy-efficient design, and recyclable materials are vital in reducing the ecological footprint of these devices. Companies producing cleaning robots are increasingly aware of these challenges and are beginning to integrate eco-friendly practices into their design and manufacturing processes. Furthermore, there is a growing emphasis on the life cycle assessment of these products, aiming to understand and minimize their impact from production to disposal. The development of effective recycling programs and regulations around electronic waste is also crucial in mitigating the environmental impact of these robots.

The environmental footprint of robotics encompasses several stages: *manufacturing, operation, and disposal*. The *manufacturing* process of robots is resource-intensive, involving the extraction and processing of various raw materials such as metals, plastics, and rare earth elements. These materials are necessary for the construction of electronic components and mechanical parts, but their extraction and processing often entail significant environmental impacts, including habitat destruction, water and air pollution, and high energy consumption. Moreover, the global supply chain involved in robot manufacturing can lead to additional carbon emissions due to transportation and logistics.

During *operation*, robots consume energy, and the source and efficiency of this energy use are critical factors in determining their environmental impact. While robots can enhance operational efficiency and reduce waste in some industries, their energy consumption can contribute to carbon emissions, especially if they rely on non-renewable energy sources. This aspect becomes increasingly important as robots become more widespread and operate over extended periods. In addition to direct energy consumption, the indirect environmental impact of robotics in operation, such as changes in employment patterns and resource utilization, also warrants consideration. These impacts are often more challenging to quantify but are crucial for a comprehensive understanding of the ecological footprint of robotics.

The *disposal* of robots represents a significant environmental challenge, primarily due to the materials used in their construction. Many components of robots, such as batteries and electronic circuits, contain hazardous materials that can be harmful to the environment if not disposed of properly. The recycling and repurposing of these materials are challenging, often requiring specialized processes. Furthermore, the rapid pace of technological advancement in robotics means that devices can become obsolete quickly, potentially leading to increased waste.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) primarily focuses on examining physical products through a comprehensive lens that encompasses their entire life cycle [1]. The concept of a "*product system*" is central to this approach, emphasizing the need to consider every single process involved in delivering a product's function. For instance, when evaluating a product like car fuel, the assessment doesn't just focus on the fuel's composition or its immediate environmental impact. Instead, it examines the complete journey of the fuel—from its extraction, processing, distribution, and eventual use in propelling a car. This view is essential in understanding the cumulative environmental footprint of a product, as it includes every stage from raw material acquisition to end-of-life disposal or recycling.

The core philosophy behind adopting a life cycle perspective in environmental assessments is the prevention of burden shifting. This concept refers to the unintended transfer of environmental impacts from one stage of a product's life cycle or process to another. Often, efforts aimed at reducing environmental harm in one aspect of a product's life can inadvertently lead to increased impacts in another. For example, a process modification in manufacturing that reduces waste or energy consumption might lead to increased emissions or resource use during the transportation or usage phase. Such shifts can sometimes result in greater overall environmental damage, negating the initial well-intentioned efforts. LCA aims to identify these potential trade-offs early in the process, allowing for a more balanced and genuinely sustainable approach to environmental management.

The significance of LCA in identifying and mitigating burden shifting cannot be overstated. This approach provides a comprehensive framework for understanding the full spectrum of environmental impacts associated with a product or process. By considering each stage of a product's life cycle, LCA helps in pinpointing where the greatest environmental burdens occur and where interventions would be most effective. It also aids in identifying opportunities for improvement that might not be apparent when examining processes in isolation. For instance, a life cycle perspective could reveal that changes in material sourcing or product design could significantly reduce environmental impacts, even if these changes might initially seem more resource-intensive.

The foundation of Life Cycle Assessment (LCA) lies in the application of natural science principles, in the quantification of potential environmental impacts. This process is grounded in empirical data collection, where various environmental flows are measured using scientific instruments like water gauges or particle counters. These measurements are typically conducted at industrial sites or within specific processes, providing a quantitative basis for the assessment. LCA relies on established models to understand the relationship between emissions or resource consumption and their subsequent environmental impacts. These models are based on proven causal relationships, such as the chemical reactions that lead to the formation of atmospheric ground-level ozone involving nitrogen oxides and volatile organic compounds. Similarly, empirical observations, like the correlation between phosphorous concentration in lakes and the impact on biodiversity and populations, are integral to LCA.

Despite its strong scientific underpinnings, LCA also incorporates elements of value judgment, in stages where environmental problems are weighted to assess a product system's overall impact. This aspect is most apparent when different types of environmental issues are evaluated and prioritized, which inevitably involves subjective decisions. LCA methodologies tries to handle these value judgments in a consistent and transparent manner. The framework allows practitioners some flexibility in modeling choices, enabling them to integrate their values and perspectives into the assessment process [2], [3].

The evolution of LCA reflects a growing global awareness and concern for environmental issues, including pollution, energy use, and material scarcity. Since the 1960s, when life-cycle-oriented methods first emerged, there has been significant progress both in the development of methodologies and their practical applications. This growth is driven by the increasing recognition of the importance of considering the entire life cycle of products in understanding and mitigating their environmental impacts. LCA has become an essential tool for businesses, policymakers, and environmental organizations, offering a detailed and holistic perspective on the environmental implications of products and processes [4], [5].

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LCA also incorporates elements of value judgment, in stages where environmental problems are weighted to assess a product system's overall impact. This aspect is most apparent when different types of environmental issues are evaluated and prioritized, which inevitably involves subjective decisions. LCA methodologies strive to handle these value judgments in a consistent and transparent manner. The framework allows practitioners some flexibility in modeling choices, enabling them to integrate their values and perspectives into the assessment process [6]. It can be tailored to specific contexts or objectives, providing a comprehensive view of environmental impacts that aligns with the values and goals of the assessment's stakeholders.

Life Cycle Assessment (LCA) evaluates the environmental impacts of a cleaning robo

Life Cycle Assessment (LCA) evaluates the environmental impacts of a cleaning robot, throughout its entire life cycle. This process encompasses four distinct stages: production, transportations, operations, and end-of-life (disposal).

Production

GHG Emissions from Production

The emissions are quantified in terms of metric tons of carbon dioxide equivalent (CO_2e), a standard unit that accounts for the global warming potential of different greenhouse gases. This measure helps in comparing the relative impact of various activities and materials involved in the production process. For instance, the energy-intensive processes like metal refining and the production of electronic components contribute significantly to the total CO_2e. Additionally, the transportation of raw materials and finished products adds to the overall emissions, with the impact varying based on factors such as transport distance and mode.

Table 1. Production stage

Category	Measure	Description
GHG Emissions from Production	Metric tons of CO2 equivalent (CO2e)	Total greenhouse gas emissions generated during the manufacturing of cleaning robots, including all stages from raw material extraction to the final assembly.
Carbon Intensity of Production Methods	Metric tons of CO2e per unit	Greenhouse gas emissions per unit of production, which could be measured per cleaning robot or per dollar of revenue generated from the sale of cleaning robots.
Share of Renewable Energy Used in Production	Percentage (%)	Proportion of renewable energy sources (such as solar, wind, hydro, etc.) used in the manufacturing process of cleaning robots.
Share of Recycled or Renewable Materials Used in Production	Percentage (%)	Proportion of materials used in the production of cleaning robots that are either recycled or sourced from renewable resources.

Total greenhouse gas (GHG) emissions associated with the manufacturing of cleaning robots encompass a range of activities contributing to the overall carbon footprint. At the initial stage, raw material extraction is a significant contributor to emissions. The production of cleaning robots requires a variety of materials, including plastics, metals, and electronic components. The extraction of these materials, such as mining for metals and drilling for petroleum (used in plastics), involves energy-intensive processes. These processes often rely on fossil fuels, leading to considerable GHG emissions. Moreover, the transportation of these raw materials to manufacturing sites further adds to the emission levels, depending on the distance and mode of transport used.

The refinement and processing of raw materials into usable forms is another stage in the manufacturing of cleaning robots that contributes to GHG emissions. Metals must be smelted and refined, which is energy-intensive and typically powered by carbon-emitting energy sources. Plastics, derived from petrochemical processes, involve significant energy use and emit GHGs both during their production and processing. Electronic components, which are integral to cleaning robots, also require energy-intensive manufacturing processes. The production of semiconductors, for instance, not only consumes large amounts of electricity but also involves the use of potent greenhouse gases like sulfur hexafluoride and nitrogen trifluoride during the manufacturing process.

The assembly phase of cleaning robots is characterized by both direct and indirect GHG emissions. Direct emissions result from the energy used in the assembly process itself, which may involve soldering, welding, and the operation of assembly line machinery. These processes are often powered by electricity, the generation of which may contribute to GHG emissions, depending on the energy mix of the region. Indirect emissions arise from the broader operational aspects of manufacturing facilities, including heating, cooling, and lighting. Additionally, the use of certain chemicals and solvents in the assembly process can result in the release of GHGs.

The production of packaging materials, which often involves the use of plastics and cardboard, contributes to emissions through both material production and processing. The distribution phase, encompassing the transportation of finished products to warehouses, retailers, or directly to consumers, further adds to the carbon footprint. This transportation is typically reliant on fossil fuel-powered vehicles, with emissions varying based on the mode of transport (air, sea, or land) and the distance covered.

Carbon Intensity of Production Methods

The carbon intensity of production methods in the manufacturing of cleaning robots can be measured in metric tons of CO2 equivalent (CO2e) per unit. This measure quantifies the amount of greenhouse gases emitted per robot produced, encompassing emissions from all stages of production, including raw material extraction, processing, assembly, and any related logistics. It serves as a key indicator of the efficiency and environmental sustainability of production methods, highlighting the relationship between the volume of production and the associated carbon footprint. For manufacturers, this metric is instrumental in identifying high-emission areas within the production process, guiding them towards more sustainable practices, such as adopting renewable energy sources, optimizing manufacturing processes for energy efficiency, or selecting materials with lower environmental impacts.

When measured per cleaning robot, the calculation considers all GHG emissions directly and indirectly associated with the production of a single unit. This encompasses a comprehensive range of activities from raw material extraction, processing, manufacturing, assembly, and distribution. For instance, the production of metals and plastics, essential components of these robots, involves substantial energy consumption and emissions. Similarly, the manufacturing and assembly processes, often reliant on electricity and other energy sources, contribute significantly to the overall emissions per unit.

On the other hand, measuring GHG emissions per dollar of revenue generated offers a different perspective. This economic-based metric aligns the environmental impact with the financial performance of the company, providing an insight into how efficiently the company is utilizing resources in terms of GHG emissions for economic output. This measure can be informative when comparing companies within the industry or assessing the environmental impact of different products. It helps in understanding whether higher revenue correlates with proportionately higher emissions or if there are efficiencies in production and supply chain that decouple economic growth from GHG emissions. This metric is increasingly relevant in the context of sustainable business practices and corporate environmental responsibility.

The GHG emissions per unit of production can vary significantly based on several factors. The geographic location of production facilities, for example, plays a crucial role as it determines the energy mix used in manufacturing processes. Facilities powered by renewable energy sources will have lower GHG emissions per unit compared to those relying on fossil fuels. Additionally, the efficiency of production processes, the choice of materials, and the logistics involved in the supply chain all contribute to the variation in emissions per unit. Advanced manufacturing technologies and sustainable material choices can significantly reduce emissions, while efficient logistics can minimize the carbon footprint associated with transportation.

Share of Renewable Energy Used in Production

The share of renewable energy used in the production of cleaning robots, expressed as a percentage, indicates the extent to which renewable sources like solar, wind, hydro, and other green energies contribute to the total energy consumption of the production process. A higher percentage signifies a greater reliance on renewable sources, reflecting a commitment to reducing carbon footprint and mitigating environmental impact. This metric not only demonstrates a company's dedication to sustainable manufacturing but also aligns with global environmental targets and increasing consumer demand for eco-friendly products.

The integration of renewable energy sources in the manufacturing process of cleaning robots is a topic of growing importance in the field, especially given the heightened awareness and commitment to sustainability. The proportion of renewable energy sources, such as solar, wind, and hydro, used in these processes significantly impacts the overall environmental footprint of the final product. When a substantial portion of the energy requirements for manufacturing cleaning robots comes from renewables, it directly reduces dependence on fossil fuels and lowers greenhouse gas (GHG) emissions.

Solar energy, among the most widely used renewable sources, offers a viable option for powering manufacturing facilities. The adoption of solar panels can be seen in various stages of the production chain, from powering machinery used in the assembly of robots to running the data centers that support their software development. The feasibility and effectiveness of solar energy depend on geographic location and technological advancement in photovoltaic cells. Similarly, wind energy, harnessed through turbines, is another renewable source increasingly being used in industrial settings. Wind farms can provide a significant portion of the energy required for manufacturing operations, especially in regions with favorable wind conditions.

Factories located near hydroelectric power sources can benefit from a consistent and reliable supply of energy with minimal GHG emissions. Moreover, advancements in small-scale hydroelectric systems have opened new possibilities for their integration into manufacturing facilities, allowing for more localized and controlled energy generation. Beyond these traditional sources, there is growing interest in other renewable technologies such as geothermal and biomass energy, which can provide additional sustainable energy solutions for the manufacturing sector.

Share of Recycled or Renewable Materials Used in Production

The use of recycled materials in cleaning robots is a significant step towards reducing the environmental impact of production. Recycled plastics and metals are commonly used in the body and internal components of these robots. For instance, recycled plastics can be utilized for casing and structural parts, reducing reliance on plastics derived from petrochemicals. Recycled metals, such as aluminum and steel, are also increasingly used, especially in structural and mechanical components. These materials often come from post-consumer waste, industrial scraps, or end-of-life electronics, contributing to a circular economy where materials are reused and kept out of landfills.

Bioplastics are appealing due to their reduced carbon footprint during production and the potential for biodegradability or compostability at the end of the product's life. However, the use of bioplastics presents challenges in terms of mechanical properties, cost, and the balance between using land for food versus industrial material production.

The electronics and batteries, components of cleaning robots, are also seeing an increase in the use of materials sourced from renewable resources or recycling programs. Advances in battery technology include the development of batteries using materials that are more abundant and less environmentally damaging. Recycling programs for electronics are becoming more sophisticated, allowing for the recovery of valuable materials like copper, gold, and rare earth elements. This not only reduces the demand for virgin materials but also mitigates the environmental impact associated with mining and material extraction.

In addition to using recycled and renewable materials, manufacturers are focusing on the design for disassembly and recycling. This approach involves designing cleaning robots in a way that at the end of their life, they can be easily disassembled, and the materials can be efficiently separated and recycled. This strategy not only facilitates recycling but also promotes the use of materials that can endure the recycling process without significant degradation in quality. Supply chain considerations, such as the availability and consistency of recycled and renewable materials, play a crucial role in their integration into production processes.

Transportation

GHG Emissions from Transportation of Cleaning Robots

Measured in metric tons of carbon dioxide equivalent (CO_2e), this metric provides an understanding of the environmental impact of the logistics involved in bringing cleaning robots to market.

Firstly, the mode of transportation is a major determinant of the GHG emissions associated with transporting cleaning robots. Road transport, commonly used for short to medium distances, typically has a higher emission factor per ton-kilometer compared to rail or sea transport. Trucks, which are frequently used for road transport, vary in their emissions depending on factors like fuel efficiency, load capacity, and route optimization. In contrast, rail and sea transport, often used for longer distances, generally have lower CO2e emissions per ton-kilometer but might not be as flexible or fast as road transport. Air freight, while the fastest mode, has significantly higher GHG emissions and is typically used only for urgent deliveries.

Table 2. Transportation stage

Category	Measure	Description
GHG Emissions from Transportation of Cleaning Robots	Metric tons of CO2 equivalent (CO2e)	Total greenhouse gas emissions associated with the transportation of cleaning robots, from the manufacturing site to distribution centers, retailers, or end-users.
Carbon Intensity of Transport Methods	Metric tons of CO2e per unit	Greenhouse gas emissions per unit of transportation, which could be measured per cleaning robot transported or per dollar of revenue generated from the sale of transported cleaning robots.
Share of Low-Carbon and Renewable Energy Used in Transport Methods	Percentage (%)	Proportion of low-carbon and renewable energy sources (like electric vehicles, biofuels, or solar-powered transport) used in the logistics and distribution of cleaning robots.

The distance traveled from the manufacturing site to the final destination is another critical factor in determining GHG emissions. Longer distances result in higher emissions, especially when the manufacturing facilities are located far from key markets. Globalization of the supply chain has led to scenarios where parts are manufactured in various locations and assembled in different countries, adding to the total distance traveled.

Packaging materials used in the transportation of cleaning robots also contribute to the total GHG emissions. While not directly related to the transportation process, the production and disposal of these materials add to the overall carbon footprint. The use of sustainable, lightweight packaging materials can reduce the overall weight of shipments, leading to lower fuel consumption and, consequently, lower GHG emissions during transportation.

Operational efficiency in the logistics chain significantly impacts the GHG emissions from transportation. This includes route optimization to reduce travel distances, maximizing load capacity to decrease the number of trips required, and employing modern, fuel-efficient vehicles. Additionally, the use of technology for better logistics management, such as real-time tracking and AI-driven route planning, can further enhance efficiency and reduce emissions.

Carbon Intensity of Transport Methods

The carbon intensity of transport methods in the distribution of cleaning robots can be measured in metric tons of CO2 equivalent (CO2e) per unit. This measure can be evaluated in two distinct ways: per cleaning robot transported, which gives a product-specific insight, or per dollar of revenue generated from the sale of transported cleaning robots, offering a more economic perspective.

When considering the carbon intensity per cleaning robot transported, the focus is on the emissions directly attributable to the movement of each unit from the production facility to its final destination. This metric encapsulates the emissions from all modes of transport involved – road, rail, air, or sea. The choice of transportation mode plays a significant role in determining the carbon intensity. For instance, air freight, while expedient, typically has a much higher carbon intensity compared to sea or rail transport. Road transport, often used for last-mile delivery, also varies significantly in its emissions profile based on factors like vehicle type, fuel efficiency, and route optimization.

Alternatively, analyzing the carbon intensity per dollar of revenue generated provides an economic dimension to the assessment. This approach ties the environmental impact to the company's financial performance, allowing for a comparative analysis across different products, sectors, or companies. It can reveal how efficiently a company is managing its logistics in terms of carbon emissions relative to its economic output. A higher carbon intensity per dollar of revenue might indicate inefficiencies or an over-dependence on high-emission transport methods.

Operational factors are key in determining the carbon intensity of transport methods. Efficient logistics management, including route planning, load optimization, and the use of modern, fuel-efficient vehicles, can significantly lower the emissions per unit transported. The application of technologies such as GPS for real-time tracking, AI for route optimization, and the use of electric or hybrid vehicles in the fleet, can further enhance these efficiencies. Additionally, the carbon intensity can be influenced by the choice of packaging materials; lighter and more compact packaging reduces the overall weight and volume of shipments, thereby decreasing fuel consumption and associated emissions. Another important consideration is the geographical distance and the logistical complexity involved in the transportation of cleaning robots. Longer distances and more complex routes typically result in higher carbon intensity.

Share of Low-Carbon and Renewable Energy Used in Transport Methods

The share of low-carbon and renewable energy sources used in the transport methods for cleaning robots is quantified as a percentage. This measure reflects the extent to which sustainable energy sources, such as electric vehicles, biofuels, or solar-powered transport, are integrated into the logistics and distribution networks for these robots.

The utilization of electric vehicles (EVs) in the distribution chain significantly contributes to this metric. The percentage of EVs used in the fleet becomes a critical factor in assessing the share of low-carbon transport. This adoption is subject to various factors, including the availability of EV models suitable for logistics, the infrastructure for charging, and the geographical range of the distribution network.

Biofuels, derived from biological sources like plants or waste, offer another avenue for reducing carbon intensity in transport. Unlike traditional fossil fuels, biofuels can significantly lower the net carbon emissions, as the carbon dioxide they release during combustion is roughly equivalent to what their source materials absorbed during growth. The integration of biofuels into the transport fleet, particularly in heavy vehicles and shipping, can increase the percentage of renewable energy used in logistics. The measure of success in this domain depends on the scalability of biofuel production, the compatibility with existing vehicle technologies, and the overall lifecycle emissions of the biofuels used.

Solar-powered transport, although less common in large-scale logistics, provides a promising option for increasing the share of renewables in transportation. Solar panels can be integrated into the infrastructure of warehouses and distribution centers, providing renewable energy for onsite operations and potentially for charging electric vehicles. The extent to which solar energy is harnessed in the logistics network directly contributes to the overall percentage of renewable energy use. This integration depends on factors such as the geographical location, availability of solar technology, and the feasibility of incorporating solar power into existing logistics infrastructure.

The operational strategies and routes chosen for distribution also play a role in determining the share of low-carbon and renewable energy sources used. Optimizing routes to reduce travel distances, using vehicles with higher fuel efficiency, and consolidating shipments to maximize load capacity are operational measures that, while indirectly, contribute to lowering the carbon footprint of transportation. These strategies, when combined with the use of low-carbon transport options, can substantially increase the proportion of renewable energy in the logistics chain.

Operations

Energy Consumption Metrics for Cleaning Robots Operations

Electricity Consumption

The electricity consumption of cleaning robots during their operational phase quantified in terawatt-hours (TWh). This measure reflects the total electricity used by these robots over a specific period, such as annually.

The energy efficiency of individual cleaning robots helps in determining their overall electricity consumption. Advances in battery technology, motor efficiency, and intelligent energy management systems have a direct impact on how much electricity a single robot consumes during its operation. For instance, robots equipped with high-efficiency motors and smart systems that optimize cleaning routes and operational speed consume less power. Furthermore, the development of advanced battery technologies not only enhances the energy density, allowing robots to operate longer on a single charge, but also improves the overall lifecycle of the batteries, indirectly affecting the total electricity consumption.

The frequency and duration of use significantly contribute to the total electricity consumption of cleaning robots. In commercial settings, where cleaning robots are often used extensively and regularly, the electricity consumption can be notably higher compared to residential settings. The operational patterns, such as the number of cleaning cycles per day and the area covered, directly influence the amount of electricity used.

Renewable Electricity Consumption

The renewable electricity consumption of cleaning robots, quantified in terawatt-hours (TWh), is a critical measure for understanding the sustainability of their energy use. This metric reflects the amount of electricity sourced from renewable energy sources utilized by these robots during their operational phase.

When robots are charged using electricity generated from renewable sources, their operation becomes more environmentally friendly. The integration of renewables in the energy mix for charging infrastructure, such as solar-powered charging stations or grid electricity sourced from wind and hydro plants, directly impacts this metric.

The growing prevalence of renewable energy in the power grid also influences the renewable electricity consumption of cleaning robots. As more countries and regions expand their renewable energy infrastructure, the proportion of green energy in the grid mix increases, indirectly boosting the renewable electricity consumption of all electrically powered devices, including cleaning robots. This broader shift towards renewables is driven by factors such as technological advancements, decreasing costs of renewable energy production, and governmental policies promoting green energy. Another aspect impacting this measure is the development and implementation of smart charging systems for cleaning robots. Such systems can optimize charging times to coincide with periods when renewable energy generation is at its peak, such as during daylight hours for solar power. Smart charging not only ensures more efficient use of renewable energy but also helps in balancing the grid load, especially in scenarios where the grid is heavily reliant on intermittent renewable sources.

Table 3. Operations stage		
Category	**Measure**	**Description**
	Energy Consumption Metrics	
Electricity Consumption	Terawatt-hours (TWh)	Total electricity used by cleaning robots during their operational phase, measured over a specific period (e.g., annually).
Renewable Electricity Consumption	Terawatt-hours (TWh)	Amount of electricity consumed by cleaning robots that is sourced from renewable energy (such as solar, wind, hydro).
Power Usage Effectiveness (PUE) for Cleaning Robots	Ratio	Ratio of total facility power (including charging stations, maintenance units, etc.) to the power specifically used by the cleaning robots. A lower PUE indicates higher energy efficiency.
	GHG Emissions Metrics	
GHG Emissions	Metric tons of CO2 equivalent (CO2e)	Total greenhouse gas emissions associated with the operation of cleaning robots, including emissions from electricity generation.
Carbon Intensity of Operations	Metric tons of CO2e per unit	GHG emissions per unit of operation, which could be measured per cleaning robot or per dollar of revenue generated from the use of cleaning robots.
Carbon Usage Effectiveness (CUE) for Cleaning Robots	Ratio	The ratio of total CO2e emissions caused by the energy consumption of cleaning robots to the energy consumption of the robots themselves. This metric assesses the carbon footprint relative to their energy use.

Power Usage Effectiveness (PUE) for Cleaning Robots

PUE is defined as the ratio of total facility power, encompassing all energy consumed by the facility (including charging stations, maintenance units, and ancillary services), to the power specifically used by the cleaning robots for their primary function. A lower PUE is indicative of higher energy efficiency, meaning a greater proportion of the facility's energy is being effectively utilized for the core operation of the robots.

The design and operation of charging stations significantly influence the PUE for cleaning robots. As these stations are a primary energy consumer in the operational lifecycle of the robots, their efficiency directly impacts the overall PUE. This includes not only the energy used to charge the robots but also any standby power consumed when they are not in use. Implementing smart charging technologies that optimize charging cycles based on the robots' usage patterns and energy demand, and integrating energy-saving features in the charging stations, can substantially improve the PUE.

Maintenance units and ancillary systems, such as robot diagnostics and repair facilities, also contribute to the total facility power consumption. These systems, while essential for the upkeep and functionality of the robots, can vary significantly in their energy efficiency. Facilities that employ energy-efficient practices, such as using LED lighting, energy-saving tools, and automated systems that minimize power usage when not in active use, contribute to a lower PUE. Furthermore, the implementation of predictive maintenance algorithms can optimize the energy use in these units by scheduling maintenance activities based on actual need rather than predetermined intervals.

Facilities designed with energy efficiency in mind, incorporating features like natural lighting, efficient HVAC systems, and proper insulation, contribute to reduced total facility power consumption. The use of renewable energy sources to power facility operations, including robot charging and maintenance, can significantly improve the

PUE by reducing the reliance on external power sources and increasing the share of energy used directly for robot operation.

Operational practices and user behavior within the facilities also impact PUE. Efficient deployment of cleaning robots, ensuring they are operating at optimal times and conditions, can reduce unnecessary power usage. For instance, scheduling cleaning tasks during off-peak energy hours or when the facility's energy demand is low can optimize overall power usage. Additionally, training staff on energy-saving practices and fostering a culture of energy consciousness can lead to more efficient use of the facility and, consequently, a better PUE. Utilizing advanced analytics and IoT technologies to monitor energy consumption in real-time allows facility managers to identify areas where energy efficiency can be improved. Regular audits and upgrades of both the robots and the facility infrastructure ensure that the latest energy-efficient technologies are being utilized, further enhancing the PUE.

GHG Emissions Metrics for Cleaning Robots Operations

GHG Emissions

The electricity consumption of cleaning robots during operation and charging constitutes the primary source of GHG emissions. These emissions largely depend on the source of the electricity used. If the robots are charged using electricity from fossil fuel-based power plants, the associated GHG emissions are significantly higher compared to charging with electricity from renewable sources like wind, solar, or hydroelectric power.

The efficiency of the cleaning robots themselves impacts GHG emissions. Robots designed with energy-efficient motors, optimized cleaning routes, and smart operational algorithms consume less electricity, thereby reducing their carbon footprint. Advances in battery technology, which can lead to longer operation times and shorter charging periods, also contribute to lowering the total GHG emissions.

Operational practices and usage patterns significantly influence the GHG emissions of cleaning robots. For instance, in commercial or industrial settings where cleaning robots are used more frequently and for longer durations, the GHG emissions will be higher compared to residential settings. The optimization of cleaning schedules to align with times of low-carbon intensity in the electricity grid can effectively reduce emissions.

The broader adoption of cleaning robots also has implications for GHG emissions. As these robots become more prevalent in various sectors, their cumulative energy demand can contribute significantly to overall GHG emissions. This necessitates the development of industry-wide standards and practices aimed at reducing the carbon footprint of these robots. The implementation of such standards could include requirements for energy-efficient designs, the use of renewable energy in operation, and responsible end-of-life management of the robots and their components.

Carbon Intensity of Operations

When assessing the carbon intensity per cleaning robot, the focus is on the GHG emissions directly attributable to the operation of each individual unit. This includes the emissions associated with electricity used for charging and powering the robots during cleaning tasks. The intensity varies based on factors such as the robot’s energy efficiency, the type of battery used, and the source of the electricity for charging. Robots that are more energy-efficient or use cleaner energy sources (like renewables) for charging have a lower carbon intensity. Additionally, the operational patterns, such as duration and frequency of use, can significantly influence this metric. For instance, robots used more intensively in commercial settings might have a higher carbon intensity compared to those used less frequently in residential settings.

Alternatively, measuring the carbon intensity per dollar of revenue offers an economic perspective, linking the environmental impact of cleaning robots to their commercial performance. This measure is insightful for evaluating the efficiency of robots in terms of environmental cost per economic output. It can vary widely depending on the business model, pricing strategies, and market segment being served. A higher carbon intensity per dollar of revenue could indicate that the environmental impact is disproportionately high compared to the economic benefit generated, which could be a concern for businesses aiming to promote sustainable practices.

Operational efficiency plays a significant role in determining the carbon intensity of cleaning robot operations. This includes not only the efficiency of the robots themselves but also the management of their deployment. In regions where the electricity grid is largely powered by fossil fuels, the carbon intensity is likely to be higher. Conversely, in regions with a high penetration of renewable energy sources the carbon intensity can be significantly lower. This highlights the importance of incorporating renewable energy sources into the energy mix for charging these robots, either through on-site renewable energy generation or by purchasing green energy from the grid.

Carbon Usage Effectiveness (CUE) for Cleaning Robots

Carbon Usage Effectiveness (CUE) for cleaning robots, defined as the ratio of total CO_2 equivalent (CO_2e) emissions caused by the energy consumption of these robots to their actual energy consumption, is a metric in assessing their environmental efficiency.

The CUE ratio directly reflects the carbon efficiency of the energy sources used to power cleaning robots. A lower CUE indicates that a larger portion of the robot's energy consumption comes from low-carbon or renewable sources. Conversely, a higher CUE suggests a greater reliance on energy sources with higher carbon emissions. This measure helps in identifying the impact of the energy mix on the overall carbon footprint of cleaning robots and underscores the importance of transitioning to cleaner energy sources for charging and operating these devices.

The energy efficiency of the cleaning robots themselves significantly affects their CUE. Robots designed with energy-efficient components, such as high-efficiency motors, advanced battery systems, and optimized operational algorithms, consume less power for the same level of performance. This reduced energy consumption directly translates to lower CO_2e emissions, assuming the energy source's carbon intensity remains constant.

Operational practices and management strategies also play a vital role in determining the CUE for cleaning robots. Efficient deployment strategies can reduce overall energy consumption. Additionally, proper maintenance of robots to ensure they operate efficiently and the implementation of smart systems to monitor and control their energy usage contribute to a lower CUE. These practices not only reduce the total energy consumed but also enhance the operational lifespan of the robots, indirectly affecting their carbon footprint. The CUE is also influenced by the broader context of the facilities where these robots are used. For instance, in a facility powered predominantly by renewable energy, the CUE of the cleaning robots will naturally be lower. This highlights the interconnectedness of the robots' energy consumption with the wider energy infrastructure and policies.

End-of-life

End-of-Life Metrics for Cleaning Robots

Electronic Waste (E-Waste)

The issue of electronic waste (E-Waste), concerning robots and their related equipment, is becoming increasingly significant in the context of environmental sustainability and waste management. Measured in metric tons, E-Waste from cleaning robots measures the total weight of these devices and their components that become waste at the end of their usable life.

The composition and lifecycle of cleaning robots are primary factors contributing to E-Waste. These robots typically comprise a variety of materials, including metals, plastics, batteries, and electronic circuitry. Over time, wear and tear, technological obsolescence, or battery degradation can render these robots unusable, leading them to be discarded. The total weight of these discarded robots constitutes a significant portion of E-Waste, especially considering the growing market penetration and replacement rate of cleaning robots in both commercial and residential sectors.

Battery disposal is a major concern within the E-Waste category, given that most cleaning robots are powered by lithium-ion or similar batteries. These batteries have a limited lifespan and can be hazardous if not disposed of properly due to their toxic and reactive elements. The weight of these batteries contributes significantly to the total E-Waste from cleaning robots.

The rapid advancement of technology in the field of robotics leads to a shorter lifespan of electronic components due to obsolescence. As new, more efficient, and feature-rich models are developed, older cleaning robots are often discarded in favor of newer versions, exacerbating the E-Waste problem. This cycle of rapid obsolescence not only contributes to the growing volume of E-Waste but also raises concerns about sustainable consumption and production patterns. Encouraging the development of upgradable robot designs and promoting repair over replacement are strategies that can help reduce E-Waste generation.

Regulatory model and consumer awareness play a significant role in managing E-Waste from cleaning robots. Governments and international bodies are increasingly implementing regulations regarding E-Waste management, including mandates for recycling and restrictions on hazardous substances. Consumer awareness and demand for sustainable products can also drive manufacturers to adopt environmentally friendly designs and end-of-life management practices. Creating incentives for manufacturers to design robots with minimal environmental impact and for consumers to participate in E-Waste recycling programs is crucial for reducing the total E-Waste generated by cleaning robots.

Recycling Rate

The recycling rate of discarded cleaning robots, measured as a percentage, can be used for gauging the efficiency and effectiveness of recycling efforts in the context of electronic waste (E-Waste) management. This rate indicates the proportion of the total weight of these discarded robots, including their components such as batteries, motors, and electronic circuitry, that is successfully recovered and recycled.

The composition of cleaning robots plays a significant role in determining the recycling rate. These robots are typically made of a mix of materials, including various metals, plastics, electronic components, and batteries. The complexity and diversity of these materials can make recycling challenging. Metals like aluminum and steel used in the robot's structure are generally more straightforward to recycle. In contrast, complex electronic components and certain plastics may require more specialized recycling processes. The ease with which these materials can be separated and processed largely influences the overall recycling rate.

Battery recycling is a critical aspect of this metric, especially considering that most cleaning robots are equipped with lithium-ion batteries. These batteries pose specific challenges due to their hazardous nature and the complexity of their chemical composition. However, they also contain valuable materials like lithium and cobalt, which can be recovered and reused. Effective recycling of these batteries not only contributes to a higher recycling rate but also reduces the demand for raw material extraction, thereby mitigating environmental impacts.

The technology and infrastructure available for recycling also significantly impact the recycling rate of cleaning robots. Advanced recycling facilities equipped to handle complex E-Waste can achieve higher recycling rates by efficiently processing diverse materials and recovering more valuable components. The presence and accessibility of such facilities, along with the logistics of transporting E-Waste to these locations, are key factors. Additionally, technological advancements in recycling processes, such as improved methods for material separation and purification, can enhance the overall efficiency and effectiveness of recycling.

Table 4. End-of-life stage

Category	Measure	Description
Electronic Waste (E-Waste)	Metric tons	Total weight of cleaning robots and related equipment that become electronic waste when they reach the end of their usable life.
Recycling Rate	Percentage (%)	Proportion of the total weight of discarded cleaning robots that is recycled, including components like batteries, motors, and electronic circuitry.
Electronics Disposal Efficiency (EDE)	Percentage (%)	Efficiency of disposing of electronic components of cleaning robots, calculated as the ratio of e-waste responsibly processed (recycled, refurbished, or reused) to the total e-waste generated.
Percentage of Electronic Waste Sent to Landfills	Percentage (%)	Proportion of the total e-waste from cleaning robots that is sent to landfills, indicating the amount of waste not recycled or processed through environmentally friendly methods.

Consumer behavior and regulatory policies play a substantial role in determining the recycling rate. Public awareness about the importance of recycling and the availability of convenient recycling options can encourage more consumers to recycle their used cleaning robots. Robust regulatory model that mandate recycling and proper E-Waste management can significantly increase recycling rates. Regulations might include producer responsibility initiatives, where manufacturers are accountable for the end-of-life management of their products, incentivizing them to design products that are easier to recycle.

The design of cleaning robots influences their recyclability and, consequently, the recycling rate. Designing for disassembly, where robots are made with recycling in mind, can greatly facilitate the recycling process. This includes using fewer types of materials, avoiding permanent adhesives and fasteners, and clearly labeling different materials for easy identification. Such design considerations can not only streamline the recycling process but also improve the quality of the recovered materials, making them more valuable for reuse.

Electronics Disposal Efficiency (EDE)

Electronics Disposal Efficiency (EDE) is a metric measured as a percentage. It quantifies the efficiency with which the electronic components of these robots are disposed of. EDE is calculated by taking the ratio of e-waste that is responsibly processed—either through recycling, refurbishing, or reusing—to the total e-waste generated by these robots.

The effectiveness of recycling programs is a major contributor to EDE. Recycling involves breaking down the electronic components of cleaning robots and extracting valuable materials for reuse. A high recycling rate boosts the EDE, indicating a responsible approach to e-waste management. This efficiency is contingent on the existence of robust recycling infrastructure and technology capable of handling complex electronic waste. The design of the robots plays a crucial role; robots designed with recycling in mind, featuring modular components and materials that are easily separable, significantly enhance recycling efficiency.

Refurbishment and reuse represent another aspect of EDE. When parts or entire cleaning robots are refurbished for further use, they contribute positively to the EDE ratio. This practice not only extends the life of electronic components but also reduces the need for producing new materials, thereby conserving resources and energy. The feasibility of refurbishment largely depends on the initial build quality of the robots, their ease of repair, and the availability of spare parts.

The total e-waste generated is the denominator in the EDE calculation and is a measure of the environmental burden posed by the disposal of cleaning robots. Reducing this total waste is as important as increasing the rate of responsible processing. Strategies like extending the life span of robots, improving repairability, and encouraging upgrades instead of replacements can effectively reduce the total volume of e-waste generated, thus improving the EDE.

Awareness and regulatory models significantly impact EDE. Consumer awareness about the importance of responsible e-waste disposal and the availability of convenient and accessible disposal options can encourage more users to participate in recycling and refurbishment programs. Regulatory policies mandating proper e-waste disposal and producer responsibility can also lead to higher EDE, ensuring that manufacturers and consumers alike contribute to responsible e-waste management. Advances in recycling technologies that allow more efficient material recovery, the development of global standards for e-waste processing, and the integration of circular economy principles into product design and end-of-life handling are pivotal. Such innovations can make the process of recycling, refurbishing, and reusing more effective and efficient, thereby enhancing the overall Electronics Disposal Efficiency.

Percentage of Electronic Waste Sent to Landfills

The percentage of electronic waste (E-Waste) from cleaning robots that is sent to landfills is a crucial environmental metric, measured as a percentage. This figure represents the proportion of the total e-waste generated by these robots that ends up in landfills, highlighting the portion that is not recycled, refurbished, or otherwise processed through environmentally friendly methods.

The high percentage of e-waste from cleaning robots that ends up in landfills is indicative of gaps in recycling and waste management systems. This could be due to a lack of adequate recycling infrastructure, insufficient consumer awareness about recycling options, or the complexity of recycling certain components of these robots. E-waste in landfills poses significant environmental risks, including soil and water contamination from hazardous substances like heavy metals and chemicals commonly found in electronics. Therefore, reducing the proportion of e-waste sent to landfills is crucial for mitigating these environmental risks.

The design and manufacturing of cleaning robots significantly influence their end-of-life disposal. Products designed with disassembly and recyclability in mind tend to have a lower percentage of their components ending up in landfills. Conversely, robots made with non-recyclable materials or complex designs that hinder disassembly contribute to higher landfill rates. This underscores the importance of adopting design-for-recyclability principles in the manufacturing of cleaning robots, promoting the use of recyclable materials and modular designs that facilitate easier recycling and refurbishment.

Many consumers may not be aware of the proper disposal methods for these products or may not have access to convenient recycling facilities. Enhancing public awareness campaigns, providing easy access to recycling centers, and offering incentives for recycling can encourage more responsible disposal practices, thus reducing the percentage of e-waste that ends up in landfills. Regulatory model s and policies are also key drivers in managing e-waste disposal. Governments and regulatory bodies can implement policies that discourage landfill disposal of e-waste, such as landfill bans on certain electronic items, mandatory recycling schemes, and extended producer responsibility programs. These policies can compel manufacturers and consumers to adopt more sustainable disposal practices, thereby reducing the reliance on landfills for e-waste management.

Conclusion

The recent surge in the adoption of cleaning robots reflects a broader trend towards automation in both domestic and commercial sectors. Fueled by significant technological advancements, these robots have become increasingly sophisticated, efficient, and user-friendly. Predominantly powered by electricity, these machines integrate various materials and electronic components to perform a range of cleaning tasks. However, the rise in their popularity and use brings into focus the environmental implications associated with their life cycle. From the extraction of raw materials needed for their production to their eventual disposal or recycling, each stage of a cleaning robot's life has potential environmental impacts. These impacts include energy consumption during use, emissions during manufacturing, and waste generation at the end of their service life. As cleaning robots become more common, it is vital to understand and address these environmental challenges to ensure that the benefits of this technology do not come at an undue ecological cost.

Life Cycle Assessment (LCA) offers a structured approach to evaluate the environmental footprint of products throughout their life span. This methodology encompasses all stages of a product's life, starting from the extraction of raw materials to the processing of these materials, manufacturing, distribution, usage, and finally, repair, maintenance, and disposal or recycling. LCA serves as a tool in making informed decisions in product development, helping manufacturers and policymakers choose options that are more sustainable and environmentally friendly. LCA can reveal insights into the most impactful stages of their life cycle, guide improvements in design and manufacturing processes, and suggest more sustainable practices in their use and disposal [7].

Most existing LCA models are too generic to accurately reflect the unique characteristics and usage patterns of cleaning robots. This limitation is significant because the environmental impact of these robots can vary greatly depending on factors like their energy efficiency, the materials used in their construction, and their durability. For example, a robot designed for heavy commercial use might have different environmental impacts compared to one designed for light domestic use. The lack of a dedicated LCA model for cleaning robots signifies a gap in our understanding of their environmental impacts. Developing a specialized LCA model for these devices would enable a more accurate assessment of their ecological footprint. Such a model would need to take into account the specific materials, energy use patterns, and disposal methods relevant to cleaning robots, leading to more effective strategies for reducing their environmental impact.

The thoroughness allows the LCA to cover a broad spectrum of environmental issues across all life cycle stages of cleaning robots: production, transportation, operation, and end-of-life. Such an all-encompassing approach can be useful for identifying significant environmental impacts at each stage. For instance, during the production phase, LCA can shed light on the environmental consequences of materials and manufacturing processes used in cleaning robots. Similarly, in the operational phase, it can assess energy consumption and its environmental footprint. This analysis is also useful in pinpointing areas where environmental impacts are most pronounced, guiding targeted improvements and innovations in the design and use of cleaning robots.

LCA may fall short in capturing the details of every individual process or the unique environmental implications of specific materials and technologies employed in cleaning robots. This limitation is relevant when considering the diverse range of components and varied manufacturing processes involved in robot production. Additionally, simplifications in modeling the environmental impacts might lead to overlooking certain subtle yet critical aspects, such as region-specific environmental effects or the long-term implications of certain materials and technologies. Therefore, LCA might not always provide the details needed to fully understand and address every environmental nuance associated with cleaning robots.

The application of the *best estimate* principle in LCA facilitates unbiased comparisons, which is advantageous when evaluating different cleaning robot systems or comparing these robots to alternative cleaning methods. This principle ensures a consistent level of precaution and methodology across various assessments, allowing for a fair and balanced comparison of environmental impacts. However, this approach has its limitations. It implies that LCA assessments are based on average performance data, which may not consider the risks associated with rare but severe environmental incidents. This is a significant consideration for cleaning robots, as the technology and usage scenarios can vary widely, potentially leading to environmental impacts that are not adequately captured by average data. For instance, a rare malfunction in a robot's battery system might have serious environmental repercussions, which would not be accounted for in an LCA based on typical performance metrics. Thus, while the "best estimate" principle aids in unbiased comparison, it may not fully encompass the spectrum of potential environmental risks associated with cleaning robots.

LCA can determine which cleaning robot model or system is more environmentally friendly relative to another, but it does not necessarily indicate that the preferred option is sustainable in absolute terms. This is a crucial distinction, as it highlights the need for ongoing evaluation and improvement. Simply because one cleaning robot performs better in an LCA compared to another does not make it wholly sustainable. It is essential to recognize that sustainability is a moving target, requiring continual advancements and reassessments. This limitation shows the importance of not only using LCA as a comparative tool but also as a means for continuous improvement in the environmental performance of cleaning robots. It serves as a reminder that achieving sustainability is process, necessitating regular updates and refinements to LCA methodologies and the environmental strategies employed in the design and operation of cleaning robots.

References

[1] F. Stuhlenmiller, S. Weyand, J. Jungblut, L. Schebek, D. Clever, and S. Rinderknecht, "Impact of Cycle Time and Payload of an Industrial Robot on Resource Efficiency," *Robotics*, vol. 10, no. 1, p. 33, Feb. 2021.
[2] L. Li *et al.*, "Life Cycle Greenhouse Gas Emissions for Last-Mile Parcel Delivery by Automated Vehicles and Robots," *Environ. Sci. Technol.*, Jul. 2021.
[3] F. Cherubini, S. Bargigli, and S. Ulgiati, "Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration," *Energy*, vol. 34, no. 12, pp. 2116–2123, Dec. 2009.
[4] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," *Renewable Sustainable Energy Rev.*, vol. 28, pp. 555–565, Dec. 2013.
[5] P. Miettinen and R. P. Hämäläinen, "How to benefit from decision analysis in environmental life cycle assessment (LCA)," *Eur. J. Oper. Res.*, vol. 102, no. 2, pp. 279–294, Oct. 1997.
[6] M. Pehnt, "Dynamic life cycle assessment (LCA) of renewable energy technologies," *Renewable Energy*, vol. 31, no. 1, pp. 55–71, Jan. 2006.
[7] S. E. Zerkane, J. Vareille, Y. Autret, and P. Le Parc, "Lca in robotics, new challenges for the future," 2014. [Online]. Available: https://core.ac.uk/download/pdf/52841563.pdf.