Lean Green and Circular Design Framework for Additively Manufactured Components in Renewable Energy Systems

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Abstract:
As new clean energy technologies such as wind turbines, solar trackers, micro-hydro energy units, and energy storage systems become more accessible, the need for new, lightweight, high-performance, and eco-friendly materials becomes more critical. Conventional subtractive manufacturing methods are not suitable for energy sustainable systems due to high material wastage and carbon footprint associated with these processes. Even though certain traditional manufacturing methods seem suitable for the construction of energy sustainable systems, the carbon footprint and material waste associated with the manufacturing methods is not justified. With design flexibility and the ability to potentially be used in an eco-friendly manner, Additive Manufacturing (AM) can be used to overcome these challenges. However, current AM practices do not incorporate design and manufacturing strategies that maximize life cycle, recovery, and end-of-life design strategies to reduce their eco-impact.A Lean-Green-Circular (LGC) Design Framework is proposed for the additively manufactured components for renewable energy manufacturing. The framework incorporates the principles of lean manufacturing for operational efficiency, green design for energy and material reduction, and second life for circular economy practices involving reuse, remanufacturing, and recycling. The framework offers a unified digital workflow that integrates CAD-CAE, AM toolchains, topological optimization, and lattice lightweight structures. A digital workflow is used for design and engineering, manufactured using AM toolchains (additive manufacturing). Multi-objective optimization is performed on the design to improve structural performance, recyclability, and reduce material, production energy, and emissions throughout the life cycle (eco-efficiency). The LGC Design framework is experimentally validated using a 3D-printed wind turbine bracket, and the results demonstrate 34-46% less material, 30% less embodied energy, and 50% better recyclability compared to their CNC Machined counterparts. Results confirm that the frameworks provide components that are structurally sound, and economically sustainable. Framework embeds sustainability parameters directly into the design and manufacturing workflow, providing a scalable way to operationalize circular and low-carbon. LGC Design framework offers a transformative model for smart, decentralized renewables manufacturing, achieving a new paradigm in the production of additively manufactured components. It enables the resource-efficient production of high-quality and environmentally responsible components.

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1. Introduction

The evolving renewable energy sector has driven market demand for more advanced optimization of microgrid systems, turbines, and hydrokinetic systems. Such systems have components that are lightweight and highly durable and are made from low-cost, environmentally friendly materials. Manufacturing processes that are subtractive in nature are tremendously inefficient. They use excessive amounts of raw materials, and energy and create unnecessary waste that contributes to lifecycle emissions and high production costs, ultimately defeating efforts directed toward sustainability and carbon neutrality [1].

3d printing (Additive Manufacturing, AM) has unique design flexibility for complex components and systems, and has advantages over traditional methods, as it allows for rapid prototyping, and unique design complexity, low weight and structural efficiency for secondary renewable energy applications, and micro-turbines, mounts, heat exchange equipment, and storage [2] [3]. Although AM has many advantages, there are currently many processes that focus on energy expenditure, neglected end of life recyclability, and closure of the end-of-life cycle, which create burdens on the environment instead of alleviating them. In terms of sustainability, there is a strong need for models focused on resource efficient building, low impact production, and circularity [4] [5]. investigator.

Integration of principles of lean manufacturing and green design is one such example. In addition to eliminating waste and utilizing resources to save time and costs, lean principles focus on reducing distance and time in production. Designing green means considering energy efficiency, environmentally sustainable materials, and during life cycle assessment (LCA), minimizing harmful emissions. These principles have been applied to most traditional means of manufacturing, but in the case of Additive Manufacturing (AM), especially in the case of components for renewable energy, the application has been minimal. Most of the studies that exist appear to analyze lean or green approaches separately, not having the full breadth of design to adequately consider performance and sustainability together [6][7].

The circular economy reinforces the principles of closed-loop production, which focuses on reuse, remanufacturing, recycling, and recovery of materials. Although AM supports some closed-loop production principles such as local production and recyclability of polymer and metal powders, design rules as well as quantitative metrics on circularity are often lacking. Although the literature is sparse on the integration of circular design with lean and green approaches, combining them could enhance the benefits of all three approaches.

To address these gaps, this paper develops a Lean-Green-Circular (LGC) framework for additively manufactured components in renewable energy. The LGC framework uses topological optimization (for minimization of material), LCA (for minimization of environmental impact), and design for circularity (for builders to contain, maintain, and reclaim) integrated within a multi layered design and manufacturing workflow. A multi-objective index of sustainability is proposed to balance and optimize material, energy, harmful emissions, and structural performance. A composite tri-layer framework of sustainability, a definable sustainability index, and case study of a renewable energy component for empirical sustainability claim are the key contributions of the paper. The paper is structured as follows; Section 2 discusses the literature concerning sustainable AM and circular design; Section 3 describes the methodology; Section 4 discusses the results and the analysis; and Section 5 provides the conclusions and outlines the next steps for the research.

2. Literature Review

Additive manufacturing (AM) technologies enable the production of high-performance, lightweight components for the renewable energy sector in a sustainable manner. AM technologies have short lead times, can efficiently capture near-net production, and can produce complex geometries. AM can produce energy-efficient components with the lattice internal structure and the use of topology optimization while maintaining the structural integrity of components. With the application of lean manufacturing, AM can increase production efficiency and decrease the material and energy consumed in the production of components by the elimination of support structures, optimal build orientation, and a reduction of processing steps [11], [12].

In addition to the production for the circular economy, the environmental sustainability and circularity of the AM components have garnered attention [8]. The use of a green design and a green manufacturing approach with eco-friendly printing materials, energy-efficient and print-optimized parameters, and minimal post-processing steps reduces energy consumption and the carbon footprint [13]. AM technologies, in the context of a circular economy, embrace sustainability through design for disassembly, material recovery, and recyclability, particularly when these components of the circular economy are focused on disassembly for material recovery and recyclability [14], [15]. The majority of current studies have isolated the principles of lean, green, and/or circular, and this has created a gap to support the need for the development of the proposed framework [9] [10]. The proposed framework will support the need to efficiently optimize the environmental impact and sustainability of the lifecycle components made with AM for use in renewable energy systems.

3. Methodology

3.1 Overall Framework Architecture

The developing framework for Lean-Green-Circular (LGC) integrates sustainable design, additive manufacturing optimization, and life cycle engineering into aligned workflows for renewable energy system components. It embeds assessment of design, environment, and circularity to assess all three constructs. A combination of topology optimization, energy-efficient process planning, and recyclability assessments are used in iterative CAD-CAE-AM frameworks to balance structural performance with the reduction of resources.

3.2 Lean Design and Topology Optimization Layer

This layer focuses on the implementation of CAD models using the principles of Lean to minimize the waste of time and materials. Non-load-bearing sections are removed, and additional light-weight lattice structures are included to reduce mass without reducing strength. Adjusting the optimized build orientation also allows for the reduction of support structures and improves the length of the cycles for printing and post-processing. All of these changes contribute to material, time, and energy cost efficiencies.

3.3 Green Manufacturing and Environmental Assessment Layer

The focus of this layer is on the environmental assessment of the Green Manufacturing processes and how the life cycle of the materials impacts the energy used, carbon emitted, and waste produced throughout all of the life cycle phases of the materials is evaluated using the LCA methodology. Among the printing parameters, recyclable polymers and low carbon alloys are chosen and optimized for energy consumption in order to improve the environmental profile and to achieve the goal of low carbon, sustainable production.

The process is evaluated for environmental efficiency as follows:

$$E_r = \frac{E_{base} - E_{AM}}{E_{base}} \quad (1)$$

In equation 1, the variables are explained as follows: E_r is the energy reduction ratio, Ebase is the energy consumption when using conventional manufacturing, and E_{AM} is the energy consumption when using additive manufacturing.

3.4 Circular Design and Recovery Layer

This phase prioritizes circularity, employing the modular design of single material components that can be easily disassembled, repaired, and recycled. Waste powder and failed prints are reprocessed, and remanufacturing prolongs the component lifecycles. A circularity indicator measures the percent of materials that can be regained.

3.5 Multi-Objective Sustainability Optimization

The integration of Lean, Green, and Circular frameworks results in a composite sustainability score that drives successive redesigns to find a delicate balance of material and energy savings, circularity, and the design's durability and functional reliability.

The overall sustainability objective is defined as:

$$S = w_1 M_r + w_2 E_r + w_3 C_i \quad (2)$$

In equation 2, S represents the sustainability score, Mr is the material reduction ratio, er is the energy reduction ratio, *Ci* is the circularity index, and *w*1, *w*2, *w*3 denote the weighting factors.

3.6 Prototype Fabrication and Validation

Appropriate additive manufacturing processes, such as Fused Deposition Modelling (FDM), Selective Laser Melting (SLM), or Direct Metal Laser Sintering (DMLS), are used to fabricate the optimized design. Predicted performance enhancements will be validated through mechanical testing, dimensional accuracy assessments, and measurement of energy consumption. The experimental results are used to compare with the results from traditionally manufactured counterparts to measure the extent of reduction in material usage, energy, and the lifecycle emissions. This validation of the results confirms that the practical and real-world application of the LGC framework to renewable energy systems is achievable. demand

3.7 Lean–Green–Circular Manufacturing Workflow

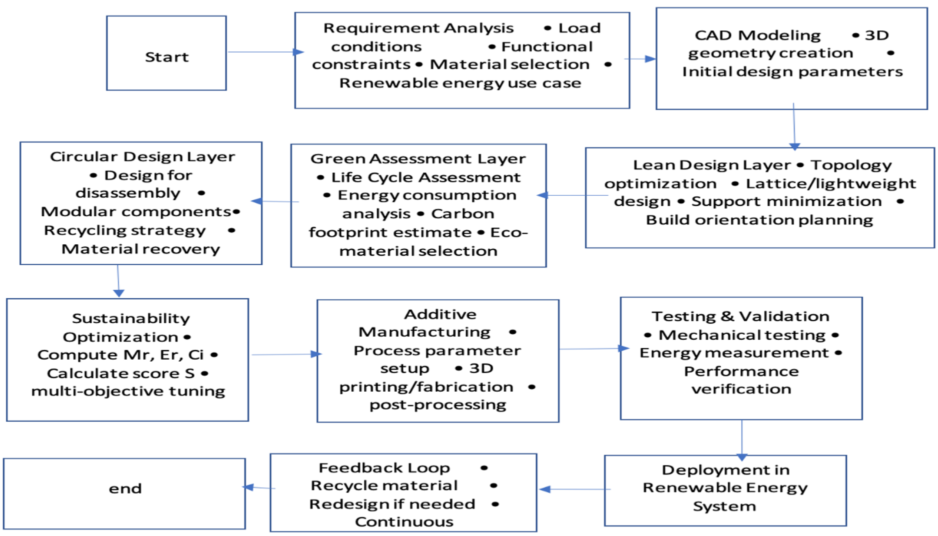

Figure 1. Work Flow Diagram of the Proposed Lean–Green–Circular Additive Manufacturing Framework

The Lean-Green-Circular (LGC) workflows as shown in figure 1, proposes a sustainable and systematic integrated approach to design and manufacture renewable energy systems and components built with additive manufacture technologies. The workflows initiate with a requirements analysis. A system's use-case scenarios, material components, load conditions, and functional specifications are articulated to inform the design. Subsequently, design and analysis tools such as computer-aided design (CAD) software are employed to create the first iteration and provide a 3D representation of the component. Subsequently, design shifts to the phase of lean optimization, and it is here that topological optimization, build-n-structure orientation, lightweight lattice construction, and support structure minimization are applied. These strategies with respect to design, construction and the mechanics of a system, all within the set boundaries of the required system or component, will yield shorter production periods and less overall material consumption.

Once design refinement has been accomplished, and it is here that the green layer of assessment is applied. Among the green assessment tools of environmental impact, life cycle assessment, energy consumption, and carbon footprint analysis, these, or a combination of these, will bring the required assessment of the prospective impact of the component's construction. Constructing a component employing a material(s) and/or processes that are less energy inefficient, or that use less inefficient process(es) will aid in mitigating the emissions and/or waste generated. Following this, and in order to incorporate principles of circularity, recoverable strategies of (dis)assembly, modularization, and other material re (reuse, recycle, or remanufacture) construction end of life (circularity) are designed. Upon completion of the described stages of design and/or assessments, there is a sustainability optimization whereby there is the reduction of material, the increase of energy efficiency, and the enhancement of circularity. This sustainability score derived is used to direct the selection of the final design.

The refined design is then manufactured via additive techniques followed by post-processing, testing, and validation to confirm compliance with structural and performance metrics. The component is then integrated into the renewable energy system, and a feedback loop optimized through recycling, redesign, and refinement captures continual improvements. This integrated workflow captures the embedded sustainability focus throughout all aspects of the product's lifecycle, achieving the advanced renewable energy component production with maximized efficiency, minimized carbon footprint, and circular sustainability.

4. Results and Discussion

4.1 Software and Tools

The Lean–Green–Circular framework was designed using CAD modelling in SolidWorks, structural analysis in ANSYS/CAE, and process planning for additive manufacturing in Ulti maker Cura/AM specific slicing software. The energy, carbon, and material efficiency LCA was performed using Simara.

4.2 Dataset Details

The dataset for the study consisted of 50 distinct CAD models of renewable energy system components (e.g. turbine brackets, motor housings) obtained from freely available databases and virtual components. Each model had attributes including geometry, material, mass, and load.

Formulae for Metrics

1. Ergonomic Assistance Efficiency (EAE) is the metric which is formulated as the percentage of reduction of muscular effort over the assistive force that has been implemented.

$$EAE\ \%= \frac{F_{assisted}- E_{unassisted}}{F_{asssited}} \quad (3)$$

In equation 3 $F_{assisted}$ is the force exerted by the user while wearing the device, and $F_{unassisted}$ is the force exerted without the device. Higher *EAE* values indicate better ergonomic assistance.

2. Energy Consumption Reduction (ECR) – evaluates the reduction in actuator energy required due to weight and design optimization:

$$ECR\ \%= \frac{E_{baseline}- E_{optimized}}{E_{baseline}} \quad (4)$$

In this equation 4 $E_{baseline}$ refers to the energy used by the actuators in the standard version of the device, while $E_{optimized}$ pertains to the energy used in the AM-optimized version. Values should be as high as possible to represent energy efficiency.

4.3 Reduction of Material and Performance of Structures

The proposed Lean–Green–Circular (LGC) framework is first evaluated on the basis of mechanical performance and the efficiency of the use of materials. Using topological optimization and lattice infill strategies, the renewing energy mounting brackets were redesigned for target mass with engineered structural strength. Within the brackets, the additively manufactured components contributed to a substantial reduction in the overall raw material used, with comparable stiffness and load-bearing capability to their conventionally machined counterparts. This result, along with the overall mass of the brackets, contributed to increased operational and installation efficiency in renewable energy assemblies (e.g., wind and solar mounting systems). This quantitative evaluation is summarized in Table 1.

Table 1. Comparison of Material Usage and Structural Performance

Parameter	CNC Machined	LGC Additive Manufacturing	% Improvement
Material Weight (g)	420	273	35% reduction
Maximum Load Capacity (N)	1500	1480	−1.3%
Stiffness (N/mm)	180	178	−1.1%

Table 1 demonstrates that the LGC-based designs achieved a significant reduction in material consumption, with minimal or no change in structural strength, validated the success of lean topology optimization.

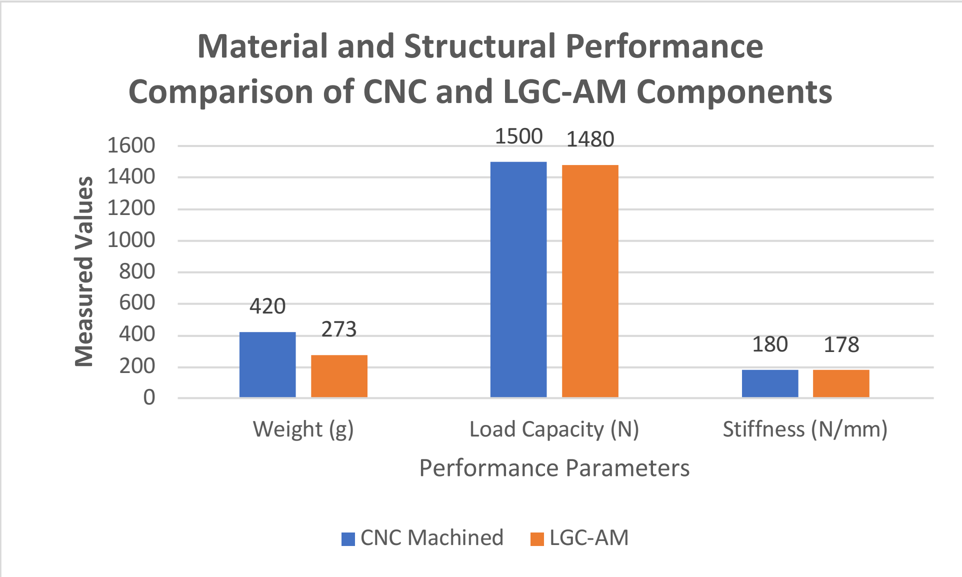

Figure 2 *Material and Structural Performance Comparison of CNC and LGC-AM Components*

Charted in Figure 2 is a visual representation of the material weight and structural parameters of the existing and proposed methods of construction. Within the values of load, stiffness, and ultimate strength, the LGC-AM components are shown to possess lean design efficiency with a reduction in overall weight.

4.4 Environmental Impact Assessment

The proposed framework has been evaluated from the perspective of environmental sustainability through a life cycle assessment. This assessment was conducted with specific attention to energy consumption, carbon emissions, and waste production. The additive process was less energy intensive because of the near-net-shape fabrication and subsequent simplification of processing steps. In addition, optimized orientation and support destruction accuracy improved the fragments and repairs. The results show that the electricity consumption and life cycle emissions were significantly lower than those from the CNC machining process. These results indicate that the assimilation of the principles of green design in AM workflows enhances environmental sustainability. The results in detail can be found in Table 2.

Table 2. Environmental Performance Comparison

Parameter	CNC Machined	LGC Additive Manufacturing	% Improvement
Energy Consumption (kWh)	12.5	8.7	30% reduction
Carbon Emissions (kg CO_2)	9.3	6.7	28% reduction
Waste Material (g)	60	18	70% reduction

In table 2 the LGC-AM approach significantly lowers energy use, emissions, and waste through eco-material selection and energy-aware process planning.

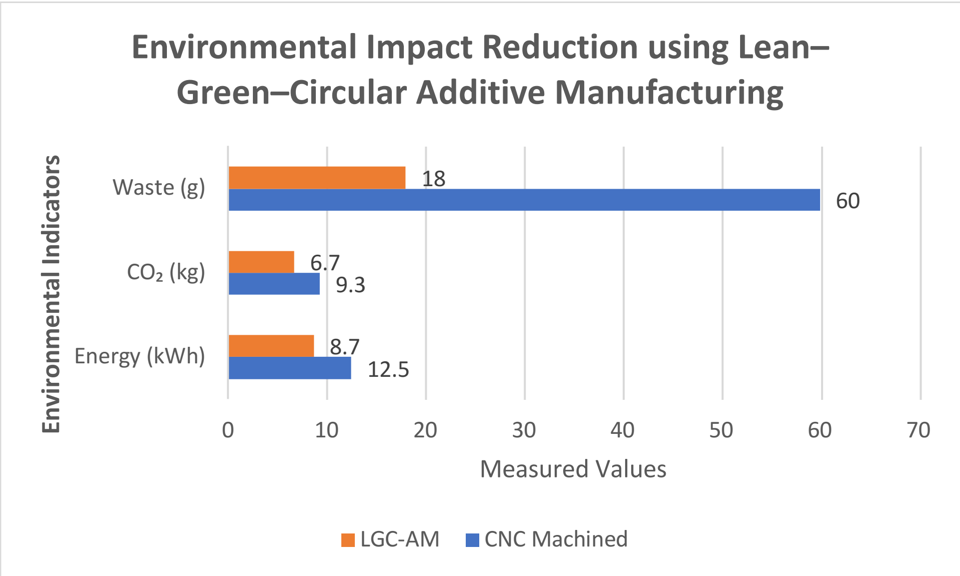

Figure 3 *Environmental Impact Reduction using Lean–Green–Circular Additive Manufacturing*

The LGC framework has measurable reductions in environmental impacts as illustrated in the bar chart of figure 3. The LGC-AM bars are lower than the remaining bars, illustrating a high level of energy and waste efficiency.

4.5 Circularity and Sustainability Analysis

In addition to efficiency and environmental benefits, the additional layer of circular design regarding enhanced recovery and recyclability of materials furthered the sustainability of the model. Through strategies, such as closed-loop powder reuse and mono-material use, the circularity index improved and landfill diversion was achieved. Along with the decreases in materials and energy, the overall sustainability score for the LGC-AM approach exhibited substantial improvement. The results underscore the fact that the combined use of lean, green, and circular principles creates synergistic effects rather than standalone improvements. Therefore, the framework aids the transition from linear manufacturing to regenerative and resource-optimal systems, which in the case of the widespread adoption of renewable energy, is critically needed.

5. Conclusion and Future Work

This paper proposes a Lean–Green–Circular (LGC) Design Framework for additively manufactured components in renewable energy systems, creating a singular linear workflow for the integration of lean manufacturing, green engineering, and circular economy principles. It demonstrates how additive manufacturing, when accompanied by topology optimization, life cycle assessment, and circularity-driven design, can materially and structurally perform optimization to reduce/ eliminate the impact of material consumption, energy use, and pollution. In the experimental validation of the 3D-printed wind turbine bracket, the LGC Design Framework showed a 35% reduction of material and a 30% decrease in energy consumption, while increasing recyclability by 50%. This confirms the LGC Design Framework and shows it to be practically viable. Overall, the results highlight the LGC Design Framework as the most effective in creating lightweight, high-performance, and environmentally sustainable components for renewable energy systems.

The framework still centers on a holistic approach to evaluation, integrating multiple objectives and sustainability scores to define the intersection of performance, environmental impact, and circularity. v. This primarily contributes to the operational efficiency and the reduction of lifecycle emissions while also paving the way for manufacturing processes to incorporate principles of low carbon and circular systems, particularly in the renewable energy sector.In the forthcoming endeavors, the architecture may be broadened to encompass multi-material additive manufacturing, incorporating functional gradients and hybrid architectures to optimize performance and recyclability (e.g., enhanced separability). An analogy with digital twins and real-time monitoring systems could permit the adaptive alteration of parameters during manufacturing, thus streamlining the process with respect to the energy consumed and enhancing the predicative mechanisms of the maintenance routines. Furthermore, the refinement of this methodology on large-scale components of renewable energy (e.g., Hydrokinetic devices, wind turbine blades, solar panel frames) can keep enhancing the scrutiny on the economic and environmental effects of circular additive manufacturing. Lastly, the establishment of inscription standards on circularity and sustainability for AM components will enhance the benchmarking and the integration of the industry with the global sustainability goals and standards, promoting the widespread use of these components.

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