Sustainability and Environmental Impact of Additive Manufacturing: A Literature Review

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Abstract. This paper reviews progress of the latest research on sustainability of Additive Manufacturing (AM). The review covers studies on the complete lifecycle of AM processes and additively manufactured products. AM sustainability evaluation methods are analyzed including the lifecycle assessment, comparative and predictive sustainability assessment frameworks, energy modeling, and sustainability improvement strategies for different types of AM processes. The review provides discussions and conclusions to highlight the current research, research gaps and recommendations for the future research on AM sustainability. The investigation shows that AM has a great potential to achieve sustainable solutions. It is found that the energy consumption is a major contributor to the environmental impact of AM whereas the design for lightweight products can effectively improve the sustainability of AM.

Keywords: Additive manufacturing, 3D printing, Sustainability, Environmental impacts, Energy consumption, Material consumption.
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1 INTRODUCTION

Additive Manufacturing (AM) uses the technique of joining materials, usually layer upon layer to make objects, as opposed to subtractive manufacturing (SM) or conventional manufacturing (CM) where an object is made by removing material processes such as turning, drilling, and milling [19]. AM has many advantages over traditional manufacturing. For example, complex geometries and light weight parts can be easily fabricated [5, 47, 64, 65, 70]. AM has wide applications in aerospace, automobile, medical and dental industries [44, 47]. Stronger, lighter and more durable parts are possible using AM for industry to adapt this technology [17]. For example, Laser Engineered Net Shaping (LENS) has been used to manufacture mixing nozzle for the gas turbine exhaust [65], Electron Beam Melting (EBM) used AM to fabricate the compressor support case for gas turbine engines [5]. Similarly, manufacturing of artificial organs, tissue scaffolds and dental implants has become possible in medical and dentistry using AM technology, such as the creation of cardiac tissue via 3D bio-printing technology [28], formation of tissue-engineered trachea [70], and fabrication of interim crowns [56]. Although AM is an emerging technology with the great potential, it still has limitations in sustainability, reliability, productivity, robustness, material limitations and quality for industries to adapt this technology [2, 4, 63, 80].

AM technologies are classified into seven different types based on ASTM International Committee [18, 19]. They are Material Extrusion (ME), Material Jetting (MJ), Binder Jetting (BJ), Sheet Lamination (SL), Directed Energy Deposition (DED), Powder Bed Fusion (PBF), and Vat Photopolymerization (VP). Differences of these technologies are the way of layers deposited, and type of materials used. An AM process consists of product modeling, designating printing layers and orientations, printing with appropriate building parameters, and post-processing for the final finish of geometry.

Table 1 shows the analysis of current review papers on sustainability of AM. The objective, methodology and focus of these review papers are investigated [1, 24, 37, 73, 82, 86]. This paper reviews research on AM sustainability in complete lifecycle of AM processes. The progress of the latest studies is analyzed on sustainability and environmental impacts of AM, covering different types of AM technologies including the complete lifecycle of AM processes and additively manufactured products (AMP), i.e., from the raw material production, product design, printing, post-processing to the product end-of-life. AM product lifecycle assessment (LCA), comparative and predictive sustainability assessment frameworks, environmental impact assessment, energy modeling, investigation and optimization of AM process parameters and environmental impact improvement strategies for different type of AM processes are discussed.

Following parts of this paper will first provide an overview of methodology of the literature review. Literature is then classified and analyzed for studies on sustainability and environmental impacts of AM to highlight the current research and methods. Finally, the discussion and recommendation are provided to identify gaps, limitations and opportunities of the future work.

2 METHODOLOGY

Our method of the literature review is shown in Figure 1. Sustainability of AM has 3 dimensions, environmental, economical and social sustainability. Our scope focuses on the environmental impact analysis of AM technologies. Databases of Scopus, Web of Science and Science Direct were used in searching relevant papers covering the scope. Keywords used for searching papers were "sustainability", "environmental impacts", "energy consumption" and "additive manufacturing", "3D printing". Over 100 papers were selected for the detail review after screening over 300 papers collected. The selection criteria were contents of environmental impacts of AM. The papers were selected after analyzing titles (20 papers excluded), abstracts (70 papers excluded) and paper contents (110 papers excluded). Detailed analysis was performed for the selected articles in the review. The analysis and summary of the state of research were conducted. Discussions present the current research focus, methods, gaps and opportunities on sustainability and environmental impacts of AM. The reviewed papers indicate that most of research on sustainability of AM was conducted in the last 10 years as shown in Figure 2.

3 SUSTAINABILITY OF ADDITIVE MANUFACTURING

The report "Our Common Future" highlights importance of sustainability in industrial sector and recommends the sustainable development [81]. A comprehensive assessment of AM from a global sustainability perspective shows that AM has the potential to reduce CO_2 emissions 130.5–525.5 Mt and the total primary energy consumption 2.54–9.30 EJ by 2025 [25]. However, while claiming advantages of the environmental aspect [2, 4], there is limited research on the environmental impact of AM technologies. Common issues considered in research on sustainability of AM for all three dimensions of sustainability, i.e., environmental, economical and social sustainability are indicated in Figure 3. This study aims at methods used for the sustainability assessment, environmental impact assessment and energy modeling of AM. Different methods such as LCA, energy and material modeling, predictive and comparative models, multi-criterion decision-making tools, genetic algorithms, linear regression, Internet of Things, optimization of printing process parameters, bioinspired geometries and design for AM methods are proposed to evaluate, predict, compare and improve environmental impacts of AM technologies in four categories: environmental sustainability from the LCA perspective, energy modeling, sustainability assessment methods, and environmental impact improvement strategies as follows.

Author & Year	**No. of papers reviewed**	**Timeframe of papers**	**Review Characteristics**
[Garcia et al. 2018]	43	1999-2016	— Methods and tools were analyzed for evaluating AM environmental impacts and in particular, the lifecycle assessment method. — Systematic review method was used to analyze the selected literature. — The review analyzed LCA aspects, impacts, energy consumption, dimensions and methods.
[Saade et al. 2020]	52	2011-2018	— Literature was reviewed for AM lifecycle environmental impacts. — Systematic review method was used to analyze literature. — The review identified challenges and trends on loads measurements focusing on the construction sector.
[Suarez et al. 2020]	73	2009-2020	— Environmental issues of AM technologies were analyzed. — The review focused on environmental issues of FDM considering environmental impact, product LCA, emissions, energy and material consumption.
[Kellens et al. 2017]	105	1999-2017	— Environmental dimensions of AM were analyzed covering different aspects of LCA, LCI, comparative models AM vs CM and impact improvement strategies. — Literature was structured according to environmental impact assessment considering AM feedstock production, unit processes and post treatment, environmental process modeling and impact improvement strategies, AMP lifecycle benefits, AM health and safety issues.
[Agarwal et al. 2019]	63	1999-2019	— Sustainability of AM was analyzed using the Triple Bottom Line approach i.e. economical, society and environment aspects. — Systematic review method was used to analyze sustainability of AM. — Review analyzed literature according to three dimensions of sustainability, environmental dimensions (environmental and sustainable aspects, energy consumption, design optimization and LCA) — A framework for sustainable AM was proposed.
[Peng, Tao et al. 2018]	100	1999-2017	— Sustainability of AM was analyzed with a focus on energy and environmental impacts. — Review analyzed literature according to environmental aspects (Resource, waste and pollution), lifecycle perspective, high-level statistics and forecasts, eco-design for AM, Process- and system-specific modeling and multi-criteria optimization.

Table 1: Summary of present review papers on sustainability and environmental impacts of AM.

3.1 Environmental Sustainability of AM from LCA Perspective

Most of the studies used LCA to study environmental impacts of AM [21, 33, 35, 36]. LCA has the advantage to study AM impacts for the complete lifecycle of an AMP. Main LCA stages are from the material production, product printing and usage to end-of-life. LCA methods, LCI databases and commercial software tools used to perform LCA for different AM technologies found in literature are summarized in Table 2.

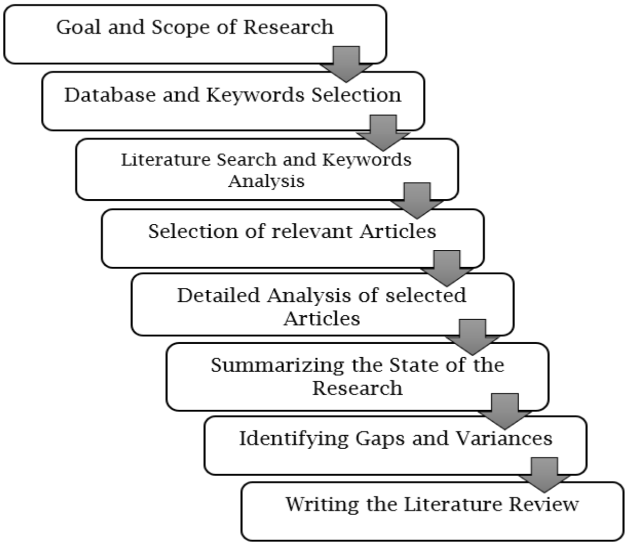

Figure 1: Literature review method.

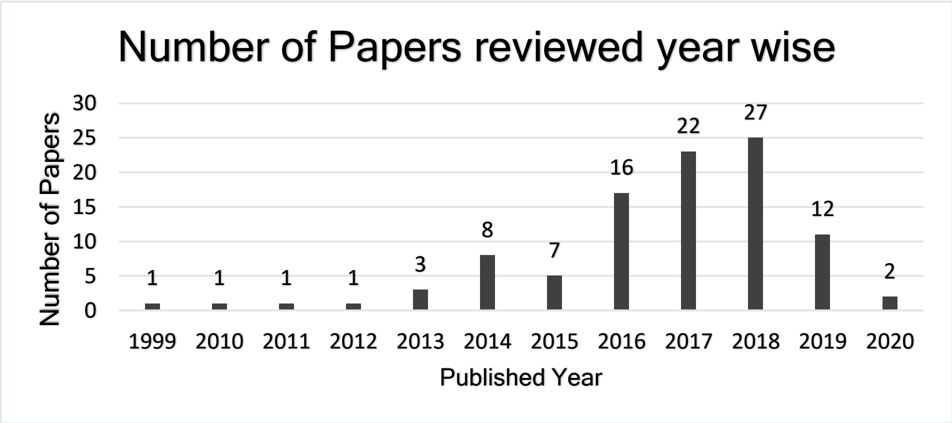

Figure 2: Reviewed papers.

ReCiPe Endpoint H is the most used method and EcoIndicator database is the mostly used LCI database. Resource flows can be analyzed for energy, material waste and emission [52]. LCA dimensions used in most of the studies are Cradle-to-Gate and Cradle-to-Grave [12, 20, 33, 59]. The Cradle-to-Gate includes the lifecycle up to the AM stage, whereas the Cradle-to-Grave includes usage and the end-of-Life stage too. An approach for the LCA framework i.e. Conception-to-Grave was presented for LCA of AMP [54]. The framework considered all three dimensions of sustainability and the impact of product design in LCA of AMP. The environmental performance analysis of different AM technologies was studied by a lifecycle based hierarchical process model [51]. LCA stages were divided into different life phases to evaluate environmental impacts of each phase using environmental and resource management data.

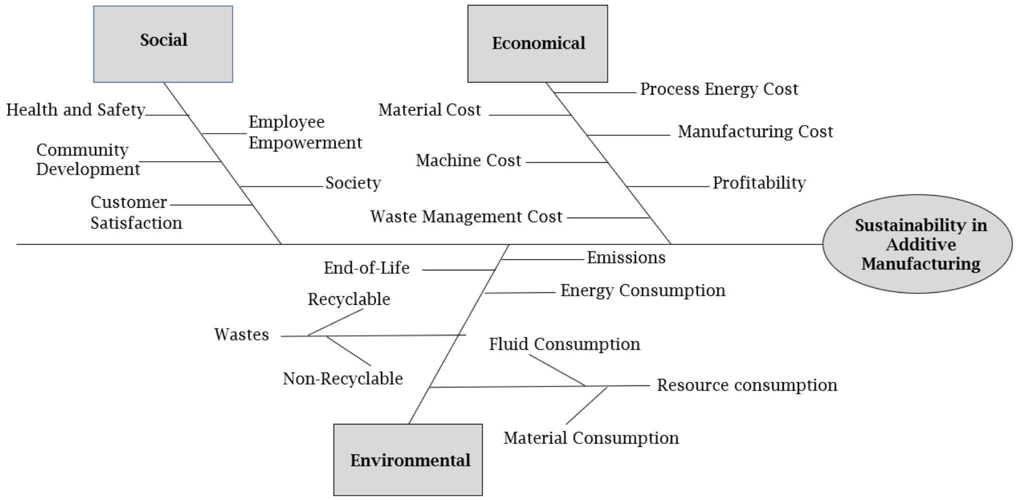

Figure 3: Issues of AM in three dimensions of Sustainability.

A study presented an overview of available lifecycle inventory studies for environmental impacts of different AM technologies, SLM, SLS, EBM, FDM and SLA [38]. It showed that the energy consumption was the main focus in most of the studies whereas the resource consumption, direct and indirect emissions were not well documented. Feedstock production and post-processing stages were not paid enough attention whereas they have the great impact on the assessment. It was recommended that an in-depth LCA for AM is required to cover all lifecycle stages. A unit-process level model was proposed to provide LCI data for LCA of a Binder-Jetting AM process to evaluate the energy and material consumption [59]. A framework was proposed according to ISO 14044 LCA and using Eco-Indicator 99 to assess the environmental impact of Powder Bed Fusion in the commercial vehicle production. The proposed method showed how to determine the improvement that is essential to reduce environmental impact of the component over lifecycle with AM implication[14]. LCA was used to study environmental impacts of selective laser melting (SLM). Environmental impacts were decided by the embodied energy, ReCiPe Endpoint H and ReCiPe Endpoint H/A methods in SimaPro software using the EcoInvent database [20]. Results showed that the process electricity consumption dominated environmental impacts for nearly all scenarios.

3.1.1 Integrated LCA models

Emergy-based LCA method was proposed to evaluate the sustainability of LENS AM and CNC machining process [33]. An Emergy-based sustainability index was formed as a ratio of the Emergy yield and Emergy loading. Emergy-LCA is a systematic tool to integrate environmental, economical and social dimensions together to analyze challenges of sustainability assessment. Their case study showed that LENS AM has much higher sustainability than the CNC machining process. Environmental impacts of Direct Metal Laser Sintering (DMLS) of the iron metal powder was investigated using the exergy analysis and Lifecycle impact assessment (LCIA) by performing a thermodynamic (exergy) analysis of resources and energy consumed or lost from the cradle to gate lifecycle to identify systematic contributors [60]. It was found that only 6% of the total process inputs were utilized, while 94% lost as the bulk waste, heat and work. LCA was performed to measure environmental impacts of these losses using a single-issue indicator (global warming potential) and aggregate indicator (ReCiPe 2008). It was observed that the electricity consumption was a main contributor to the central process and upstream processes. A study used the exergy analysis and LCA to identify and demonstrate factors influencing the environmental performance of AM processes [61]. A thermo-dynamic (exergy) analysis was conducted for resources and energy consumed and lost from the cradle to gate lifecycle for DMLS and FDM AM processes. It showed that only 10% of the total DMLS process inputs were utilized by the system and remaining 90% lost as heat, work and bulk waste. Similarly, only 7% of the total FDM process inputs were utilized by the system and remaining 93% lost. LCA results showed that the electricity consumption is the key contributor in the environmental performance of both processes.

LCA Dimensions	Aspects Analyzed	LCA Methods	LCA Databases	Indicators (Impact Categories)	LCA Software	AM Technologies studied
Cradle to Gate Cradle to Grave Conception to Grave	Energy Material Fluid Wastes Emissions	IMPACT 2002+ ReCiPe 2008 ReCiPe H/A weighting ReCiPe Europe Midpoint H ReCiPe Europe Endpoint H/A ReCiPe Endpoint H Global Warming Potential CExD CML 2 Baseline 2000 CML2001 IPCC 2013	Ecoinvent EcoIndicator 99 ERMD data Eco-indicator (PR Consultants of Netherlands)	Midpoint level Damage Endpoint level Upstream and Downstream ILCD	SimaPro Gabi	SLS, SLA, FDM, DMLS, EBM, LBM, PBF, LENS

Table 2: Summary of LCA articles for environmental impacts of AM.

An integrated product design method and cradle-to-grave LCA were used to estimate energy and CO2 emissions for a LPBF AM process [77], the topology optimization was applied for product redesign, design of support structures, allowances and features for post-AM operations. Results show that product design has a significant role to reduce energy and CO2 emissions in both of AM manufacturing and using phases because of lightweight parts. A modified LCA model was proposed to study the hidden phase of the feedstock production in the lifecycle of a metal AM product and the feedstock utilization factor [55]. It was concluded that recycling and reusing of the waste feedstock powder could help improve environmental sustainability of the laser metal deposition AM. It would help in reduction of the energy consumption during the feedstock production process. A general framework was proposed for sustainable design optimization in LCA for the BJ process [88], and for evaluation of the environmental impact of the fabrication process of an engine bracket via BJ. A topology optimization method was used to reduce weight of the product. The product can be made more environmentally sustainable by taking the feedback of the environmental assessment model. It was also claimed that most of the existing AM environmental assessment models based on LCA were not valid to evaluate sustainability of AM processes, because these models usually considered design results as the input and neglected design freedom potential of AM. A study showed uses of LCA and decision criteria methods for selection of manufacturing strategies for an aeronautic turbine [69]. They introduced a dimensionless indicator to compare AM and SM methods i.e. environmental impact ratio. Environmental impact ratio was combined with another indicator i.e. a volume of material removal ratio (Shape Complexity). EBM and milling technologies were compared and found that EBM has a low environmental impact and suitable for complex part geometries. But for parts with the less shape complexity, the milling process generates lower environmental impact. Both processes consumed same amount of energy in the manufacturing stage, so if a raw part with geometry close to the final part, the milling operation is still competitive in terms of environmental impacts. An LCA-based predictive assessment tool was proposed to evaluate the environmental impacts of AM processes considering energy consumption, material, fluid, unused material and recycling [22]. LCA scores were used for decision makers to analyze environmental impacts of the process. LCA analysis was performed using the SimaPro 7 software and EcoIndicator 99 method for a case study to compare sustainability of different AM processes and traditional manufacturing. Results showed that the FDM environmental impact is higher than SLS and Milling. It was concluded that it cannot be stated that AM is more sustainable than SM or vice-versa at this stage.

3.1.2 Comparative LCA models

A comparison study was performed to analyze environmental impacts of conventional and additive manufacturing using cradle to grave LCA [35]. Four mold core making scenarios for CFRP production were studied and found that AM is more environment friendly. A comparison LCA method was used to investigate environmental impacts of FDM, Polyjet and CNC milling machine to determine the most sustainable manufacturing method [21]. LCA scores were measured using the ReCiPe endpoint H and IMPACT 2002+ methodologies. Results showed that sustainability of these machines depends on the percentage utilization of each machine. The high utilization leads to reduction of the idle energy use and environmental impacts. For 3D printing, energy consumption is the dominant impact whereas for CNC machines, material waste is dominant impact for higher utilization scenarios. FDM was found more environment friendly. A comparative LCA Cradle-to-grave model was proposed for two different AM production routines, i.e., assembly design and consolidated design [98]. A cradle-to-gate comparative LCA analysis was performed for Laser Beam Melting (LBM) and conventional methods in an industrial repair process of gas turbine burners [95]. Results demonstrated that the repair process based on AM has less primary energy consumption, material footprint and carbon footprint than conventional manufacturing.

LCA was used to examine environmental and resource implications of AM in short-term and long-term perspectives for the technological development and adoption of AM technologies [12]. PBF was studied for manufacturing metal parts of a light truck engine in three scenarios i.e. conventional manufacturing, present and future states of AM technology. Results showed that AM in the future case scenario has the potential of environmental improvements mainly because of the weight reduction potential of AM. An investigation showed influence of the total building height and batch size on the environmental performance of EBM AM using LCA [41]. The environmental performance of EBM was compared with finish machining (FM) and conventional manufacturing. Results showed that EBM+FM has a good environmental performance when the batch size is close to a full-building configuration, and less environment friendly when the total building height increases. An LCA-based method was proposed for evaluating environmental impacts of EBM [42], particularly, the impact of different parameters was studied including the total building height, batch size and material waste due to support structures on environmental performance. The LCA analysis was conducted in SimaPro software with the Ecoinvent database. The IMPACT 2002+ method was used to evaluate the environmental impact for a comparative analysis of AM with SM from Cradle to Grave. Results showed that environmental impacts improve when the total building height is decreased and batch size is fully utilized, whereas support structures have no significant effect. The environmental lifecycle analysis of the RepRap 3D printer and injection molding for polymer products was performed using the cradle-to-gate LCA method [39]. Results showed that open-source 3D printers can lead to lower environmental impacts than conventional manufacturing for polymer products.

3.2 Energy Modelling of AM

Energy models for LCA were developed to compare the energy consumption of different AM and SM methods [3, 8, 88] in the material production, printing part, post-processing, usage and end-of-Life. Specific energy consumption (SEC) of different AM processes found in literature is shown in Figure 4. It can be seen that there are large variations in energy consumption of different AM technologies. Studies found that the printing stage has the highest energy consumption which represents it as a major contributor in the environmental impact of AM [30, 33, 59, 66, 87, 103]. Quantitative methods were also developed for the energy analysis. Generalized multi-objective decision-making methods were proposed considering the total energy consumption and environmental impacts [72]. Data analytics techniques including linear regression, decision tree, neural networks, genetic algorithm and Internet of Things framework were proposed for understanding and prediction of the energy consumption in AM [79]. Process selection tools to compare AM vs SM sustainability potential were also presented to model energy and CO_2 emissions for all lifecycle stages [41, 97].

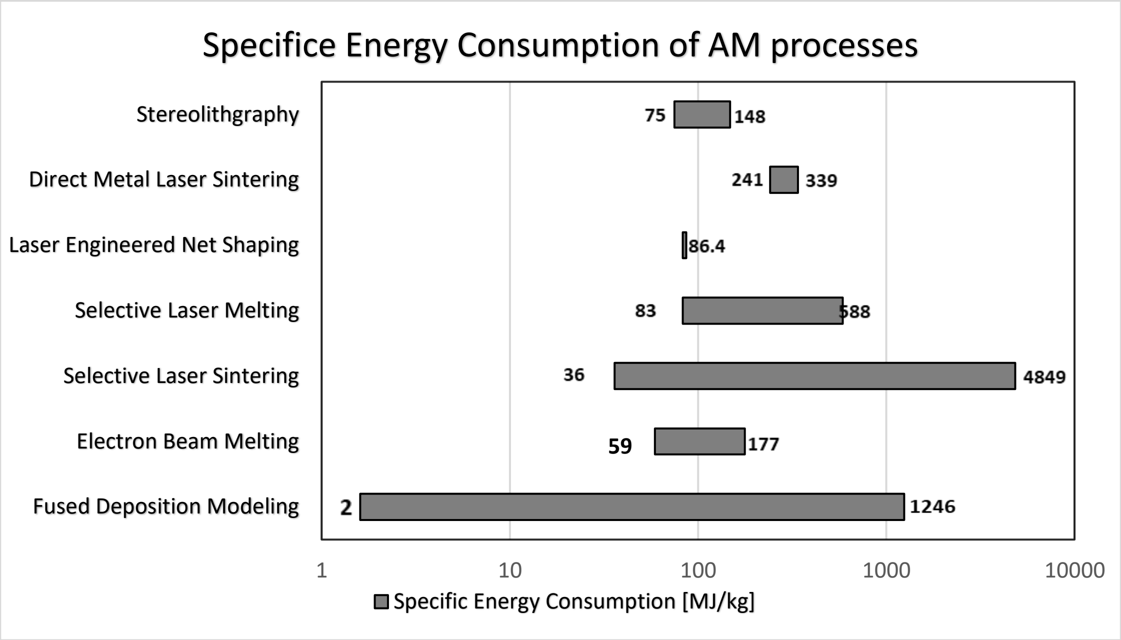

Figure 4: Specific energy consumption of different AM technologies found in literature.

3.2.1 Energy consumption modeling framework

An energy model was created that performs a cradle to gate analysis to compare energy consumption of wire-based and powder-based additive-subtractive manufacturing processes [31]. Specific energy consumptions were compared at different stages, i.e., primary metal production, deposition and machining. A case study showed that both consumed similar amounts of energy for the overall process, but energy consumption at the wire production stage was greater than powder production, whereas the wire-based deposition consumed 85% less energy than powder-based deposition. A system modeling framework was proposed with five major steps to facilitate an integrated analysis of net changes in the primary energy use and GHG emissions with the adoption of AM in the U.S manufacturing and air transport sectors for the time period of 36 years (2014-2050) [30]. The cumulative saving in the primary energy was estimated as 1.2-2.8 billion GJ, and the cumulative reduction in GHG emissions as 92.1-215 million metric tons. It was concluded that use-phase savings can be important, and AM has the potential to make light weight parts or improved designs. LCA results also showed significant material and energy savings with the adoption of AM. A preliminary analysis of energy consumption in 3D printing processes using analytical approach has been performed [72]. Quantitative calculation methods and evaluation methods were used for the energy analysis. The overall energy consumption was divided into two parts, primary energy, i.e., energy consumed to change the raw material form and properties, and secondary energy, i.e., energy consumed by ancillary components of 3D printer.

A comparative model was presented for the energy efficiency of AM and SM for metal parts [96]. The volume fraction of parts was used to determine the total energy consumption in producing the parts in both AM and SM. If volume fractions are less than a critical value, AM is more energy efficient and if volume fractions are greater than critical value, SM is considered more energy efficient. The idle stage of both AM and SM machines have also been considered for the evaluation model of energy consumption. A service-oriented Internet of Things framework was developed for the energy consumption problem of AM process [78]. The energy consumption of SLS systems was identified and predicted by collecting, integrating and analysing data from the entire production atmosphere. It was concluded that current AM processes lack the sufficient energy consumption analysis and more work is required in this category. Data analytics techniques and Internet of Things framework were used for understanding and prediction of the energy consumption in digital manufacturing systems [79]. Data analytics techniques used the linear regression, decision tree and back-propagation neural network. In a case study, SLS machine data logs were combined with product layout data to examine energy consumption of the system. Energy consumptions of three FDM machines were compared using the proposed mathematical model to understand variability among different machine systems [8]. The energy modeling compared the energy intensity of different FDM machines and SM machine. An empirical study of characterizing the energy consumption of FDM was performed using a benchmark approach for different components of a 3D printer i.e. motors, heater and fans [3]. The energy characterization showed that motors and heater dominate the energy sector. An energy model was built for each stage of FDM AM i.e. the material production, printing, post-production and related transportation [74]. Measures were also proposed for the unit energy consumption to decide the total lifecycle energy consumption.

A generic model was developed to assess the lifecycle inventory of AM processes during the manufacturing stage considering all inputs and outputs flows of the AM system [103]. The flows included electrical energy consumption, primary material and support material consumption. The energy consumption was considered in the design stage, printing stage and idle stage. The method was used to assess the environmental performance of FDM process. A theoretical approach was presented to measure the potential effect of AM on the global energy demand by 2050 for two case studies in the aerospace sector and construction sector [92]. The energy savings can be 5-25% for the aerospace sector and 4-21% for the construction sector. It was concluded that the global energy demand will decrease at least by 5% and as much as 27% by 2050. A tool was implemented for the combined estimation of energy and cost for DMLS AM using the voxel-based time estimation technique and activity-based costing framework [11]. It was concluded the part quantity, variety and fully utilization of AM machine capacity have impact on the process efficiency, and the cost minimization may lead to the minimization of the process energy consumption. Different AM processes were investigated for relations of SEC and material characteristics as well as input parameters [46]. It was found that it is possible to increase the energy efficiency without affecting the part quality. Investigation of the energy consumption of three pre-heating methods in SLM/SLS AM processes was presented [68]. The pre-heating methods included building chamber pre-heating, base-plate heating and laser pre-scanning heating. Transient thermal modeling with the finite element method was used in the evaluation of energy consumption, and results showed that laser pre-scanning heating has the less energy consumption for low volume parts whereas in case of high-volume parts, the chamber and base-plate heating are more energy efficient.

3.2.2 Investigation and Optimization of AM Process Parameters

An empirical investigation was conducted for the energy consumption in an SLS AM process using an optimization framework of genetic programming for function relations of the laser energy consumption between the part orientation and slice thickness [67]. Results showed that the slice thickness has a significant impact on the laser energy consumption. The method can also determine optimal values for the slice thickness with a less energy consumption during the manufacturing stage. An experimental study was presented for the FDM process to highlight effects of operating procedures and printing parameters on the energy consumption and particulate emissions [84]. An energy smart socket electrical energy meter was used to monitor the energy consumption whereas Nano scanning mobility particle sizer and optical particle sizer were used to evaluate the particle emissions. Results shows that printing bed heating and temperature maintaining are big contributors on the energy consumption whereas the printing speed and material flow have minor effects on the particle emission rate. An experimental study was performed to measure the energy efficiency of an SLS printing process [87]. An energy logger was used to measure the power usage. It was concluded that energy efficiency of the SLS process can be increased by densely packing the building volume, reducing print time and energy consumption of preheating and preparation phase.

An investigation was performed for impacts of input variables i.e. laser power, scanning speed, and powder feed rate on the total energy consumption for laser AM [48]. Results showed that the laser power and scanning speed are proportional to the energy consumption whereas the powder feed rate is inversely proportional to the energy consumption. The potential energy-saving benefits were also examined for an ultrasonic vibration-assisted LENS process to reduce energy consumption and improve part quality. Energy consumptions of AM on machine and process levels were studied [49]. On the machine level, the energy consumption was overviewed by subsystems at different modes and different AM machines. On the process level, the energy flow distribution, relations between input energy and product quality (microstructure and mechanical properties) were studied. Metal AM parts were highlighted for the indirect energy consumption (feedstock production) with a big contribution in the total energy consumption. Energy consumption reduction strategies were also proposed based on process optimization and design optimization techniques. An energy modeling tool was developed to optimize the part geometry considering the energy consumption based on used time and power material [97]. An experimental study evaluated the energy consumption and carbon footprint of FDM machine, and identified that a part with the large volume of the complex design can increase the building time, electrical energy consumption and carbon footprint [7]. Post-processing also has a significant impact on the total energy consumption and carbon footprint. A power-monitoring method was used to evaluate the energy consumption of a laser sintering process [9]. The main variable used in this study for measurement was the mean real power consumption per measurement cycle. The energy consumption was classified in four categories: job-dependent, time-dependent, geometry-dependent and Z-height-dependent. It was concluded that the energy efficiency of laser sintering can be improved by reduction of the time-dependent energy consumption.

A mathematical model was proposed to evaluate the energy consumption of a stereolithography-based AM process [102]. Design of experiments approach investigated different parameters and effects on the total energy consumption. It was concluded that the energy consumption can be reduced by using optimal parameter settings for the AM process. An optimization framework was proposed for reducing energy consumption and improving part quality [89]. Linear regression models were used to investigate relations between process design parameters, the part quality and energy consumption. The proposed framework optimized the energy consumption in the AM fabrication without compromising the product quality. An empirical model was developed for the relation between process parameters and energy efficiency in the metal laser direct deposition AM [45]. Results showed that the laser power has a significant impact on the process energy efficiency. The energy efficiency was improved up to 5.7% for single-track multi-layer stacking and 50.3% for multi-track single-layer lapping using optimal process parameters. A study showed the relation between product shape complexity and process energy consumption in an EBM AM process and concluded that the process energy consumption does not depend on the shape complexity [10]. An experimental approach was used for the energy assessment of an SLS AM machine. Results showed that 40% of the energy were consumed by the powder feed and part bed heater, 25% by feed and building piston stepper motors and 16% consumed by the laser system [85]. It was suggested that the energy consumption can be reduced by elimination of powder heating, using high-efficiency lasers and better thermal management. A mathematical approach was used for the analysis of laser energy consumption of an SLS process [71]. A convex hull method was used to define the total energy as a function of the total area of sintering. The total energy was correlated with the slice thickness, part geometry and building orientation to select the optimal part orientation and slice thickness for fabrication of the part with the less energy consumption.

3.3 Sustainability Analysis of AM

Many sustainability analysis studies have been found in literature for AM processes. Predictive models, generic methods, analytical methods, experimental methods, LCA based assessment, Road mapping frameworks and Design for environment methods have been proposed to evaluate sustainability of AM methods. The detailed analysis of methods is as follow.

3.3.1 Sustainability assessment methods

A predictive model was proposed to jointly evaluate the technical, economic and environmental impacts of AM processes [105]. A generic method was proposed to investigate environmental impacts in the manufacturing stage and these impacts were then combined with technical and cost evaluations. Energy, material and fluid consumptions in pre-processing and post-processing were also considered. A model of environmental performance was proposed to evaluate sustainability of different 3D printers i.e. FDM, SLA and Polyjet [43]. The cost, sustainability and surface roughness quality of products were investigated for parts made by different 3D printers, i.e., FDM, SLA and Polyjet. It was found that Polyjet has high quality products and environmental impact, and the highest cost whereas FDM has the low-quality products, lower environmental impact and lowest cost. It was concluded that the high surface quality can lead to the high manufacturing cost and environmental impact. A framework was proposed for the environmental impact evaluation of AM, combined with a technical and economical assessment [104]. The method evaluated the technical, economical and environmental assessment of a part fabricated by an AM process for a global view of the consumption according to its geometry. It provides a decision-making tool based on multi-criteria to select a manufacturing process based on both analytical and experimental models. Data for the environmental impact evaluation consist of electricity consumption, material consumption and fluid consumption.

Product sustainability index method was proposed as a metrics-based framework to evaluate the total lifecycle sustainability of manufactured products [83]. It covers the complete lifecycle of a product, i.e., pre-manufacturing, manufacturing, use and end of life. The hierarchical approach has five levels: ProdSI, Sub-indices, Clusters, Sub-clusters and Individual metric and evaluates Triple Bottom Line sustainability of manufactured products. It was used in a case study of AM products for the product sustainability evaluation [29]. Two variations of both CM and AM products were compared and found that AM products have better sustainable solutions in complex geometry scenarios. A method was proposed for sustainability characterization of AM as a reference for community to benchmark AM processes for sustainability [57]. A sustainable value road mapping tool (SVRT) was developed, integrating the road mapping approach and sustainable value analysis [16]. The proposed framework was based on the lifecycle perspective and SVRT to highlight the future business opportunities and challenges in adopting AM technology. An experimental approach was used for the energy assessment and sustainability analysis of the SLS AM machine [85]. Eco-Indicator 95 was used to measure environmental impacts. The total power, process productivity, energy consumption rate (ECR) were considered to calculate the total energy indicator as 8.3, which was better than Stereo Lithography SLA®5000 and Fused Deposition Modeling FDM-8000 with values of 12 and 13, respectively.

3.3.2 Environmental performance analysis

Environmental impact assessment (EIA) was conducted for a fast mask image projection stereolithography AM process using an LCIA approach [62]. EIA investigated energy, material and wastes impact on the human health, ecosystem quality and resource depletion. The approach used time and energy modeling techniques for the relation of part design attributes and process energy consumption to control the process energy consumption in the design stage. An experimental study was presented for environmental sustainability evaluation of the AM batch production [100]. Three factors were considered for the environmental sustainability evaluation, i.e., energy consumption, emission and material waste. Energy consumption, TVOC emissions and material waste were compared for different batch sizes. It was found that the SLA batch production has the potential of energy saving but TVOC emissions and material wastes need improvement. An investigation presented the SEC and environmental impacts of different AM processes [46]. A relation study of SEC and material characteristics as well as input parameters found that SEC is related to both material characteristics and process input parameters. It showed the possible increase of energy efficiency without affecting part quality by optimizing input parameters. The environmental impact analysis showed that GWP is brought by the energy production process. DMD has a big impact on GWP whereas LMD and SLA has less impact than other AM processes. A predictive model of environmental assessment of AM processes was proposed for the design stage to evaluate environmental impacts of a product based on the CAD model [13]. Electricity, material and fluid consumptions were considered in the model. The method used a feedback loop to optimize the environmental impact of parts so that many strategies can be used for a same part with less environmental impact for manufacturing. The method was illustrated with an example of the aeronautical part using a direct metal deposition AM process. A nozzle was used in the DMD process for the low environmental impact.

A Design for Environment tool based on eco-design principles was proposed to evaluate the environmental impact of a product from the lifecycle perspective [23]. The tool supports design decision-making to evaluate the environmental impact at the early design stage. A case study was presented for printing a part using an FDM machine with different building orientations and internal fillings, to study its effects on the production time, energy consumption and end-of-life measure. A method was proposed based on a predictive model of flows consumption (energy, material, fluid) defined from the manufacturing path and CAD model to evaluate the environmental impact of AM [40]. An analytical model was proposed for evaluation of the total volatile organic compound emission for a stereolithography AM process [101]. Emission reduction strategies were also proposed for reduction of the total volatile organic compound emissions compared to current commercial technologies.

3.4 Environmental Impact Improvement Strategies

Strategies were also presented to reduce environmental impacts of AM. Design for AM methods like the topology optimization, mass customization and part consolidation were proposed to reduce energy and material consumption, and waste generation [6, 75, 84, 87]. Design of experiments was also used to optimize energy and waste to reduce environmental impacts of AM [27]. The optimization of AM building parameters such as layer height, build orientation, raster angle, shells, percentage infill etc. can improve environmental impacts of AM [26, 27, 53, 91]. Process planning was performed with the help of algorithms to optimize the process energy and material waste [32, 34]. Few studies highlighted the role of redesign for AM [76]. Results showed that the reduced weight of printed parts has big impact to reduce the process energy, material consumption and emissions in the lifecycle of AMP. Bio-inspired geometries like honeycomb, diamond and bone structures were also used to achieve the goal of light parts to reduce environmental impacts of AM [106]. Modelling and simulation were also applied in investigating lightweight component structures. A finite element simulation model predicted the microstructure of optimized components to achieve lightweight design and essential properties [50].

3.4.1 Optimization for environment

A Design of Experiment (DOE) approach was used to optimize the part at the design stage [27]. FDM parameters, i.e., slice orientation, number of shells, infill percentage and layer height were investigated to find optimum settings for the part weight, scrap weight, production time and energy consumption. Taguchi DOE was used to plan experiments. Four parameters were studied at 2-levels to find optimal solutions for energy and waste. An approach was suggested to investigate relations of SLS parameters, energy consumption and material cost for optimal SLS parameters to reduce energy consumption and material cost [53]. A multi-objective model was built for optimization by using a non-dominated sorting genetic algorithm to find optimal process parameters for energy consumption and material cost reduction in SLS. An integrated design-oriented framework was proposed for the resource selection (material, machine-process) of AM [90]. The framework was used to structure the design knowledge for decision-making in each of the conceptual and embodied design stages via defined axioms and extracted rules. A design strategy was proposed for process planning to reduce the material consumption in AM [34]. The strategy used sliced data of the CAD model to optimize the internal topology considering requirements of the minimal wall thickness and self-supporting capability. It improved the filling quality by using a skeleton-based method for the path optimization. The method reduced the material consumption by reducing the volume of the whole part to be filled.

A generation strategy was proposed to optimize printing path and orientation to reduce the material consumption, energy consumption and production time [32]. The strategy used Printable Threshold Overhang Angle and the Longest Printable Bridge Length to determine areas to be filled on each layer for the optimized part. Results showed effectiveness of the optimization of process planning to reduce material consumption in AM. An optimization technique was used for AM to accomplish the optimal process plan and improve process sustainability [93]. Heuristic-based optimization techniques were used, i.e., simulation annealing and genetic algorithm to solve optimization problems. An investigation was performed for environmental impacts of AM. Benefits and limitations of AM technologies were highlighted and compared sustainability advantages of AM with traditional manufacturing processes [58]. It was found that the electricity consumption was the biggest factor of environmental impact in AM.

3.4.2 Lightweight designs

Benefits of sustainability improvements were also identified in the use stage of AM manufactured parts, i.e., light weight parts, especially in transport systems. The fuel consumption reduction and environmental impact savings were compared for the weight reduction per kg of parts to improve environmental impacts. A strategic sustainability approach with the LCA method was used to highlight sustainability benefits and challenges of AM technologies at the early stage of AM [94]. The method identified challenges and opportunities of AM considering a complete lifecycle of product. It was concluded that AM has a great potential in sustainability production but still few areas require improvements like the concept design, repair and redesign, optimized material usage, value chain management and social sustainability. Modelling and simulation play an important role in understanding lightweight component structures [50]. Finite element simulation modeling can predict the microstructure of optimized component to achieve lightweight design and essential properties. A general framework was proposed to integrate the sustainable design optimization in a LCA model for a BJ AM process [88]. The framework was used to evaluate the environmental impact of the fabrication process of an engine bracket via BJ. A topology optimization method was used to reduce weight of the product. Topology optimized product data were then fed into the framework. The product can be updated towards more environmentally sustainable by taking feedback of the environmental assessment model. A comparison was also conducted to CNC milling for the same product and results showed that Binder Jetting with a topology optimized part consumed less energy and produced less CO_2.

A sustainability assessment framework of AM-enabled part consolidation (PC) was proposed to evaluate the environmental impact, energy consumption and health impact [99]. The framework considered different Lifecycle stages of AM, i.e., product design, manufacturing, assembly, service, and end-of-life. The proposed quantitative model was used to evaluate sustainability of the BJ process. The case study showed that the consolidated design can reduce the energy consumption and environmental impact but increase the health toxicity level. An investigation was made to find impact of the lightweight design on cost and energy efficiency using cost assessment and cradle-to-gate LCA methods for three manufacturing processes: machining, Hobbing, and LBM [36]. It was concluded that the lightweight design has a vital role in reducing cost and energy consumption both at usage and manufacturing stages. LBM has the benefit of attaining lightweight designs to achieve cost-and-energy efficient products. A conceptual model was developed to integrate multiple AM design and bioinspired design factors to redesign products and achieve sustainable product design goals [106]. The bioinspired design factors included raw material quality, process parameters and product functionality. Three bioinspired geometries were investigated for honeycomb structure, diamond structure and bone structure. The method was used in the early design stage to achieve sustainable product design.

A comparative LCA model was proposed to investigate the environmental performance of two different production routines for AM i.e. assembly design and consolidated design [98]. Results showed that the consolidated design production routine is more environmentally friendly and provided the lifespan improvement of 200% and weight reduction of more than 30%. A study highlighted the potential of AM in improving resource efficiency and sustainability of industrial systems in four main areas where adoption of AM can lead to improvement in resource efficiency i.e. product and process design, material input processing, make-to-order product and component manufacturing, and closing the loop [15]. A systematic method was proposed to identify the production system with the lowest energy demand or CO2 emissions [75]. The method measured the primary energy demand and CO2 emissions for all LC stages, i.e., material production, manufacturing and usage of a production system. A comparison was made between the machining system and integrated system for environmental solutions. A case study was conducted for redesign for AM to meet the efficient energy use and CO2 emission reduction [76]. LC of a redesigned Jet-engine component was used to compare the environmental impact of EBM and machining processes. It was found that AM is more environment-friendly because of the less material consumption in manufacturing stage and benefits of the lightweight part in the use phase.

4 DISCUSSION AND RECOMMENDATIONS

Based on the review of the current research on sustainability and environmental impacts of AM, four areas were identified as presented in Section 3 to recognize, differentiate and understand current research. Research opportunities and limitations are also identified for the future work on the sustainability assessment, environmental performance analysis, energy modeling and environmental impact improvement strategies for AM.

LCA methods have been used by researchers for evaluating environmental impacts of different AM technologies [21, 29, 33, 42, 54]. LCA comparison models for AM and CM were also presented to study environmental impacts of both technologies [21, 39]. Many case studies were performed for different AM and CM technologies to evaluate their energy and material consumptions. The waste generation was also examined. LCA has been a very attractive method to study the environmental performance of AM. But the presented LCA results were not comparable to each other because of the different data inventory, LCA methods, LCA boundaries (Cradle to Gate, Cradle to Grave) and research focuses. Variations of LCA results exist in different AM processes and strategies as a lack of understanding of LCA. A detailed analysis of LCA methods for sustainability of AM is required to identify challenges in current LCA methods by classifying AM strategies, technologies and LCA measurements.

Energy models for different AM technologies found in literature were also quite different from each other. The focus, approach, measurement and boundary were different from models with variations in results. Ranges of specific energy consumptions were presented in Figure 4 to identify the variations found in literature. A critical analysis of these models is required to identify causes of variations of the models.

For AM sustainability improvement strategies, the reduction of both energy and material consumptions can improve sustainability of AM technologies. Optimization of printing parameters and lighting weight design are identified as promising opportunities to reduce production time, energy and material consumptions, and waste generations to improve sustainability of AM.

It is identified from literature that AM is more environment friendly than conventional manufacturing methods [21, 29, 33, 39, 42, 54]. AM provides a great potential in sustainable production, but there are still many areas that require improvements for the optimized energy and material usage and value chain management of AM. Following important solutions are concluded from the literature review.

- Cradle-to-Grave is a complete LCA method for investigating environmental impacts of AM. But improvements are required to consider impacts of AM on product design, feedstock production, usage, and end-of-life processes. A detailed evaluation of lifecycle impacts of the AM process is required.
- The sustainable AM analysis should include the product design in the sustainability evaluation. Conceptual design and redesign sustainable opportunities in AM are very important for sustainable AM solutions. The design solution has a big impact on environmental performances with most opportunities of the sustainability improvement.
- Lightweight design is identified as a significant factor for reducing environmental impacts both in manufacturing and usage phases. Design for AM methods play an important role in this area. Methods like the part consolidation, topology optimization, lattice structure, and bio-inspired geometries are promising for improving the lightweight design of AM products.
- Formation and analysis of the sustainability index for AM processes can provide effective tools in evaluating sustainability impacts of AM.
- Big variations are found in energy consumption rates for different AM processes in both energy models and experiments. More experimental work is required to improve the variations. More detailed energy models are required to include all those factors that have impact on the energy consumption of AM. Identification of those factors will not only help to create precise energy models but also provide opportunities to reduce the energy consumption.
- Product quality is a very important factor in manufacturing industries. Integrating product quality and sustainability for the final product design is essential. Product quality and sustainability have an inverse relation, but AM has the potential to achieve sustainability in desired part quality. Multi-criteria decision-making methods should be developed to consider product quality in a close-loop control system for sustainability assessment frameworks.
- Lack of standards for AM processes is a major disadvantage for understanding the sustainability potential of AM, which hinders the adoption of AM by industries. Development of sustainability characterization methods for AM in conjunction with standards organizations will help to identify the sustainability potential of AM.
- For achieving sustainable AM for all three dimensions, research is required from the triple bottom line perspective. AM has the potential to make sustainable products considering all three dimensions of sustainability. Unfortunately, there is not enough research in this area. Most of the researchers consider only one of the three dimensions of sustainability. Multi-criteria decision-making methods should be developed in a close-loop control system to predict the sustainability from all three dimensions of sustainability i.e. economical, environmental and social measures.
- Optimization of AM printing parameters can benefit the reduction of environmental impacts of AM. Investigation is required for the impact of printing parameters on energy and material consumptions and optimal parameter setting to reduce process energy and material consumptions for different AM processes.
- Achieving environmental sustainability also benefits reduction in cost. Research is required to develop models to integrate sustainability and AM cost for the relation and highlight of the economic and sustainable potentials of AM.

5 CONCLUSIONS

This paper reviewed sustainability and environmental impacts of AM, covering different types of AM technologies including the complete lifecycle of AM processes and additively manufactured products, i.e., from the raw material production, product design, printing, post-processing to the product end-of-life. The progress of the latest research was analyzed considering environmental impacts from LCA perspective, energy modeling, sustainability analysis and environmental impact improvement strategies for AM technologies.

It is found that there is a growth in research on sustainability of AM in the last 10 years. Most of the research has focused on sustainable LCA of AM and energy consumption frameworks of AM. There is also progress in the lightweight design of AM considering design for AM methods like the topology optimization, mass customization and part consolidation. Research has also focused on the investigation and optimization of process parameters to reduce the processing energy and material consumption.

In general, we can conclude that AM has a great potential to achieve sustainable production than SM. Energy consumption is found as a major contributor to the environmental impact of AM whereas product redesign opportunities are promising to achieve AM sustainability. This review could facilitate research to cope up with Industry 4.0 challenges and provide research opportunities for AM sustainability to benefit the AM adoption by industries.

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