ORIGINAL ARTICLE

Energy Mapping of Additive Manufacturing Processes Using Sankey Diagrams

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Abstract

In the last decade, the use of additive manufacturing (AM) systems in manufacturing has increased drastically and studies show that additive manufacturing has potential of becoming the next sustainable manufacturing solution. There are multiple additive manufacturing processes currently in research and practice and have varying degrees of energy consumption. Energy consumption could be an important consideration in adopting a specific AM Method. However, the current literature review reveals that there is a lack of well-established methodology to map the energy consumption in an AM process. This paper aims to narrow this gap by developing a structured and robust method to map energy footprint in additive manufacturing processes using modified Sankey diagrams. The proposed approach allows engineers and researchers to visualize energy consumption in different steps of the additive manufacturing process and select the optimal energy efficient method. The paper demonstrates the proposed methodology through two case studies involving selective laser melting (SLM) process and fused filament fabrication (FFF) process. The novelty of using Sankey diagrams for mapping energy consumption in AM lies in their ability to provide a clear and intuitive representation of complex energy systems. The modular architecture of the Sankey diagrams aids in the effective mapping, visualization, and analysis of energy flow. It is shown that the proposed methodology can provide insight into potential changes for energy saving in additive manufacturing processes.

Keywords Additive manufacturing · Sankey diagrams · Energy mapping and visualization · Energy consumption

1 Introduction

Additive manufacturing (AM) is one of the revolutionizing advanced manufacturing techniques which produces complex three-dimensional parts in a layer-by-layer method. In contrast to subtractive manufacturing approaches, AM has been characterized as "the process of combining materials to produce items from 3D model data, usually layer by layer." The terms "additive fabrication," "additive processes," "additive procedures," "additive layer manufacturing," "layer manufacturing," and "freeform fabrication" are all synonyms for "additive layer manufacturing" [1]. It is widely used in aerospace, automotive, semiconductor, and biomedical industries [2]. AM complements and has potential to replace some traditional manufacturing processes as it enables high degree of design freedom, and it offers an advantage of economic production of small scale [3]. AM also has the potential to become an important sustainable manufacturing technology [4]. Sustainable production necessitates careful planning throughout the product life cycle, particularly during the design phase. One of the most important aspects determining production's total environmental performance is energy usage. As a result, both subtractive manufacturing [5, 6] and additive manufacturing benefit from energy prediction in the design process. Furthermore, accurate and practicable energy consumption prediction can aid in the coordination of part quality and energy consumption optimization [7], enhancing manufacturing profits while lowering environmental effect [8].

AM has the potential to cut overall primary energy demand (PED) by 2.54 to 9.30 exajoules by 2025, which is a reduction of 5% of the worldwide primary energy supply in the

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industrial sector, according to research [9]. A wide range of AM technologies have different levels of energy consumption depending upon a particular AM method and materials employed. Therefore, it is necessary to measure and map energy consumption in every step of the AM process. To that end, this challenge of measuring and mapping of the energy consumption in additive manufacturing processes is attracting increased attention with prediction and reduction of energy consumption being important research targets [10]. AM's versatility has fueled continual innovation and progress, with the potential for more industrial applications. Products with complex geometries may be easily created using AM methods thanks to this new feature, which reduces production time, reduces material waste, and increases customization and design freedom. Recent research has shown, however, that the long-term value of AM is not always there, and that it should be evaluated more critically. Different AM methods' specific energy consumptions (SEC) can be one or two orders of magnitude higher than typical subtractive manufacturing unit processes [11]. Few recent studies in application of AM processes have recognized the energy consumption issues in additive manufacturing but have not addressed the issue of energy mapping and optimization [7, 12].

Most of the energy mapping research works can be classified into two broad categories. First category consists of methods dealing with "physics-based" energy modeling. This approach focuses only on the printing stage and formulates energy consumption models based on physical characteristics of the AM process. The second category of research can be identified as "system-based" energy modeling. Efforts are being made towards mapping energy consumption in all stages of the AM process instead of just focusing on the printing stage. In these methods, the energy footprint of AM is evaluated by considering electricity consumptions of different subsystems.

One of the tools to map energy consumption is the use of Sankey diagrams. These diagrams focus on energy flow and its distribution to various sources or sinks, represented by arrows, the width of which indicates the amount of energy flow. Sankey diagrams have been previously used to plot energy and material flow visualization in different industries [13] and have been recognized as useful tools to analyze energy consumptions by worldwide energy management standards such as ISO 50001 (Energy Management Systems). Very few prior research works have used Sankey diagrams to specifically represent energy flows in additive manufacturing processes. Furthermore, most of the existing research papers only concentrated on certain stages of the process, neglecting some AM steps while mapping energy [14]. Neglecting some steps in the energy mapping process can lead to inefficient decision making related to energy efficiency.

This paper aims to develop a structured and robust approach to map the energy footprint in an additive manufacturing process. The authors show how a modified Sankey diagram can be used for energy footprint representation. The unique advantage is it is very scalable and can be used for any type of additive manufacturing process. From the standpoint of energy optimization, this approach would graphically highlight which activities consume the most energy, and thus serve as a target for energy savings. Having a visual mapping could help design and manufacturing engineers communicate/demonstrate cost benefit analysis of multiple manufacturing options to a non-technical audience, even though AM process selection is mostly determined by the materials type and level of precision required (e.g., sales and marketing, finance, and materials management team which may be involved in the decision-making process at some level). Lastly, the proposed methodology allows mapping energy consumption at every stage of AM including pre- and post-processing activities, which is a unique contribution of this research.

The remainder of this paper is organized as follows. Section 2 reviews the existing research done in energy modeling systems and visual mapping of energy consumption. Section 3 describes the methodology to create a Sankey diagram used for visual representation of the step-by-step process of energy consumption. Section 4 discusses the application of the Sankey diagram in energy mapping using two case studies. Finally, Sect. 5 concludes the paper with discussion on the insights gathered from the case studies.

2 Literature review

This section reviews the existing research on system-based energy modeling and the visual mapping of energy consumption which includes Sankey diagrams.

2.1 System-based energy modeling

From a system-based energy modeling perspective, measuring energy consumption during the AM process should involve all three stages: pre-production, printing stage, and post-production. Literature review of previous works reveals that most of the studies deal with measuring the energy consumption during printing or closely related sub-stages, and there are very few studies that address energy consumption in the pre- and post-processing stages. The study conducted by Sreenivasan et al. [15] measured the power consumed by each of the sub-systems (such as laser, heaters, roller drives, stepper motors, blowers) for the SLS method. On the other hand, Mognol et al. [16] discussed the effect of part orientations on energy footprint during AM. In another research

paper, Baumers et al. [1] analyzed the effect of capacity utilization on energy consumption and also showed that the purely time-dependent energy consumption is the main energy drain. More recently, in the electric consumption study for SLM process by Faludi et al. [17], it was identified that machine utilization, EDM part removal, and auxiliary equipment have more impact on energy consumption.

Yoon et al. [18] conducted a comparative case study between FDM and subtractive manufacturing processes, reporting that a large percentage of energy was wasted during set-up, i.e., the warm-up step to preheat the chamber, using a system-based modeling approach. The findings led the authors to the conclusion that reliable environmental footprint estimations required a study of the full manufacturing cycle. Morrow et al. [19] showed that AM methods such as direct metal deposition (DMD) can lower the energy footprint of tool and die remanufacturing (repair). Three experimental case studies comparing energy consumption in traditional CNC milling and DMD processes to make different tool parts supported findings.

It is important to note that a few studies have attempted to analyze the sustainability of additive manufacturing methods considering the entire lifecycle of the process. Luo et al. [20] divided AM processes into life cycles and presented a hierarchical layered process model to assess impact of AM processes on the environment. Furthermore, a case study was presented to compare environmental performance in terms of energy and material usages for three different AM processes. Telenko and Seepersad et al. [21] compared material and energy wastages in selective laser sintering and injection molding processes during different stages from nylon powder production to SLS part printing. Using a similar framework, Paris et al. [22] proposed a life cycle assessment (LCA) method to select a more energy efficient process between traditional milling and AM electron beam melting (EBM) to manufacture aeronautic turbine parts.

2.2 Visual mapping of energy footprint

Reviews of prior research reveal that several prior studies addressed the calculation of energy consumption during AM processes. Junk and Côté et al. [23] investigated the energy consumption of 3D printing and fused layer modeling (FLM) methods in terms of rapid prototyping (RP). Likewise, Balogun and Mativenga et al. [24] measured energy consumption during start-up, warm-up, ready, and build stages of RP using 3D printing. Considering volume fraction as a variable, a computational model was developed by Watson and Taminger et al. [25] to compare energy efficiencies of subtractive and additive manufacturing methods. In the paper, energy consumptions in all stages of the production cycle such as producing starting materials, actual manufacturing, and transportation were considered. In another study,

total environmental impact of FDM-based 3D printing was estimated by Yosofi et al. [26]. In this estimation, historical data of electricity consumption during FDM processes were used to build a predictive model. Electric consumption for each stage of the AM process was represented in a 3D graph. A comparative energy, resource and recycling life cycle analysis was done by Walachowicz et al. [27] for the industrial repair process of gas turbine burners using conventional machining and AM. The paper demonstrated the use of diagrams for re-manufacturing and conventional manufacturing to map the energy consumption in the entire life cycle of the process.

A graphical visualization helps in easy interpretation and identification of stages with higher energy consumptions. The literature review highlights that there are gaps present in the previous research conducted in the energy mapping and visualization. This paper attempts to narrow the gap in the literature by proposing a methodology to include all AM process stages. It is demonstrated by two case studies involving selective laser melting (SLM) processes and fused filament fabrication (FFF) processes. The Sankey diagram maps the energy consumption flow and aids in effective and easy-to-understand visualization that leads to observations for potential energy savings in AM.

3 Methodology

A short introduction of the Sankey diagram is first presented herein. Figure 1 shows how the Sankey diagram can be used to visualize data and aid in simplifying the interpretation. Based on the work of Soundararajan et al. [28], the diagram represents the energy flowing through the industrial heating processes in the UK's industrial energy consumption data. There are three major sources of energy: natural gas, electricity, and other fuel sources. The processes considered are high temperature processes, low temperature processes, and space heating. This Sankey diagram shows the flow of energy and how much percentage of energy is consumed by each of the three processes and how much energy is lost in the process. From the figure, we can interpret that 35.87% of the total input energy is lost in the system. We can also infer that natural gas and other fuels are major sources of energy with natural gas constituting ~50% of the total energy input to the UK's industrial heating process. Thus, the Sankey diagram helps us easily interpret the data and helps gather insights from it.

The process of mapping AM energy use and interpreting the results can be organized into steps. The first step of constructing a Sankey diagram is to list the process stages based on its process flow and identify the sub-stages that involve energy consumption. The second step in energy mapping includes collecting data of energy consumptions at all stages/
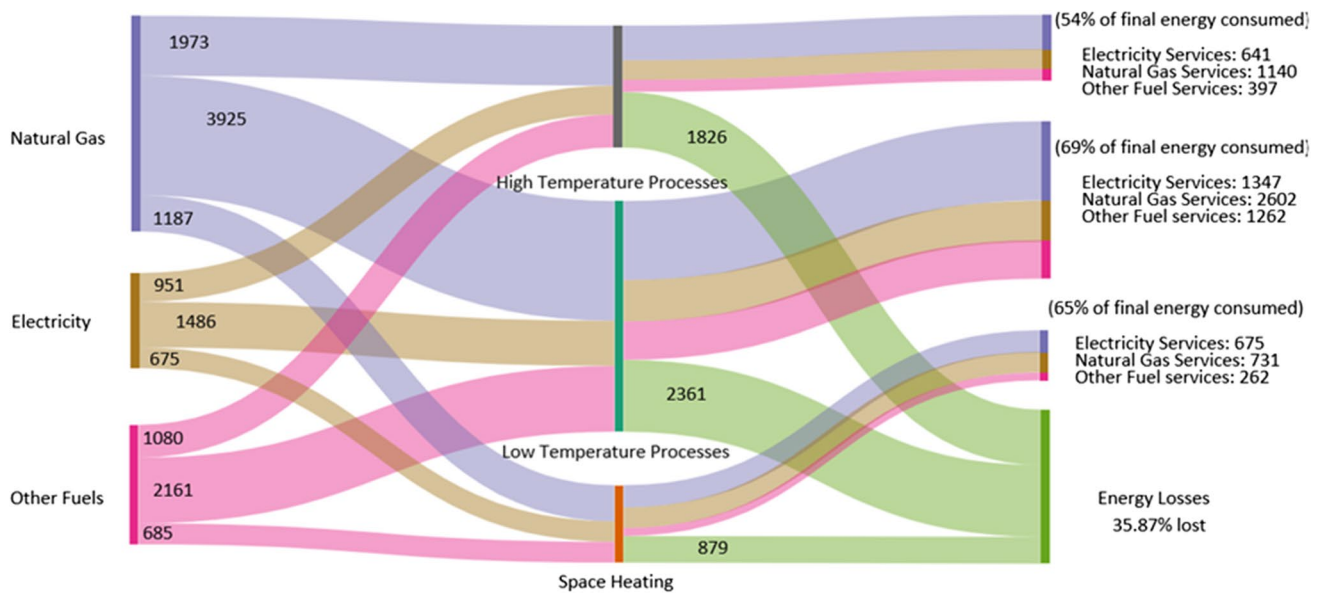
Fig. 1 Sankey diagram of UK's industrial heating process energy consumption (in million tons of oil equivalent)

sub-stages either by experimental measurements or references from the literature. Step 3 involves creating Sankey diagram visualization from the energy consumption values. The next step is to gather insights from the Sankey diagram and identify the potential areas of improvement.

Figure 2 shows a modified Sankey diagram representation of the energy consumption cycle of additive manufacturing process. The diagram does not identify the energy source, but the involved manufacturing stages are clearly depicted. We can see that there are five stages present: raw material production, pre-processing, printing stage, post processing, and recycling. There are various energy input sources at each stage of the additive manufacturing, and they are represented by input branches at each stage. Thus, the Sankey diagram is a useful tool to visualize the energy flow and make it easily interpretable. The use of a similar Sankey diagram is demonstrated using two case studies in Sect. 4.

4 Application of Sankey diagram for AM energy mapping

To demonstrate the methodology, applications of Sankey diagram for energy mapping of a selective laser melting (SLM) process and a fused filament fabrication (FFF) process are presented in the following subsections. The insights offered by reviewing the Sankey diagrams are also discussed.

4.1 Case study: selective laser melting (SLM) process

In the selective laser melting process, the parts are pre-processed from three-dimensional CAD files into two dimensional layers. Layers of powder are distributed by a powder feeding mechanism on a plate which can move in the z-axis, powder at each layer is melted as per part design by a laser
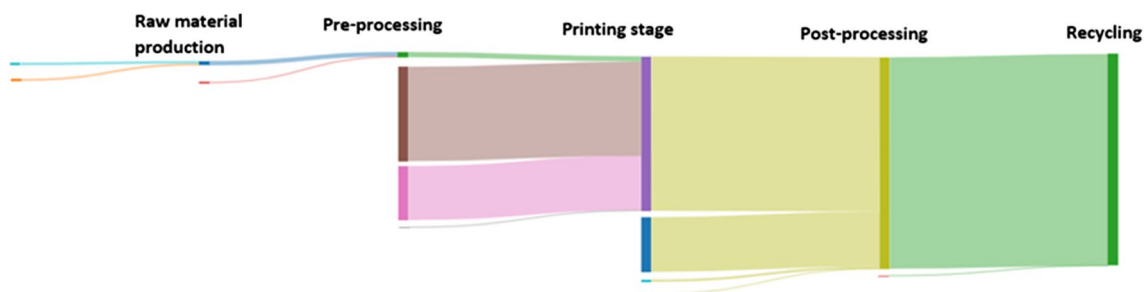

Fig. 2 Model Sankey diagram of the AM process

beam which is directed in the *x* and *y* axes. This process is repeated for every 2D layer. Each melted layer fuses with the previous layer and a solid part is formed. The manufacturing process takes place inside a build chamber with controlled inert gas atmosphere. The first step of constructing a Sankey diagram is to list the process stages based on its process flow and identify the sub-stages that involve energy consumption. As shown in Table 1, the stages and sub-stages of a typical SLM process are listed in the first two columns. The second step in energy mapping includes collecting data of energy consumptions at all stages/sub-stages either by experimental measurements physics-based modeling, or references from the literature (as in the present study). To illustrate the difference in energy consumption for a single part and a manufacturing lot of multiple parts printed in one build cycle, two columns of data are listed in Table 1. In the case when

multiple parts are produced (a manufacturing lot of 12), the energy consumption for producing multiple parts has been scaled down to make direct comparison with energy consumption of producing a single part. Values of these energy consumptions are derived from literature [17, 29–32] where the energy consumption is calculated based on SLM of a specific turbine blade.

Step 3 involves creating Sankey diagram visualization from the energy consumption values. Figure 3 presents the Sankey diagram of a single part built using the energy consumption values from Table 1. Figure 4 is a Sankey diagram constructed based on the energy consumption of printing one part from the lot size of 12 in one build cycle. In both diagrams, each stage is indicated by a vertical black bar including raw material production, pre-processing, printing (laser melting of powder), post-processing, and recycling.

Table 1 Energy consumption in SLM process [17, 29–32]

| Stage	Sub-stage	Energy consumption (MJ)	
		Single part build	Mfg. Lot (12 parts)
Raw material production	Aluminum powder production	0.57	6.80
	Argon gas production	0.41	4.87
Pre-processing	Preheating of chamber	2.88	2.11
Printing stage	Printing of parts	26.81	245.00
	Laser cooling by chiller	31.45	140.81
	Idle period between prints	1.34	1.34
Post-processing	Cool down process	6.19	6.23
	Part removal by EDM separation method	33.45	142.46
	Cleaning of build chamber by vacuum immersion separator	0.15	0.15
Recycling	Recycling/sieving to filter large Al particles	0.05	0.05
	Total energy consumption	103.29	549.83
	Total energy consumption per part	103.29	45.82
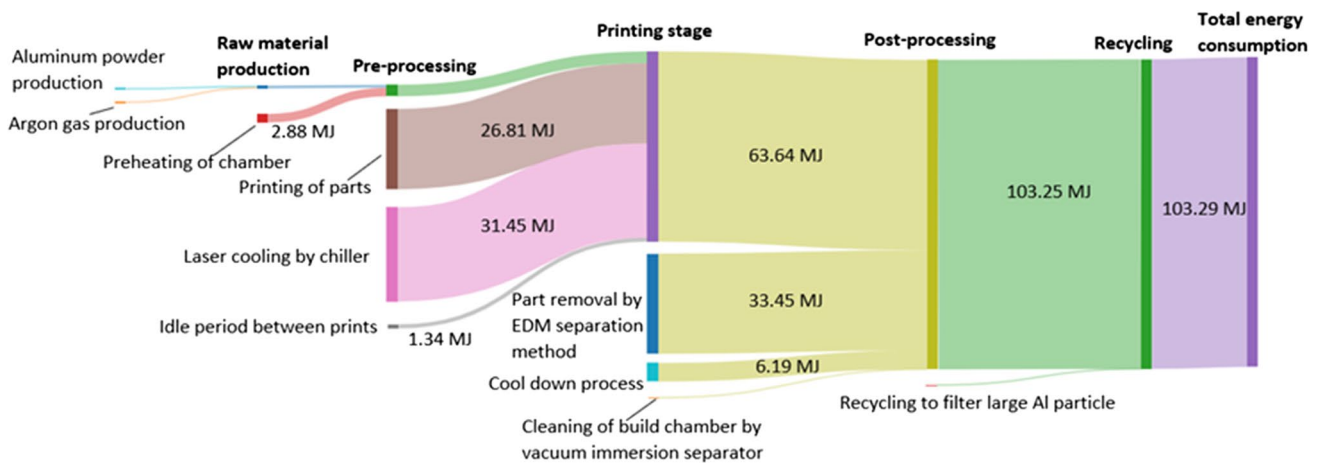
Fig. 3 Energy Sankey diagram for single part build in an SLM process
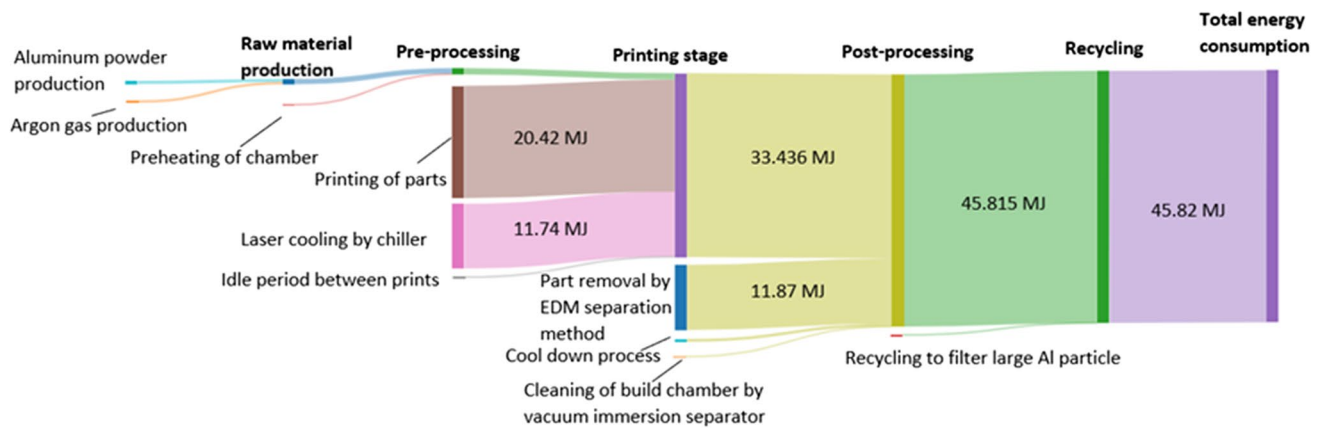
Fig. 4 Energy Sankey diagram for energy consumed by one part in a manufacturing lot of 12

Each stage has various inputs, each represented by a flow line whose width is proportional to the amount of energy consumed.

4.1.1 Discussion of insights obtained from SLM Sankey diagram

As seen in Fig. 3, the total energy consumption of manufacturing a single part by SLM method is 103.3 MJ. Furthermore, we observe that only 26% of total energy is utilized in building the printed part. It involves laser operation and movement of various mechanical systems. Furthermore, chilling of the laser constitutes around 30% of the total energy consumption. Raw material preparation, preprocessing, and post processing consume the remaining 44% of energy. Figure 4 illustrates the Sankey diagram for energy consumed by one part in a manufacturing lot of 12. The total energy consumption of a single part in a manufacturing lot is 45.8 MJ. This is approximately 45% less when compared to manufacturing an individual part. Thus, by observing Sankey diagrams, the energy reduction potentials can be identified and the steps with high energy usage could be altered or improved. Some of the potential energy reductions are discussed below.

In the selective laser melting (SLM) process, a high-power laser melts and fuses metallic powder together. Hence, after completion of printing of the part, it gets welded to the base plate or build-plate. In the post-processing stage, a separation procedure is necessary to separate the printed object from the build-plate while maintaining precision and surface finish. In commercial operation, electric discharge machining (EDM) is commonly used to separate printed parts from the build plate. To cut down and detach the printed part from the build plate, EDM uses fast repeated current discharges. This process consumes a high amount of energy.

As seen from Table 1 and Fig. 3, part removal by EDM method contributes to 32% of total energy consumption in the entire process. In addition to its high energy consumption, EDM has a low material removal rate making it an extremely slow method. Users can opt for a comparatively energy efficient method such as traditional sawing or machining to separate printed parts from the build platform. The traditional mechanical removal methods consume only 0.0064 MJ energy which is negligible compared to total energy consumption of the process [17]. Using a mechanical part separation technique instead of an EDM saves around 32% of energy.

Another way of increasing AM efficiency is to maximize the utilization of build volume which will minimize energy consumed in preheating and cooling down steps [30]. Pre-processing in SLM involves chamber preheating and heating the build plate. Preheating step constitutes a large portion of energy consumption, in some cases up to 40% of the total energy consumed for building a part with SLM/SLS [21]. After the printing, the part and build chambers need to be cooled down before the part is taken out for post-processing. Research conducted by Baumers et al. [1] showed that huge savings can be realized by using full build configuration instead of printing a single part. Sankey diagrams facilitate the visualization of the difference in energy consumption. As seen from Figs. 3 and 4, energy used in the printing stage accounts for 60 to 70% of the total energy consumption; and the amount of energy used per part depends heavily on the lot size. Also, it can be observed that certain process steps (such as the pre-processing, cool down process, cleaning of the build chamber, and recycling) consume the same amount of energy regardless the number of parts in a build cycle. This shows that it is more efficient to produce parts in batches. Hence, printing multiple parts in one build cycle can save a significant amount of energy.

4.2 Case study: fused filament fabrication (FFF) process

Fused filament fabrication (FFF) or fused deposition modeling (FDM) is a material extrusion AM process. The process prints parts of thermoplastic material in layer-by-layer fashion using an extruder. Material in the form of filament is fed to the extruder with a heating element which melts and deposits material from a nozzle. To construct a Sankey diagram, the basic process flow and the stages and sub-stages of the process are identified as the first step. The energy consumption data from experimentation are then collected. In the present work, the energy consumption data for printing one part and an additional part were derived from Balogun et al. [24] and Peng [33] as shown in Table 2.

The energy consumption for FFF additive manufacturing of the part can be visualized in the Sankey diagram shown in Fig. 5. There are four major stages: material production (indicating the energy used to manufacture filament), pre-processing, printing, and post-processing. The stages and sub-stages are identified by the flow lines with the width of the flow line representing the amount of energy consumed.

4.2.1 Discussion of insights obtained from FFF Sankey diagram

It can be observed from the flow line in the Sankey diagram that only a small percentage ($< 8\%$) of the energy is used in actual printing of the part. The remaining energy is consumed in other processes such as filament production, pre-processing, and post processing. By visually inspecting the

Table 2 Energy consumption in FFF process [24, 33]

Stage	Sub-stage	Energy consumptions (MJ)	
		For printing first part	For printing second part
Material production	Manufacturing of ABS filament	0.03	0.03
Pre-processing stage	Start-up of machine	0.10	-
	Build chamber heating	2.37	0.09
Printing stage	Ready state delay	0.44	0.20
	Printing of part	0.31	0.35
Post processing	Support structure removal (ultrasonic dissolution method)	0.90	0.90
Total	-	4.16	1.57

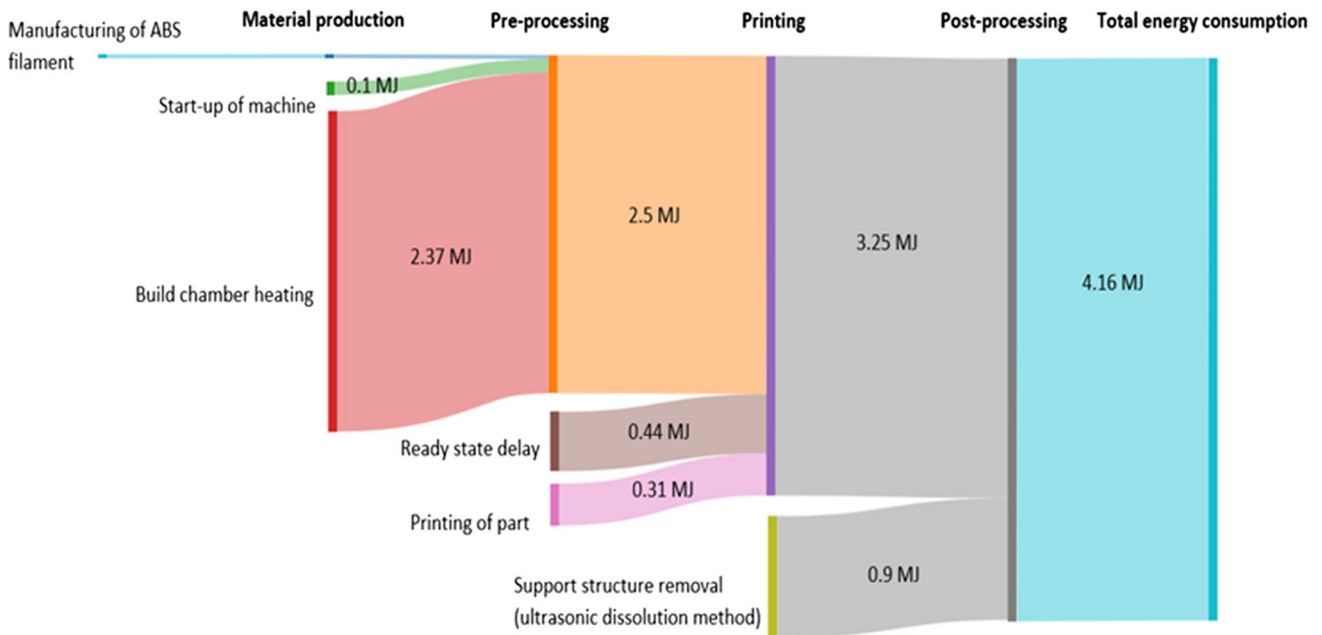**Fig. 5** Energy Sankey diagram for FFF process of printing first part
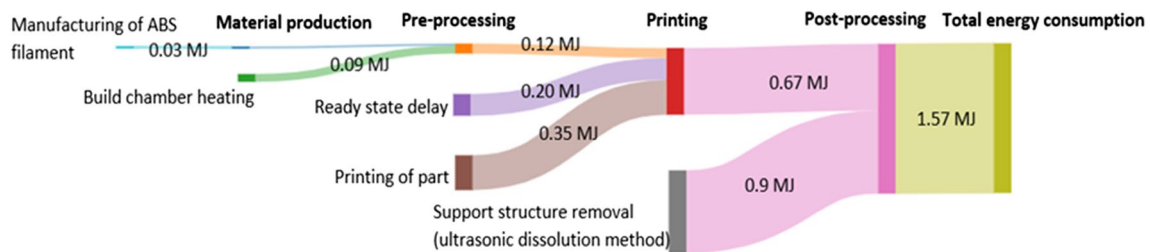
Fig. 6 Energy Sankey diagram of FFF process of printing second part

diagram, the high energy usage steps can be easily identified and further investigated to improve energy efficiency.

Figure 5 shows that the most energy intensive step is build chamber heating which consumes more than 50% of the total energy. The purpose of pre-heating the build chamber is to ensure that the part/parts can be successfully printed on the build plate with minimal distortion. Printing parts in succession without heating and cooling cycle in the build chamber can significantly reduce energy use. That is, once the printing starts, the machine should run print jobs successively to increase machine utilization, reduce total printing time, and conserve energy. Such observation calls for scheduling of print jobs that are often overlooked by the machine operators.

Figure 6 shows the energy consumption for printing the second part just after the first part. The Sankey diagram shows that the energy consumption drops while printing the second part. Energy consumption is saved in some steps like the start-up of the machine and the total energy consumption for printing the second part is just around 38% of energy consumption for printing the first part. Also, during the *ready state delay* stage, the operator loads SLICE files before printing. The SLICE file consists of the geometries of perimeter and infill of each layer. The energy wasted in the ready state delay stage can be reduced when all SLICE part geometries are consolidated and uploaded as one batch print job.

In the FFF process, parts with overhang require support structures. The support structures are printed layer by layer from the build plate and are removed after printing. To reduce its impact on surface finish and dimensional accuracy, one of the popular support removal methods is dissolution of the support structures in water or solvent in an ultrasonic cleaning tank. As seen from the Sankey diagram, a significant amount of energy (22% of the total energy) is consumed in support structures removal. Since printing and removing support structures requires energy, the orientation of the part can be carefully chosen to eliminate or reduce overhang such that the minimum amount of support material is printed and removed [1]. The energy consumption can be

further reduced by choosing a low energy alternative such as the mechanical removal method.

One of the research areas in material extrusion-based AM is to extrude material from polymer pellets instead of filament. Efforts have also been made to determine the printing path to minimize print time. It can be observed from the Sankey diagram that the width of flow lines for both material production and part printing are narrow, indicating the potential of improving energy consumption with these efforts is limited.

5 Conclusion

This paper first reviewed and discussed the literature on physics and system-based energy modeling of additive manufacturing processes. A system-based modeling method for construction of Sankey diagrams to map the energy flow of AM is then presented. These diagrams represent rich information in a consolidated and compact format, which could help decision-makers to analyze energy uses before adopting an AM operation. The development of SLM and FFF Sankey diagrams was demonstrated, and the insights interpreted from the energy flow diagrams were presented. For SLM, it is shown that the dominant factors in energy consumption were part printing, laser cooling, and part removal operations. Comparative Sankey diagrams for single part and multiple parts printing gave the indication that increased lot size could significantly reduce the energy consumption per part. The diagram also showed the energy reduction potential of replacing EDM with mechanical separation of parts from the build-plate. The Sankey diagram of FFF shows that build chamber heating and support structure removal are the two most energy intensive stages in the FFF process. The insight pointed to the importance of job scheduling in FFF as significant energy saving could be achieved through maintaining build chamber temperature for successive printing. The modular nature of the Sankey diagrams helps to effectively

map, visualize, and analyze energy flow of manufacturing processes. The methodology can be adopted to explore energy saving opportunities for other AM processes.

Author contribution SPT performed the data analysis and wrote the first draft of the manuscript. BN directed and supervised the writing. JW developed the original concept, reviewed the data analysis, and edited the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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