Energy inputs to additive manufacturing: Does capacity utilization matter?

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ENERGY INPUTS TO ADDITIVE MANUFACTURING: DOES CAPACITY UTILIZATION MATTER?

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Abstract

The available additive manufacturing (AM) platforms differ in terms of their operating principle, but also with respect to energy input usage. This study presents an overview of electricity consumption across several major AM technology variants, reporting specific energy consumption during the production of dedicated test parts (ranging from 61 to 4849 MJ per kg deposited). Applying a consistent methodology, energy consumption during single part builds is compared to the energy requirements of full build experiments with multiple parts (up to 240 units). It is shown empirically that the effect of capacity utilization on energy efficiency varies strongly across different platforms.

Introduction

Researchers have argued that the world population's current ecological footprint far exceeds the planet's long-term capacity (Westkämper et al., 2000; Jovane et al., 2008). Energy generation and industrial activity contribute significantly to the overall emission of greenhouse gases (DECC, 2010), which are thought to be the key driver of global warming. A reduction of manufacturing energy consumption would thus be highly relevant for the limitation of overall greenhouse gas emissions. In this context, an understanding of the energy inputs consumed by the available manufacturing processes is critical. Foran et al. (2005) have remarked that "if you can't measure, you can't manage".

The term 'additive manufacturing' describes the use of a collection of technologies capable of joining materials to manufacture complex products in a single process step. Moreover, the technique allows the production of multiple components in a parallel manner (Ruffo et al., 2006) entirely without the need for tooling (Hague et al., 2004). The single-step nature of the additive processes affords an unprecedented level of transparency with respect to the energy inputs employed in the manufacture of complex end-use components. This advantage has received little attention in the literature and motivates the current paper. Due to the parallel characteristics of additive processes, allowing the contemporaneous production of multiple parts in a build, it must be expected that the degree of capacity utilization during additive production impacts the total energy inputs. Hence, any corresponding summary metrics of energy consumption, such as the specific energy consumption per kg of material deposited, are also likely to be affected.

The current paper proposes a universally applicable methodology for the measurement of the electric energy inputs to additive processes. This approach is able to accommodate some of the differences exhibited by the various additive technology variants available in the marketplace. Such variations include:

- differences in build volume size,
- the ability to produce fully three-dimensional build volume packing configurations,
- a requirement for pre-heating and/or cool-down procedures.

It is important to note that due to differences in terms of build material, layer thickness, mechanical properties and surface finish, the results reported in the current paper are not useful for direct comparisons of the energy efficiency (or environmental performance) of individual additive platforms. The results reached in this paper do however offer a consistent and reliable absolute measure of energy consumption across a number of widely adopted additive manufacturing systems.

The current paper concentrates on the spectrum of additive technology variants suited for the production of end-use parts and products, with an emphasis on metallic additive technologies. The following technology variants have been assessed experimentally for this research: selective laser melting (SLM), direct metal laser sintering (DMLS), electron beam melting (EBM), laser sintering (LS) and fused deposition modeling (FDM) of polymers. Table 1 summarizes system type, manufacturer reference, operating principle and nominal build volume size of the machines assessed in the performed experiments. Also, an indication of the layer thickness and build material selected for the performed power monitoring experiments is provided.

System	Manufacturer reference	Operating principle	Nominal build vol. size (X * Y * Z)	Layer thickness	Build material
SLM250	MTT Group, UK (2009)	Selective laser melting (SLM)	250 × 250 × 300 mm	50 µm	Stainless steel 316L
M3 Linear	Concept Laser GmbH (2011)	Selective laser melting (SLM)	250 × 250 × 250 mm (used configuration)	30 µm	Stainless steel 316L
EOSINT M 270	EOS GmbH (2011)	Direct metal laser sintering (DMLS)	250 × 250 × 215 mm	20 µm	Stainless steel 17-4 PH
A1	Arcam AB (2010)	Electron beam melting (EBM)	200 × 200 × 180 mm	70 µm	Ti-6Al-4V
EOSINT P 390	EOS GmbH (2011)	Laser sintering (LS)	340 × 340 × 620 mm	100 µm	PA 12
FDM 400 mc	Stratasys Inc. (2011)	Fused deposition modeling (FDM)	406 × 355 × 406 mm	178 µm (nozzle Ø)	Polycarbonate

Table 1: Machine characteristics and build material in the performed experiments

The energy consumption characteristics of various additive systems have been the subject of a number of publications. In most cases, the literature provides an indication of specific energy consumption expressed in energy used (in MJ or kWh) per kg of material deposited. Table 2 provides an overview of the cited energy consumption results; where necessary, values were converted from kWh to MJ. Further, the table states if the data are derived from build experiments or estimated using secondary data. Regarding the work based on experimental results, it also reports whether the data were obtained from build configurations holding only a single test part or from builds with multiple parts. As the current paper will show, this is an important point.

Study	Technology variant	Energy consumption result	Methodology
Luo et al. (1999)	Stereolithography	74.52 – 148.97 MJ / kg	Energy consumption not empirically measured
	LS	107.39 – 144.32 MJ / kg	
	FDM	83.09 – 1247.04 MJ / kg	
Mognol et al. (2006)	3D Printing	7.56 – 13.68 MJ per part	Single part build experiments, in various orientations
	FDM	1.80 – 4.50 MJ per part	
	DMLS	115.20 – 201.60 MJ per part	
Sreenivasan and Bourell (2009)	LS	52.20 MJ / kg	Empirical energy results not reported
Kellens et al. (2010a & 2010b)	LS	129.73 MJ / kg*	Full build experiments
	SLM	96.82 MJ / kg*	
Baumers et al. (2010)	SLM	111.60 – 139.50 MJ /kg†	Single part and full build experiments, compared
	EBM	61.20 – 176.67 MJ / kg†	

* - Calculated from data provided by Kellens et al. (2010a; 2010b)
† - Calculated from data provided by Baumers et al. (2010)

Table 2: Specific energy consumption results for additive processes in the literature

The specific energy consumption results reported in the literature for the same additive technology variant can differ significantly, as noted by Telenko and Seepersad (2010), who suggest that differences in Z-height and density of the build experiments are responsible. This supports the assumption that the degree of capacity utilization is very likely to have a bearing on energy requirements. Thus, a consistent methodology in energy input measurement is needed for the analysis of process energy consumption. This also prompts an important question about the efficient operation of additive manufacturing systems: to what extent does the degree of capacity utilization matter for each additive technology variant?

Methodology

If the parallel nature of additive technology is ignored in measurements of specific energy consumption, the usefulness of results may be impaired. To produce consistent results, such data should ideally be collected from experiments with a controlled degree of capacity utilization. The approach taken in the current paper rests on the assumption that for the efficient operation of additive manufacturing processes, it is necessary to produce parts in fully utilized build volumes, thereby operating the machinery at maximum capacity. This premise is confronted with the empirical data collected. The underlying experimental strategy is to record the energy consumption during two specifically designed build experiments for each additive technology variant:

- In a first build experiment, the additive system is operated at full capacity. Where the technology's operating principle dictates that all parts are attached to a (removable) build plate or substrate, this is achieved by placing as many test parts as possible on the available substrate area. Hence, in this case the available build capacity is exhausted in the X/Y plane. For technology variants allowing an unconstrained three-dimensional placement of parts in the build volume (for example LS), full capacity operation necessitates a three dimensional workspace configuration that uses up all available space in the X/Y/Z dimensions.

- The second experiment surveys the production of a single test part located in the center of the build volume floor plane. This experiment provides information on the energy consumption characteristics if the available capacity is only minimally used, thereby allowing an analysis of the impact of capacity utilization on process energy efficiency.

Due to additive manufacturing platforms normally being single-machine electricity driven systems, the measurement of electric energy inputs to build experiments is not complex. For the current research, process energy consumption was recorded using a digital power meter (Yokogawa CW240) attached to each system's AC power supply. Energy consumption was monitored throughout the entire build process, including any necessary process steps preceding and following the actual build activity. This includes, for example, process elements such as bed heating or vacuum drawing. With regards to the data gathered with the power meter, the focus lies on mean real power consumed per one-second measurement cycle (measured in W) and total cumulative electric energy consumed (measured in Wh). This cycle length is selected as the Yokogawa CW240 generates a full dataset of all available 137 measurement variables in this setting.

The implementation of power monitoring experiments with consistent packing efficiency is based on the use of a standardized test part, shown in Figure 1. A reason for the 'spider' shape is that it has a relatively large footprint in the X/Y dimensions, thereby limiting the achievable overall packing density and improving the economy and manageability of the experiments. Due to the two-dimensional method of build volume packing found on some additive platforms, this is particularly effective for approaches that require every part to be attached to the build substrate.

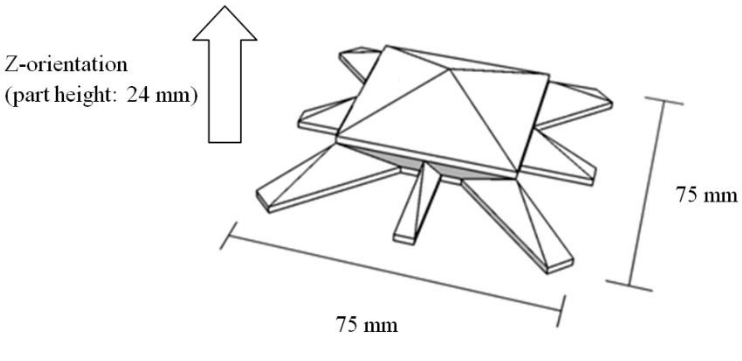

Figure 1: A standardized test part

A further consideration in the design of the test part is that it should not require auxiliary structures for the support of overhanging areas or the dissipation of heat. In the build experiments on the MTT SLM250 and the Stratasys FDM 400 mc, support structures were generated to connect the parts to the build plate. This configuration was chosen idiosyncratically for the MTT SLM250 and the build could have been performed directly on the substrate, therefore the energy expended for the supports is not factored into the energy consumption results. On the FDM 400 mc, parts are normally connected to the removable substrate using a secondary support material. For this reason, the energy consumption results include the generation of support structures on this platform. For all analyzed platforms, the energy consumption of ancillary equipment, such as optics chillers and post processing equipment (e.g. used to cut the parts off the build plates) is not considered.

In contrast to the simplicity of the power monitoring setup, the creation of a standardized level of full build capacity utilization across different additive platforms proved non-trivial. The idea pursued in this research was to apply a custom-developed build volume packing algorithm, producing densely packed, albeit sub-optimal, build configurations for use in the full build experiments. The resulting implementation is capable of generating build configurations both in full 3D mode as well as in a 2D mode constrained to the substrate area. A simple algorithm is used to insert and translate voxel representations of the test part in the build volumes in order to produce a densely packed configuration. In the full 3D packing mode, used only for the full build on EOSINT P 390, the algorithm was also allowed to flip test parts upside-down.

The build volumes of the surveyed metallic additive systems exhibit an approximately square horizontal cross-section with a similar side length ranging from 200 mm (Arcam A1) to 250 mm (EOSINT M 270 and both SLM systems). However, the presence of rounded build volume corners and holes in the substrates made the algorithm-generated build configurations unacceptable. Thus for the metal platforms, it was decided to use human operator packed builds in the full build experiments, resulting in a total number of five (Arcam A1) and six (EOSINT M 270 and both SLM systems) test parts included, as shown in Figure 2. While all metallic additive platforms feature atmosphere generation and (in some cases) pre-heating routines, only the EBM platform runs a controlled cool-down procedure after each build.

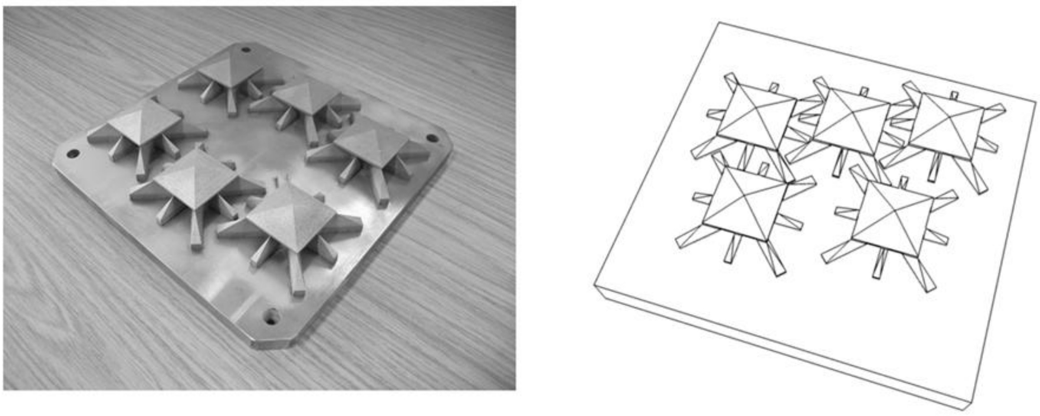

Figure 2: Full build configuration for SLM and DMLS (left) and EBM (right)

Both full build experiments on polymeric systems were successfully configured with the build volume packing algorithm. As the EOSINT P 390 features a very tall build envelope (nominal Z-height: 620 mm), it was decided to limit the build experiment to a 50 mm horizontal ‘slice’ of the available build space. The resulting packing configuration (holding 20 test parts) is shown in Figure 3. The full build energy consumption result for this system was obtained by extrapolating the energy consumption data measured during the 50 mm build phase to the full 600 mm of available build height. No adjustments were made to the energy consumption increments added during system warm up (160 min) and cool down (914 min).

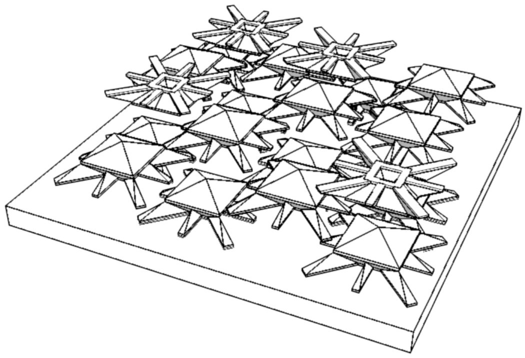

Figure 3: 3D build configuration for EOSINT P 390, 50 mm Z-height

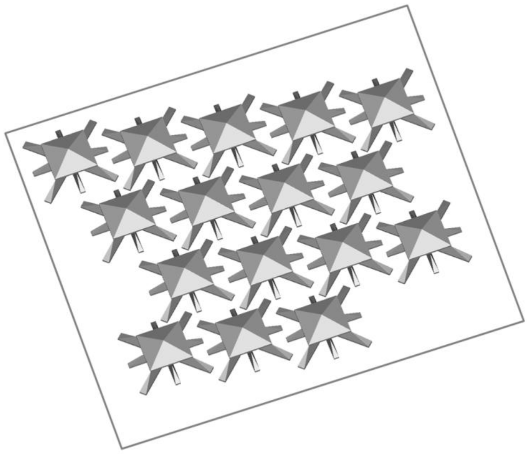

Figure 4: Build configuration for FDM, nominal build volume area: 406 × 355 mm

For the build experiment on the FDM 400 mc, the packing algorithm was used in the two-dimensional mode, this resulted in the insertion of 16 parts (Figure 4). A further characteristic of the FDM 400 mc affects the energy consumption results: as the interchange of substrates is carried out in a fully heated machine and the machine is designed for continuous operation, zero warm-up and cool-down time and energy consumption are assumed.

Results and Discussion

The current research pursues two goals: firstly, it aims to contribute reliable summary data of additive process energy consumption in an inter-platform study. As the density of the parts in the build volume is expected to play an important role, an emphasis is placed on keeping the degree of capacity utilization constant across platforms (although no attempt is made to quantify this). This additional clarity is needed, as the existing literature reports a wide range of energy consumption levels, even for technologically closely related platforms. Secondly, the application of the above described methodology allows an analysis of the impact of variation in the degree of capacity utilization - comparing production in a state of incomplete utilization (one test part per build volume) to production at exhausted capacity (fully occupied build volume).

In an effort to understand the determinants of additive process energy consumption, it is instructive to compare mean real power consumption throughout the performed full build experiments. Figure 5 shows that the variation of mean power consumption observed for the assessed platforms is not very large, ranging from 1.09 kW to 3.33 kW, with a standard deviation of 0.76 kW. This is in contrast to the extensive differences in specific energy consumption reported in the literature (52.20 to 1247.04 MJ per kg). It should be noted that a contributing factor to the small mean power consumption exhibited by the MTT SLM250 (1.09 kW) is that the external optics chiller draws power from an external source (~ 0.6 kW) and does not appear in the data.

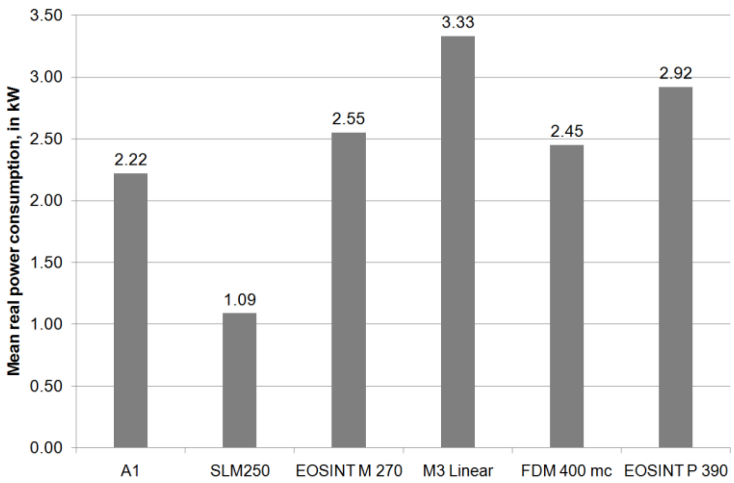

Figure 5: Mean real power consumption during the build experiments

Figure 6 reports the specific energy consumption per kg of material deposited during the build experiments for both the single part (dark column) and full build (light column) experiments. For all surveyed systems, as expected, full capacity utilization results in a lower specific energy consumption. However, the size of this saving varies heavily from platform to platform.

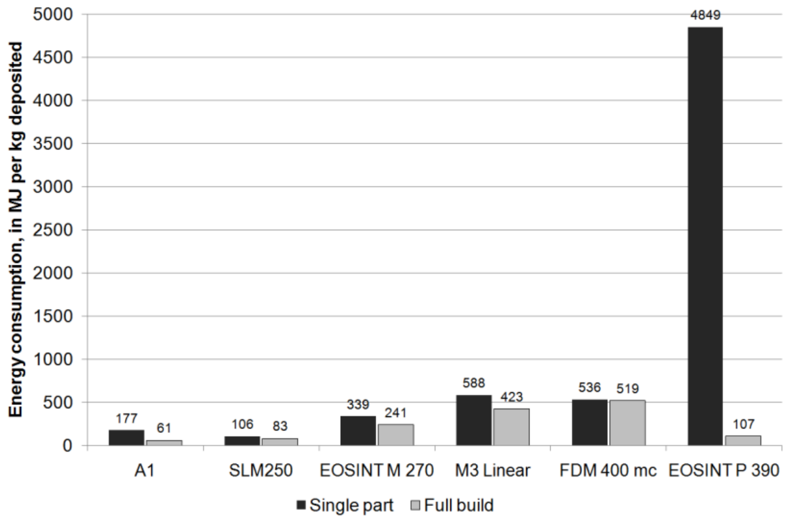

Figure 6: Single part and full build energy consumption per kg deposited

It appears that for the energy efficient operation of some additive systems, capacity utilization is critical. The two polymer-processing systems form the extremes in this comparison. While the specific energy consumption observed on the FDM 400 mc appears relatively insensitive to the switch to full capacity utilization (-3.17 %), the change to full utilization produces a huge specific energy saving on the EOSINT P 390 (-97.79 %).

Contributing factors to the disproportionately large variation are likely to be the extensive energy investments in machine warm-up and cool-down. As Table 3 shows, these energy investments are large during both build experiments on the EOSINT P 390. The much greater number of parts generated in a full build configuration (240) enables the listed energy consumption to be allocated to a far greater part mass, thereby producing a favorable process energy consumption result (107 MJ per kg).

Build phase	**Single part build**		**Full build experiment**	
	Energy consumption	**Duration**	**Energy consumption**	**Duration**
Warm-up	31.55 MJ	125 min	37.96 MJ	160 min
Cool-down	66.94 MJ	600 min	97.33 MJ	914 min

Table 3: EOSINT P 390 warm-up and cool-down energy consumption and time

Contrary to this, the FDM 400 mc is assumed to operate continuously. Therefore, extra energy consumption increments for build volume warm-up and cool-down are unnecessary. The substrate carrying the produced parts is removed from the machine at operating temperature and replaced by an empty substrate for the next build. This, of course, ignores periods in which the machine may in practice sit idle due to other reasons.

The metallic platforms exhibit a smaller variation in specific energy consumption. Operating at full capacity, the Arcam A1 exhibits a far greater energy saving (-65.54 %), than the MTT SLM250 (-21.70 %). Again, the reason for this is likely to be the significant energy expenditure for build volume pre-heating and cool-down procedures. While consuming markedly more energy per kg of material deposited than the other metallic systems, the EOSINT M 270 and Concept Laser M3 Linear, show a similar variation in specific energy consumption (-28.91 % and -28.06 %). A possible reason for the comparatively high specific energy consumption levels observed during both experiments is the small layer thickness setting used on these platforms (20 µm and 30 µm).

The presented results show that the change to full capacity operation results in a reduction of the energy consumed per kg of material deposited for all assessed operating principles and build materials. This gives support to the proposition that the energy consumption data derived from full build experiments are reflective of technically efficient machine operation. Full capacity production should therefore serve as the yardstick in the evaluation of process energy efficiency. Considering that the differences in mean real power consumption do not appear large across the surveyed platforms, the prime candidate for the determination of specific energy consumption of additive processes appears to be machine productivity. A direct relationship between process productivity and specific energy consumption is proposed by Luo et al. (1999). The specific energy consumption rate in MJ per kg deposited is denoted by *SEC*, process productivity is symbolized by *PP* and *PR* denotes the mean real power consumption (power rate), such that:

$$SEC\ (in\ MJ/kg\ ) = \frac{PR(in\ kW)}{PP(in\ kg/h)} \qquad (1)$$

A scatter plot (Figure 7) of the full build results against the process productivity measure illustrates the negative relationship between machine speed and energy efficiency.

The results for the single part build experiments were not included in Figure 7 as they are not seen to be reflective of efficient technology utilization.

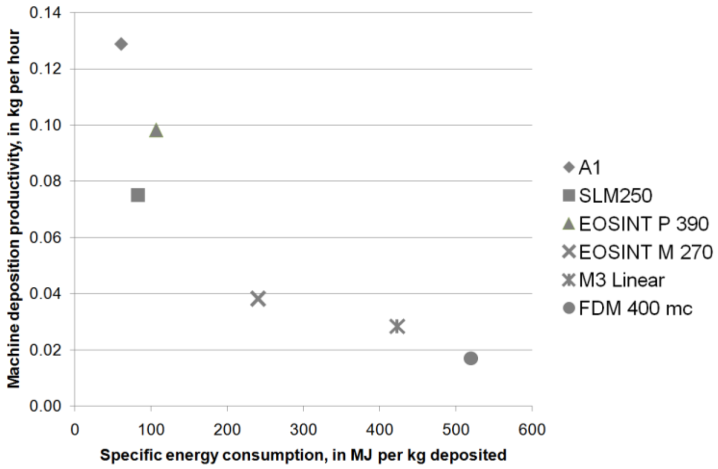

Figure 7: Specific energy consumption versus machine productivity

Conclusions

The heterogeneity in the approaches taken in the literature towards the measurement or estimation of the specific energy consumption of additive machines highlights the need for the development of a more consistent methodology. The technique presented in the current paper allows the calculation of specific energy consumption metrics for different platforms and systems, irrespective of the fundamental differences in operating principle and build materials. Even though all power monitoring experiments were based on the same test part geometry and some of the resulting parts look and feel quite similar, it is likely that the applications of these processes vary due to differences in material, mechanical properties, and surface quality. Therefore, these results should not be interpreted as statements on the relative environmental performance of the assessed additive technology variants.

However, the current research has conclusively demonstrated that the realized degree of capacity utilization has an impact on process energy efficiency. In the performed experiments, this impact on energy savings in terms of specific energy consumption per kg of material deposited ranged from small (-3.17 % for FDM) to extreme (-97.79 % for LS). Considering the LS and EBM processes, which include extensive energy expenditure for atmosphere generation, warm-up and cool-down, full capacity utilization will result in far greater energy efficiency compared to a single part mode of production. This may pose problems in the estimation of process energy consumption for additively produced parts if the composition of the production build is unknown. Contrasting this, the results indicate that the FDM process (where system warm-up and cool-down do not enter the energy consumption metric at all) does not benefit significantly from full capacity utilization. It appears that FDM can be applied in a serial fashion generating output part-by-part without incurring a significant energy efficiency loss. Operating LS or EBM equipment in this way would result in a severe penalty to the environmental performance of the process.

Acknowledgements

- To be inserted after completion of peer review -

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