**Summary**

This life cycle assessment measured environmental impacts of selective laser melting, to determine where most impacts arise: machine and supporting hardware; aluminum powder material used; or electricity used to print. Machine impacts and aluminum powder impacts were calculated by generating life cycle inventories of materials and processing; electricity use was measured by in-line power meter; transport and disposal were also assessed. Impacts were calculated as energy use (megajoules; MJ), ReCiPe Europe Midpoint H, and ReCiPe Europe Endpoint H/A. Previous research has shown that the efficiency of additive manufacturing depends on machine operation patterns; thus, scenarios were demarcated through notation listing different configurations of machine utilization, system idling, and postbuild part removal. Results showed that electricity use during printing was the dominant impact per part for nearly all scenarios, both in MJ and ReCiPe Endpoint H/A. However, some low-utilization scenarios caused printer embodied impacts to dominate these metrics, and some ReCiPe Midpoint H categories were always dominated by other sources. For printer operators, results indicate that maximizing capacity utilization can reduce impacts per part by a factor of 14 to 18, whereas avoiding electron discharge machining part removal can reduce impacts per part by 25% to 28%. For system designers, results indicate that reductions in energy consumption, both in the printer and auxiliary equipment, could significantly reduce the environmental burden of the process.

**Keywords:** 3D printing, additive manufacturing, embodied energy, industrial ecology, life cycle assessment, selective laser melting

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**Introduction**

Additive Manufacturing (AM; or “3D [three-dimensional] printing”) is an emerging technology, mature enough to receive significant attention in the manufacturing community, but new enough for its environmental impacts to be incompletely studied. Given that manufacturing is responsible for roughly one third of global greenhouse gas emissions (Pachauri et al., 2014), plus many other environmental impacts, it is important to measure manufacturing impacts and understand their origins. Quantifying which aspects of a manufacturing process cause the largest environmental impacts allows factory managers and machine designers to prioritize actions for sustainability and measure their success. Such prioritization should improve the effectiveness and return on investment of environmental initiatives.

The Renishaw AM250 selective laser melting (SLM) system studied in this research belongs to the class of powder bed fusion technologies (ASTM 2012). In it, a bed of fine powdered metal sits in a sealed chamber, where a 200-watt (W) fiber laser draws its beam across the top of the powder bed to fuse particles in specified locations. After one layer of powder has been processed, the bed is lowered by one increment and another layer of metal powder is deposited smoothly onto the bed by a
wiper mechanism. The laser then melts this layer to itself and to the layer below in specified locations, and the process repeats. To avoid oxidation in the high heat of melting, the chamber’s air is replaced with argon gas before printing. Once printing is complete, the build chamber is opened and the bed is raised, with an operator manually brushing unmelted powder off of the solidified model. Unmelted powder is captured in a bottle for reuse, to the best of the operator’s ability.

Several studies on AM sustainability are limited to measuring operational energy use (Telenko and Seepersad 2012; Sreenivasan and Bourell 2010; Baumers et al. 2011a, 2011b; Mognol et al. 2006). A range of studies have investigated the toxicity of AM materials (Huang et al. 2013; Stephens et al. 2013; Merlo et al. 2015) and AM waste products (Huang et al. 2013; Drizo and Pegna 2006), but without weighing these impacts against energy inputs. Drizo and Pegna (2006) note that very few studies comprehensively measure impacts, such as waste and toxicity, in a way that would allow AM operators and machine designers to determine priorities for sustainability. Luo and colleagues’ (1999) approach was more holistic, including operational material and waste, scoring them alongside energy with a comprehensive life cycle assessment (LCA) method (EcoIndicator). Kellens and colleagues (2011), similar to Luo and colleagues, scored SLM energy and materials with ReCiPe Endpoint H/A Europe. Previous studies adding production of the AM machine as well as energy use, material use, and material waste for a comprehensive set of environmental impacts, such as ReCiPe Endpoint H/A (Faludi et al. 2015a, 2015b), are restricted to polymer-based AM, not metal AM.

This article effectively extends the literature on environmental impact and energy consumption of AM processes (Luo et al. 1999; Baumers et al. 2013; Kellens et al. 2011) by systematically considering the impact embodied by the AM machine and its ancillaries. By doing so, it is able to make a comprehensive statement on where the largest environmental impacts originate: the raw material used, the printer hardware, or the process and ancillary process energy consumption.

In this article, Methods presents boundaries and functional units for analysis, the body of data collected, and the article’s approach in terms of use-phase scenarios. Results and Discussion presents and analyzes the energy usage characteristics and ReCiPe metrics calculated, determining which aspect of SLM dominates its environmental footprint. Conclusion lists recommendations for action and further research.

**Methods**

Calculating environmental impacts of the AM machine, aluminum powder, energy use, machine transport, and disposal followed standard LCA practices, as detailed below, so results could be easily replicable and comparable to studies of different manufacturing methods. Impacts were calculated in three ways:

- First, for clarity and precision, primary (source) energy demand in megajoules (MJ).
- Second, for comprehensive inclusion of impacts, such as toxicity, land use, and other variables not captured by energy measurements, the ReCiPe Europe Midpoint H method v1.12 (Goedkoop et al. 2009) separately measured 18 different environmental impact categories in their own units of measure. Third, for a metric actionable by decision makers, the ReCiPe Europe Endpoint H/A method v1.12 (Goedkoop et al. 2009) integrated 17 environmental impact categories into a single normalized and weighed score. All analyses were carried out with SimaPro 8.0.5.13 software in conjunction with the ecoinvent 3 database.

**Scope, Boundaries, Functional Unit**

Because capacity utilization has been demonstrated to have an effect on environmental performance of AM platforms (Baumers et al. 2011b), the functional unit of analysis selected for this article was environmental impact per part produced. This investigation’s test specimen was a small, geometrically complex turbine, shown in figure 1. This part was deemed representative of the size, shape complexity, and application of
products manufactured by SLM. In order to identify dominant factors, all impacts of machine production, end of life (EoL), and transportation were amortized over the number of parts printed throughout the life span of the SLM system.

Average lifetime of powder bed fusion machines is debated, with anecdotal reports of long-lived machines competing against equally anecdotal reports of rapid obsolescence attributed to the fast pace of industry advances. Manufacturer claims cannot be assumed to be reliable, given that economic incentives encourage exaggeration. Ruffo and colleagues (2006) found the average useful life of laser sinterers to be 8 years; Baumer and colleagues (2013) also used 8 years for an EOS M270 laser sinterer, and Hopkinson and Dickens (2003) used 8 years as a generic value for fused deposition modeling, laser sintering, and stereolithography. Arzeni and colleagues reported 5-year lifetimes for EOS M270, EOS P390, and EOS P730 laser sinterers (Arzeni et al. 2010; Arzeni and Salmi 2012). Khamjai and colleagues (2014) reported 10 years for a 3D Systems sPro 60, and Gibson and colleagues (2010) listed 7 years for a 3D Systems SLA Viper Pro. Thus, taking the median value of these studies, the machine studied here is assumed to have an 8-year life.

The scope of this analysis covers cradle-to-gate and gate-to-grave environmental impacts arising from the manufacture of test specimens in an aluminum build material—effectively including all aspects lying outside of the test specimens use phase. Thus, this investigation’s scope includes the following:

- Impacts embodied in raw materials and manufacturing of the AM system hardware, amortized per part produced. This includes the SLM machine, external chiller for laser and optics, vacuum immersion separator, and powder sieve. It does not include a convection oven used to control powder humidity, because this is optional. It also excludes the wire electron discharge machining (EDM) hardware or conventional machine tool hardware used to remove printed parts from the build platform, because this separation takes so little time, it would be an insignificantly small percentage of such machines’ lifetime usage; thus, the percentage of their impacts allocated to this process would be vanishingly small.

- Impacts of transporting the AM system’s components from various manufacturing locations to the present operating location, amortized per part produced.

- Impacts from extraction and processing of raw materials consumed to manufacture the test parts, including support structures and in-process material losses.

- Impacts from energy consumption during the build process. This includes auxiliary equipment required to operate the AM machine, energy consumption while idling, and energy required to remove printed parts from the machine’s build platform. This research does not consider energy consumed by postprocessing equipment, because such postprocessing (e.g., shot-blasting or machining for smoother surface finish) is application dependent.

- Impacts from EoL for all materials, including parts printed, support structures and other waste from printing, and the AM system hardware, amortized per part produced.

Data Collected

Operational Energy

This study measured real power consumption of the investigated systems using a Yokogawa CW240 power meter. To collect the required data at varying levels of capacity utilization, two build experiments were performed: The first measured system electricity consumption to build a single test specimen in the middle of the build volume. The second printed a full build containing 12 specimens. Table 1 summarizes both build experiments.

To correspond to the SLM operating procedure and the batch nature of the SLM process, the system’s electricity consumption was divided into three operational modes—warmup, build, and cool down—and an idle mode. During build, the SLM system and the chiller draw power, the vacuum and sieve are inactive. Following the build, preparing the system for a new build requires an estimated 52 minutes. The system idles during this time, with the chiller operating.

Printed parts may be separated from the machine’s build platform in various ways. This study considers two common alternatives: wire EDM and mechanical means. EDM separation incurs an additional energy expense of 33.45 MJ for the single part build and 142.46 MJ for the full build (based on Baumer et al. 2013). Traditional mechanical removal (sawing and machining) incurs a far lower energy consumption of 0.0064 MJ per part that is removed (Granta Design 2009).

Impacts for electricity use were modeled for Great Britain average grid mix, using the ecoinvent 3 process “Electricity, low voltage [GB]1 market for 1 Alloc Def, S.” This consisted of 44% gas, 31% coal, 16% nuclear, 7% renewables, the rest oil, and other (Treyer and Bauer 2013). It produces 0.695 kilograms carbon dioxide equivalents (kg CO₂-eq) per kilowatt-hour. Readers in other countries (or in Britain as more renewables are added to the grid) can adjust results for their own electricity mix.

Material Use and Waste

The aluminum powder used was aluminum-silicon 10 milligrams, specified as 89% aluminum, 10% silicon, and trace amounts of iron, copper, manganese, tin, magnesium, nickel, zinc, lead, and titanium (LPW 2013). Powder production by atomization was modeled as adding 8.1 MJ/kg of embodied energy to the material, based on vaporization energy of the similar aluminum alloy, UNS A4132 (Granta Design 2009). This added energy was assumed to come entirely from natural gas burned in an industrial furnace. Thus, total powder specific energy was 224 MJ/kg. Granta documentation and personnel were unclear about whether this energy included embodied energy from inert gases (nitrogen, argon, or helium) used during atomization. Representatives of LPW reported nitrogen use, but did not divulge...
Table 1  Process electricity consumption (site energy/power) and mass

|                                | Single part build | Full build |
|--------------------------------|-------------------|------------|
| No. of test specimens included | 1                 | 12         |
| Mass per part                  | 58 g              |            |
| Net material volume deposited  | 20.62 cm³         | 247.44 cm³|
| Idling power consumption       | 430 W             |            |
| Typical between-build idling energy consumption<sup>a</sup> | 1.34 MJ           |            |
| Warm-up time                   | 39 min            |            |
| Build time                     | 462 min           | 3343 min   |
| Cool-down time                 | 240 min           | 233 min    |
| Total build time               | 767 min           | 3,615 min  |
| Warmup, mean power consumption | 738 W             | 897 W      |
| Build, mean power consumption  | 968 W             | 1,222 W    |
| Cool down, mean power consumption | 430 W          |            |
| Mean power consumption         | 783 W             | 1,166 W    |
| Warm-up energy consumption     | 2.88 MJ           | 2.11 MJ    |
| Build energy consumption       | 26.81 MJ          | 245 MJ     |
| Cool-down energy consumption   | 6.19 MJ           | 6.23 MJ    |
| Total SLM energy consumption   | 35.88 MJ          | 253.34 MJ  |
| Constant chiller power consumption | 640 W         |            |
| Chiller energy consumption     | 31.45 MJ          | 140.81 MJ  |
| Sieving, mean power consumption| 60 W              |            |
| Sieving, duration              | 15 min            |            |
| Sieving, energy consumption    | 0.05 MJ           |            |
| Vacuum immersion separator mean power consumption | 2.463 W | |
| Vacuum immersion separator, duration | 1 min | |
| Vacuum immersion separator, energy consumption | 0.15 MJ | |
| Part separation by EDM process, energy consumption<sup>b</sup> | 33.45 MJ | 142.46 MJ |
| Mechanical part separation, energy consumption<sup>c</sup> | 0.0064 MJ | 0.08 MJ |
| **Total energy consumption per part, including ancillaries, EDM route** | **102.32 MJ** | **44.85 MJ** |
| **Total energy consumption per part, including ancillaries, mechanical separation route** | **68.88 MJ** | **32.98 MJ** |

<sup>a</sup>Estimate, based on a machine turnaround time of 52 minutes.
<sup>b</sup>Estimate, based on Baumers and colleagues (2013).
<sup>c</sup>Estimate, based on Granta Design (2009).

SLM = selective laser melting; EDM = electron discharge machining; cm³ = cubic centimeters; W = watts; MJ = megajoules; min = minutes.

Gas usage per kg, saying that processes varied. Representatives of other metal atomization suppliers (Valimet and ALD Vacuum Technologies) reported helium use with 99.9999% or 99.99999% reuse. According to Unal (1990), gas-to-powder mass ratios vary from 2:1 to 10:1; company personnel reported ratios of 3:1 to 5:1, and 99.9999% reuse would decrease this to, at most, 0.0005:1. Adding embodied energy for 3 kg of 99.9999% reused helium, specific energy of the aluminum powder would increase 0.1%; adding 5 kg of nonreused nitrogen would increase specific energy 20% and would increase ReCiPe Endpoint H points per kg by 11%. Further study could clarify, but even the worst-case scenario here would not change this study’s conclusions. For both material use and material waste, calculated impacts included landfill disposal at EoL, but it was insignificant (0.003% of material embodied energy and 0.005% of impacts in ReCiPe Endpoint H/A points).

The majority of unused aluminum powder is reused in subsequent prints and can be reused many times. SLOTWINSKI and colleagues’ study of steel SLM powder reused eight times showed that although material properties drift, they do not drift far when properly sieved (Slotwinski et al. 2014). Thus, although some demanding applications may require 100% virgin powder, the machine measured in this study typically prints with mostly reused powder, only requiring enough virgin powder to compensate for volume lost to printed parts and waste. This operation practice has been corroborated by conversation with an industry SLM machine operator. Total material losses associated with sieve filtering of reused powder, the deposition
of support structures, residues accumulated in the system filters, emissions of aerosols, and platform separation are assumed to increase material consumption by 20%, as identified by Kellens and colleagues (2011).

This research assumes that capacity utilization and the processes used to separate the test parts from the build platform do not affect material losses. Thus, because final parts were weighed at 58 grams (g), total material consumption per part was assumed to be 70 g, corresponding to an embedded energy of 16 MJ per part (13 MJ for material in the part, 2.6 MJ for waste).

Argon consumption was estimated at 208 cubic decimeters per build operation. After initially evacuating the build volume and circulation system (estimated to total twice the volume of the build chamber), the system is flooded with argon to approximately ambient pressure. Unlike other SLM processes (Kellens et al. 2011), the investigated AM250 does not require continuous flooding of argon during the build process. Therefore, it is permissible to ignore protective gas losses during build. Powder storage requires no argon. However, no argon is recaptured after build completion.

**Machine Embodied Impacts**

Using the methodology developed by Diaz and colleagues (2010) and previously applied to AM equipment by Faludi and colleagues (2015a, 2015b) indicated that the Renishaw AM250 printer is comprised of approximately 86% steel by mass, both low alloyed and stainless, primarily bent sheet or welded plate, but with many parts machined or cast. Approximately 5% of printer mass is aluminum, largely cast and/or machined; other materials comprise smaller percentages. Several motors are required to move print bed components, steer the laser, and run pumps. Control electronics include a desktop-equivalent computer, custom circuit boards, various sensors, power supplies, and smaller controllers. Miscellaneous materials include glass windows and rubber gloves to manipulate parts or powder without opening the build chamber door.

The SLM printer also requires ancillary devices to operate. An SMC Model HRGC002-A chiller cools the laser with water in a closed-loop system. Argon gas is supplied by facilities. A Ruwac NA35-110 vacuum immersion separator is required to clean the build chamber between print runs, because fine aluminum powder is dangerously flammable (Carnegie Mellon University, Environmental Health and Safety n.d.). A Russell Finex MS400 vibrating sieve with a “vibrasonic deblinding” system removes leftover aluminum powder that has been partially melted into grains too large to be reused in the next print.

Ideally, machine impacts would be measured by disassembling all machines to their individual material components, weighing those parts, then determining each part’s material composition and manufacturing. However, this is impractical for such expensive, complex devices. Relying on manufacturer data also proved infeasible, given that information on component masses are generally not tracked. Therefore, masses of materials for all components in all machines were determined by measuring their physical dimensions with calipers and/or tape measures, calculating the volume of each material, and multiplying by standard densities of materials (primarily from EngineeringToolbox.com). Manufacturing processes were estimated based on part geometry, surface finish, and knowledge of which processes are typical for what materials. For parts deemed to use multiple manufacturing methods, or where manufacturing methods were unclear, ecoinvent’s “average” processing for that material was used.

Although this method does not have high precision, it does allow analysis of machines impractical to disassemble, with no data from the manufacturer, and has been used before with success (Diaz et al. 2010; Faludi et al. 2015a, 2015b). To ensure accuracy, the sums of calculated component masses were checked against manufacturers’ published total masses (Renishaw 2007; SMC 2007; Ruwac 2008). They matched within 3% for the SLM machine, 6% for the chiller, 1% for the sieve, and 1% for the vacuum. See the Results section for a table of masses, embodied energies, and ReCiPe points. The full bill of materials for all machines encompassed nearly 500 items and was consolidated into slightly more than 200 groups by material and manufacturing methods for entry into LCA software. The full bill of materials listing masses, LCA database material selections, and manufacturing process selections is available to the reader in the Supporting Information available on the Journal’s website.

Masses of motors were taken from published datasheets for the specific model, where available (Leybold 2005; Vibtec 2010); otherwise, for similar size and wattage motors (Baldor 2012, 2014), or assuming 90% solid volume, 10% hollow. All motors were assumed to be comprised of 85% mild steel, 11% copper wire, and 3% neodymium magnets. The percentage of total environmental impacts attributed to motors was not large enough to warrant more refined modeling (e.g., for the SLM unit hardware, only 3% of total ReCiPe Endpoint H/A impacts were attributed to motors).

Masses and material compositions of electronic components were taken from published datasheets for 21 devices; otherwise, they were estimated from datasheets of similar products or through measurement of the dimensions of circuit boards and counting major components, such as capacitors, transistors, integrated circuits, and light-emitting diodes. Where available in the ecoinvent database, electronic components were modeled as whole devices, rather than by material.

Masses and material composition of the SLM unit’s RedLaser D Series 200W fiber laser system by SPI Lasers were estimated by disassembly of a similar fiber laser (Spectra-Physics Alliant 100W), of which some components were weighed and some were calculated from dimensions. Because the Spectra-Physics laser was smaller, its masses were scaled up by the ratio of its total mass to the total mass of the SPI laser. Personal communication with SPI Lasers verified the validity of this technique. No data were available for the laser optics assembly, but discussion with a laser engineer and inspection of alternative laser aiming systems (Chan 2006) allowed estimation of components. Given that the impacts of this assembly were roughly 0.05% of total ReCiPe
Endpoint H/A impacts for SLM unit hardware, further precision was not deemed necessary.

**Machine Transportation and End of Life**

EoL was assumed to be landfill for all materials of all machines, printed parts, and printing waste. Transportation of machines was modeled as oceangoing freighter and trucking distance from the various locations of manufacture to Nottingham, England, where the system resides. Given that AM machines are still relatively uncommon, transport utilization was assumed to be half industry average (modeled by doubling distances). Because transportation did not exceed 0.3% of LCA impacts or 0.6% of embodied energy, further refinement was not deemed unnecessary.

**Patterns of Machine Operation**

Many operation-dependent variables affect the environmental impacts of AM. Several were altered for sensitivity analysis, but did not notably alter results (e.g., heat source for aluminum powder vaporization, transportation distances). However, three variables drastically changed results: capacity utilization; machine state when idle; and the means of removing printed parts from the build platform.

Because energy and resource efficiency of AM depend so heavily on operational settings that it must be discussed in terms of specific scenarios, a compact notation for these settings makes discussion more concise. Notation here was inspired by literature on machine scheduling (e.g., Pinedo 2012), which summarizes different problem configurations in a "triplet." To classify the investigated patterns of machine operation in studies of AM efficiency, this research uses a four-digit notation \( \alpha | \beta | \gamma | \delta \). The \( \alpha \) describes the degree of utilization of the available build space, distinguishing in this research between single part ("1P") and full build ("FULL") configurations. The \( \beta \) quantifies temporal capacity utilization, for example, "90%T" represents the system performing print jobs during 90% of its lifetime, only inactive 10% of the time. The \( \gamma \) indicates the system state when inactive, distinguishing between SLM and chiller idling but inactive ("IDLE") and all devices deactivated ("OFF"). The \( \delta \) describes the technology used to separate the deposited parts from the build platform, allowing either removal by EDM ("EDM") or by mechanical means ("MECH").

**Utilization**

Utilization rates of 3D printers vary widely, and are not well known, but utilization has been demonstrated to have a significant effect on ecological impacts per part (Baumers et al. 2011b; Faludi et al. 2015b). This is both attributed to amortization of the machine hardware's impacts over the number of parts printed in its lifetime and attributed to energy use per part printed. To accommodate the wide range of utilization levels encountered in industry, three utilization scenarios were calculated: First, low-utilization scenarios were defined as one build job per week, one part per build. Building this study's part required 13.6 hours, thus the system operated 8% of the available time. Using the notation proposed above, these scenarios are written 1P|18%T|\( \gamma \) |\( \delta \).

Next, low build volume utilization with maximum temporal utilization was defined as one part per job, but printing as close as possible to 24 hours per day, 7 days per week for the entire life of the machine. Modeling such a pattern of machine usage, Hopkinson and Dickens (2003) determined a feasible temporal utilization of 90% (7,889.4 hours per year). To allow maintenance and service procedures, the systems were assumed to be off the remaining 10% of time. These scenarios are notated 1P|90%T|\( \gamma \) |\( \delta \). Because, by definition, there is no idle time at maximum utilization, there cannot be any \( \alpha \) 90%T | IDLE | \( \delta \) scenarios, only \( \alpha \) 90%T | OFF | \( \delta \).

Finally, maximum utilization scenarios produced as many parts as possible per print job with as many builds as possible. To ensure maximum utilization, a computational build volume packing algorithm was employed to specify the full build configuration; 12 parts fit (see photograph in table 1). Using the proposed notation, these scenarios are FULL|90%T | OFF | \( \delta \).

**Part Removal**

As shown by the reported energy consumption data, separating parts from the build plate by wire EDM (\( \delta = EDM \) in above notation) was extremely energy intensive (see table 1). As an alternative to EDM, part recovery was also modeled as sawing/traditional machining removing 1.3 g of sacrificial support material (\( \delta = MECH \)). Using published values for the energy intensiveness of machining (Granta Design 2009), this energy consumption was modeled as 0.0064 MJ per part.

**Uncertainty**

Uncertainties for life cycle inventory (LCI) measurements, calculations, and estimates are summarized in table 2. As noted by Ashby (2012), embodied energy and emissions data should generally be assumed no more precise than a \( \pm 10\% \) baseline. For this study, electricity and aluminum powder material use were precisely measured, therefore they were assumed to have baseline uncertainty. The powder material waste fraction was obtained from Kellens and colleagues (2011); because Kellens and colleagues studied a different AM system, and observation suggested that material waste here is likely smaller, an uncertainty of \( \pm 50\% \) was assumed. Argon use was assumed to have \( \pm 30\% \) uncertainty because of the simplifying assumption of its volume equaling double the build chamber volume. Transport impacts were assumed to have 5% over baseline uncertainty attributed to estimation rather than measurement; it should, however, be noted that even \( \pm 100\% \) uncertainty would leave them negligible in all scenarios. Disposal was considered to be \( \pm 100\% \), but was negligible in all scenarios. Measuring machine impacts by dimensions rather than weighing was assumed to add 5% to baseline. Motor and cable impacts were assumed to have \( \pm 30\% \) uncertainty because of the simplifying assumption of its volume equaling double the build chamber volume. Transport impacts were assumed to have 5% over baseline uncertainty attributed to estimation rather than measurement; it should, however, be noted that even \( \pm 100\% \) uncertainty would leave them negligible in all scenarios.
Table 2 Uncertainties for LCI data categories

| LCI item category                  | Data source       | Uncertainty |
|-----------------------------------|-------------------|-------------|
| Electricity use                    | Measured          | ± 10%       |
| Aluminum powder material use       | Measured          | ± 10%       |
| Aluminum powder material waste     | (Kellens et al. 2011) | ± 50%      |
| Argon use                         | Dimensions        | ± 30%       |
| Transport                          | Calculated        | ± 15%       |
| Disposal                           | Assumed           | ± 100%      |
| Combined machine hardware (see below) | (see below)      | ± 26%       |
| Machine components                 | Data source       |             |
| Structural framing, piping, other (steel, aluminum, glass, plastic, etc.) | Dimensions | 92 | ± 13% |
| Motors and wiring                  | Dimensions and specification sheets | 4 to 5 | ± 30% |
| Fiber laser                        | Dimensions        | 1           | ± 30% |
| Laser optics assembly              | Estimate          | 0.08        | ± 100% |
| Electronics                        | Dimensions and specification sheets | 2 | ± 60% |

Note: LCI = life cycle inventory.

at ±1,000% uncertainty. Electronics impacts were assumed to have ±60% uncertainty attributed to lack of detailed data on assembly compositions, and because of the high variance in impacts of electronics, even for similar devices. Overall, aggregate machine hardware uncertainty was estimated at ±26%, calculated by averaging all component categories weighted by their contributions to total ReCiPe Endpoint H/A score.

Results and Discussion

Dominant Impacts

Operational electricity caused the majority of embodied energy and LCA impacts in almost all scenarios. Figures 2 and 3 show energy and ReCiPe Endpoint H/A results. In both graphs, 1P18%T1IDLE1EDM is the low-utilization scenario with printer and chiller powered on while idle, using EDM to remove parts; 1P18%T1OFF1EDM is the scenario with the same utilization, but with all machines fully deactivated when idle. The scenario 1P190%T1OFF1EDM represents maximum temporal utilization—printing nearly 24 hours per day, 7 days per week, but still only printing one part per build, again removing parts by EDM. Finally, FULL190%T1OFF1EDM is maximum temporal utilization and filling the print bed with 12 parts, with EDM removal. The scenarios modeling mechanical part removal are named as above, but with MECH instead of EDM.

This section presents the results of relative impact in the form of bar charts for each scenario. Whereas the graphs show percentages of impacts, total amounts are listed to the right of the graph bars for absolute comparison. For error bars on all graphs, see the uncertainties listed in Methods; because of uncertainty, all numeric values are listed to two significant figures.

Figures 2 and 3 illustrate the importance of modeling multiple scenarios for utilization and EDM. The results demonstrate that removing parts by conventional machining instead of EDM reduced total energy demand 28% for 1P190%T1OFF1MECH and 22% for maximum utilization (FULL190%T1OFF1MECH). Correspondingly, avoiding EDM reduced ReCiPe Endpoint H/A points 25% for 1P190%T1OFF1MECH and 19% for maximum utilization. ReCiPe percentages differed notably from the energy-only analysis because of the importance of non-energy-related factors, such as human toxicity and mineral depletion, in the ReCiPe framework. However, in all scenarios, both energy and ReCiPe analysis showed a similar trend from EDM to non-EDM scenarios. This implies that although postprocessing (e.g., shot-blasting, EDM, or machining for surface finish or geometric tolerance) was outside the scope of this study, future studies should quantify it for multiple scenarios, because such processes can have significant energy impacts.

For utilization variance, figure 2 shows that the highest energy demand (2,400 MJ per part for 1P18%T1IDLE1EDM) was 14 times the lowest demand (170 MJ per part at maximum utilization) when removing parts by EDM. Without EDM, low utilization demanded 17 times the energy per part of maximum utilization. Utilization scenarios also changed the dominant cause of environmental impacts: For both energy demand and ReCiPe points, electricity dominated in all cases except 1P18%T1OFF1δ (both EDM and MECH) scenarios. Electricity’s portion of energy demand in figure 2 varied from 84% to 85% in 1P18%T1IDLE1EDM, 1P190%T1OFF1EDM, and FULL190%T1OFF1EDM to 36% for 1P18%T1OFF1MECH. Electricity’s portion of ReCiPe points in figure 3 varied from 73% to 74% in 1P190%T1OFF1EDM, and FULL190%T1OFF1EDM to 19% in 1P18%T1OFF1MECH. Amortized machinery’s share of total energy varied from 59% in 1P18%T1OFF1MECH to 7% in FULL190%T1OFF1EDM. Machinery’s share of ReCiPe points varied from 78% in 1P18%T1OFF1MECH to 15% in FULL190%T1OFF1EDM. Aluminum powder’s fraction of total energy varied from 9.6% in FULL190%T1OFF1MECH to 0.5% to 0.6% in 1P18%T1IDLE1δ. Powder’s fraction of ReCiPe points varied from 12% in FULL190%T1OFF1MECH to 0.7% in
Figure 2  Embodied energy per part for different scenarios. IDLE = printer and chiller left on while inactive; EDM = part separation by electron discharge machining; MECH = part separation by mechanical machining; OFF = all machines shut off when inactive; FULL = full build configuration; 1P = single part; T = time. For example, “90%T” represents the system performing print jobs during 90% of its lifetime, only inactive 10% of the time. MJ = megajoules.

Figure 3  ReCiPe Endpoint H/A Europe points per part for different scenarios. IDLE = printer and chiller left on while inactive; EDM = part separation by electron discharge machining; MECH = part separation by mechanical machining; OFF = all machines shut off when inactive; FULL = full build configuration; 1P = single part; T = time. For example, “90%T” represents the system performing print jobs during 90% of its lifetime, only inactive 10% of the time. Pts = points.

1P | 8%T | IDLE | δ. All other factors in figures 2 and 3 were below 1% of impacts in all scenarios, except that argon comprised 2% to 3% of energy and ReCiPe impacts in 1P | 90%T | OFF | δ, and powder waste comprised 1% to 2% of energy and ReCiPe impacts in 1P | 90%T | OFF | δ and FULL | 90%T | OFF | δ.

As discussed above, ReCiPe scores differ notably from the energy-only analysis because of the importance of non-energy-related factors. Both energy and ReCiPe analysis showed the same dominant impacts across low- and high-utilization scenarios. However, in 1P | 8%T | OFF | δ, the percentages of impacts attributed to electricity versus machinery differed more significantly: In energy-only analysis, machinery’s dominance was within uncertainty, thus inconclusive; in ReCiPe analysis, it was not.

**Comprehensive Life Cycle Analysis Breakdown**

To explain the differences between figure 2’s energy-only scores and Figure 3’s ReCiPe scores, the single-score ReCiPe points should be broken down into their separate environmental impact categories. Figures 4 and 5 show percentages of ReCiPe Midpoint H impacts from machines, electricity, aluminum powder, etc., for two scenarios: 1P | 8%T | IDLE | EDM and FULL | 90%T | OFF | MECH. In
Figure 4  ReCiPe Midpoint H Europe scores per part for 1P|8%T|IDLE|EDM scenario. 1P = single part; T = time. For example, “90%T” represents the system performing print jobs during 90% of its lifetime, only inactive 10% of the time. IDLE = printer and chiller left on while inactive; EDM = part separation by electron discharge machining. kg = kilograms; eq = equivalents; CO₂ = carbon dioxide; CFC-11 = trichlorofluoromethane; SO₂ = sulfur dioxide; P = phosphorous; N = nitrogen; 1,4-DB = 1,4-dichlorobenzene; NMVOC = nonmethane volatile organic carbon compound; PM10 = particulate matter up to 10 micrometers in size; kBq = kilobecquerels; U235 = uranium-235; m²a = square meter-year; m² = square meters; m³ = cubic meters; Fe = iron.

Figure 5  ReCiPe Midpoint H Europe scores per part for FULL|90%T|OFF|MECH scenario. FULL = full build configuration; T = time. For example, “90%T” represents the system performing print jobs during 90% of its lifetime, only inactive 10% of the time; OFF = all machines shut off when inactive; MECH = part separation by mechanical machining. kg = kilograms; eq = equivalents; CO₂ = carbon dioxide; CFC-11 = trichlorofluoromethane; SO₂ = sulfur dioxide; P = phosphorous; N = nitrogen; 1,4-DB = 1,4-dichlorobenzene; NMVOC = nonmethane volatile organic carbon compound; PM10 = particulate matter up to 10 micrometers in size; kBq = kilobecquerels; U235 = uranium-235; m²a = square meter-year; m² = square meters; m³ = cubic meters; Fe = iron.

Each graph, labels on the right list total impacts in the unit of measurement for that impact category.

Figures 4 and 5 show that even in these two scenarios where overall environmental impacts were clearly dominated by electricity use in figure 3, two impact categories were not dominated by electricity: water depletion and mineral depletion. Human toxicity was within the uncertainty range of being dominated by machinery rather than electricity in both graphs. In addition, figure 5 shows material use’s portion of impacts to vary a great deal among different impact categories, often within uncertainty of (and thus possibly larger than) machine impacts. Thus, although differences in individual impact categories did
not sway ReCiPe endpoint scores enough to change overall conclusions compared to energy-only analysis, they could change conclusions for readers particularly concerned with specific environmental impact categories.

**Electricity Breakdown**

Because electricity was the dominant environmental impact in most cases, it bore deeper investigation. Auxiliary machines and processes other than the SLM caused much operational energy use, sometimes the majority, as shown in figure 6.

Figure 6 shows on-site electricity use by process element and operational phase. Britain’s electrical grid mix has a site-to-source ratio of 3.3 in the ecoinvent database; thus, for example, 45 MJ of on-site energy consumption in figure 6 causes 149 MJ of primary energy consumption in figure 2. SLM machine printing energy comprised as little as 4% of total on-site electricity use per part for 1P | 8% T | IDLE | EDM. At most, it comprised 62% of total on-site electricity per part for FULL | 90% T | OFF | MECH. The chiller used more electricity than the SLM process for all scenarios except FULL | 90% T | OFF | MECH; this was because it remains on during setup/cleanup, warmup, and cool down. EDM (which comprised over 99% of setup/cleanup electricity

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**Table 3** Embodied energy and LCA impacts for machines

|                     | Measured mass (kg) | Advertised mass (kg) | Embodied energy (MJ) | ReCiPe Endpoint H (Pts.) |
|---------------------|--------------------|----------------------|----------------------|--------------------------|
| Renishaw AM250      |                    |                      |                      |                          |
| Total               | 1,215              | 1,225                | 124,000              | 1,700                    |
| Steel parts         | 1,045              | —                    | 75,000               | 1,000                    |
| Aluminum parts      | 62.0               | —                    | 17,000               | 140                      |
| Motors and cables   | 50.9               | —                    | 3,000                | 110                      |
| Electronics         | 41.6               | —                    | 26,000               | 350                      |
| Other parts         | 15.3               | —                    | 1,400                | 24                       |
| Auxiliary equipment |                    |                      |                      |                          |
| Vacuum              | 98.8               | 100                  | 12,000               | 140                      |
| Chiller             | 70.8               | 75                   | 6,000                | 80                       |
| sieve, without frame| 29.6               | 30                   | 1,600                | 24                       |
| Sieve frame         | 35.0               | —                    | 1,900                | 29                       |

Note: kg = kilograms; MJ = megajoules; Pts. = points. Listed totals may not match sum of parts due to significant figures.
when used) accounted for up to 35% of total electricity use in 1P|8%T|OFF|EDM and 1P|90%T|OFF|EDM; this was more than the SLM machine printing. As noted earlier, this implies that although postprocessing was outside the scope of this study, future studies should quantify it for multiple scenarios. Vacuum and sieve electricity were insignificant in all scenarios. Summing all auxiliaries including EDM showed that they comprised 65% of total electricity use in 1P|8%T|OFF|EDM and 1P|90%T|OFF|EDM, over 50% in 1P|8%T|IDLE|MECH and FULL|90%T|OFF|EDM, and were never below 36% of electricity use (in FULL|90%T|OFF|IMECH). Thus, figure 6 shows that auxiliaries should be a significant target for energy reduction. These results are similar to those found for several other manufacturing methods (Gutowski et al. 2009).

**Machine Impacts Breakdown**

Embodied impacts of the machines also bear further examination because of their dominance in some impact categories and scenarios. Table 3 lists the measured/calculated masses, advertised masses, embodied energy, and LCA impacts for the machines measured, including breakdown of printer impacts by major material category.

As table 3 shows, over half the embodied impacts for all hardware come from steel in the Renishaw printer (51% of MJ, 54% of ReCiPe points). All auxiliary equipment combined comprise just 15% of MJ and 14% of ReCiPe points. Energy and LCA score ratios are within a few percent of each other for all rows in the table except “aluminum parts” (12% of MJ, but 7% of ReCiPe points) and “motors and cables” (3% of MJ, but 6% of ReCiPe points). This is attributed to aluminum’s high embodied energy relative to its resource scarcity and toxicity and copper’s relatively high toxicity and scarcity.

**Conclusion**

For SLM printing of the aluminum test specimen part, impacts were calculated by embodied energy (MJ/part), ReCiPe Midpoint H scores (various units), and single-score LCA (ReCiPe Endpoint H/A Europe points per part). Energy and ReCiPe Endpoint H/A results differed in exact percentages, but agreed that, for most scenarios, process electricity consumption dominated environmental impacts. It often comprised four fifths of embodied energy and two thirds to three fourths of ReCiPe Endpoint H/A impacts. Powder material impacts never accounted for more than 10% to 12% of impacts by energy or ReCiPe endpoint H/A and were sometimes less than 1%. Material waste, argon, machine transportation, and machine disposal impacts were negligible. Thus, in the question of “printer, powder, or power,” this research suggests that power generally dominates, even in Britain, where the electricity grid uses less coal than many countries. Significant shares of this energy consumption arise from auxiliary equipment or processing—the chiller often used more energy per part than the printer itself, as did EDM part removal.

However, machine utilization rates and EDM part removal greatly affected impacts, even changing whether electric power dominates impacts or not. Low utilization with power on while idling caused 14 to 17 times the energy demand per part as maximum utilization and 15 to 18 times the ReCiPe Endpoint H/A points per part. Machines dominated ReCiPe Endpoint H/A scores in scenarios printing one part per week, with machines off when idle; for energy-only scores, machine impacts were within uncertainty of dominating electricity impacts. Further, ReCiPe Midpoint H analysis showed certain impact categories (water depletion, metal depletion, and human toxicity) to be dominated by machines even when other categories (climate change, acidification, land use, etc.) are not. Removing parts by traditional machining instead of EDM reduced energy demand per part by up to 28% and reduced ReCiPe Endpoint H/A impacts up to 25% per part. This implies that future studies should measure impacts of postprocessing alternatives, given that these could significantly increase impacts per part.

The $\alpha$ | $\beta$ | $\gamma$ | $\delta$ notation developed here proved useful to assess possible permutations. Researchers should investigate these and other scenarios in other machine types. As the 2009 Roadmap for Additive Manufacturing stated, “a total lifecycle analysis and a comprehensive sustainability evaluation of each AM process must be made” (Bourell et al. 2009, 30). Future studies should also perform full cradle-to-grave LCAs of SLM parts for specific applications (such as turbine blades, fuel injection nozzles, etc.), so that SLM can be compared to other manufacturing methods.

Ultimately, these results suggest that SLM owners wishing to improve operational sustainability should maximize machine utilization, switch machines off when idle, avoid EDM part removal, and source renewable energy. Similarly, SLM machine designers should reduce power demand, both in the printer and auxiliaries. Given that utilization increase and power reduction both improve profits, economics align with sustainability to incentivize such improvements.

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Supporting Information

Supporting information is linked to this article on the JIE website:

Supporting Information S1: This supporting information includes tables showing life cycle inventory characteristics of the selective laser melting process. These characteristics include name, mass, material, and manufacturing information of various components and parts, transportation distances and modes, aluminum powder material used, and density of materials.