Comparative Energy, Resource and Recycling Lifecycle Analysis of the Industrial Repair Process of Gas Turbine Burners Using Conventional Machining and Additive Manufacturing

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Summary

Laser beam melting (LBM), also known as selective laser melting, is a powder bed fusion type of additive manufacturing (AM) technology used to fabricate metal parts from metal powder. LBM is a promising technology that offers new opportunities for increasing resource efficiency. The aim of this study was to compare environmental impacts of conventional manufacturing methods with AM for a real industrial application. Analysis was performed on the repair process of a burner used in a Siemens industrial gas turbine. The results of this study show that the repair process based on AM provides significant reduction in material footprint (abiotic depletion potential), primary energy consumption, and carbon footprint compared to conventional machining and welding processes. Even though the AM process has increased power and inert gas consumption on the shop floor, the complete life cycle shows that the conventional processes have a much higher environmental footprint from material use upstream. Different recycling models of nickel-based alloy and stainless steel scrap strongly influence the cradle-to-gate life cycle footprint. The results show that an AM process can have a sustainability advantage if it is designed in a holistic cradle-to-gate approach. The study also shows potentials for the LBM machine developers for entry into the industrialization of AM. Energy reduction potentials were identified during the idle mode, during operation mode from the supply of cooling duty, and also related to inert gas consumption. Careful consideration of these potentials can further improve the primary energy footprint of the LBM process.

Introduction

In recent years, additive manufacturing (AM), also known as three-dimensional (3D) printing technology, has been introduced to the commercial market by industrial companies located in different countries (the United States, Germany, Sweden, the United Kingdom, Israel, etc.) (US DOE 2015).
Siemens has been involved in AM advancement as a software provider and a hardware controller supplier as well as a parts manufacturer.

This paper presents a comparison of the environmental impacts of the conventional and laser beam melting (LBM)-based manufacturing process through a case study for the repair of a burner for industrial-scale gas turbine unit. The paper also discusses the impact of various recycling options and their effect on the life cycle assessment (LCA) impact results. Started as a laboratory prototype method in the early 2000s, the LBM technology has improved dramatically and is currently on its way to becoming an industrial-scale manufacturing technology that offers new opportunities for improving energy and resource efficiency. Currently, there are very few studies evaluating the environmental impact of additive manufacturing, specifically LBM, during industrial production and this study hopes to contribute with a comparison of environmental impacts of conventional manufacturing methods with AM for a real industrial application.

Additive Manufacturing and Environmental Performance

Among various advanced manufacturing technologies, AM stands out as a leading technology with enormous potential for changing the traditional landscape of manufacturing. At an industrial scale, studies have shown that AM has the potential to reduce the total primary energy demand (PED) by 2.54 to 9.30 exajoules by 2025, which is a reduction potential of 5% of the global primary energy supply in the industrial sector (Gebler et al. 2014).

Some studies have been conducted in recent years to evaluate the environmental and economic life cycle impact of manufacturing; in these studies, additive technologies were mainly considered as a substitute for existing subtractive manufacturing processes. One such study performed by AM machine manufacturer EOS in cooperation with one of their customers, EADS, compares the life cycle impact of manufacturing titanium airplane parts (using AM) to conventional casting process using steel (EOS 2013). This study showed potential for lower environmental and energetic impacts for the AM route mainly due to an improved degree of material utilization (conventional casting and machining 48%, versus AM 67%) of the topology optimized lightweight titanium part.

Even though it cannot be categorically stated that AM is an environmentally superior option to conventional manufacturing mainly because of the variability in type of process, materials, and components (Faludi et al. 2014), there are many examples that prove that AM provides significant impact reduction due to improved geometry, reduced material use, and lower machining requirements for certain types of materials and processes, such as, for example, injection molding. A recent work by Chen and colleagues (2015) has shown an example of use of AM for reduction of energy demand for injection molding (IM) process. The authors have shown that the selective laser sintering (SLS) process which could be used to replace IM takes longer processing time (10 to 100 times longer), but has much lower power demand (factor of 1 to 10 in kilowatts [kW]) as compared to IM. Kellens and colleagues (2011) analyzed SLS and selective laser melting processes with respect to building time, power, and materials consumption. The work showed that electricity consumption and the consumption of inert gases proved to be the top causes of environmental impact. Despeisse and Ford (2015) provided insight into resource efficiency and sustainability regarding AM applications. They investigated sustainability impacts on industrialization of AM and estimated that metal powder can potentially be recycled up to 95% to 98% in weight, even with consideration of material losses due to support structures and limitations of recycling loops due to degradation of metal powder.

Laser Beam Melting Process

The term AM encompasses multiple technologies, such as binder jetting, polyjetting, directed energy deposition, powder bed fusion, or fiber deposition modeling (ISO 2015). In industrial settings, LBM technology, which is a type of powder bed fusion method, currently is the most commonly used method for production of metal-based components. These metal components are constructed by melting metal powder using micro laser welding in an inert gas-filled powder chamber. The lower surface of the component is connected to a metal building plate, usually via a support structure, which is removed after the part has been completed.

LBM technology gained popularity within the industrial manufacturing sector in the mid-2000s due to acceptable building speeds and precision. Since then, the technology has been steadily developing with ongoing work in machine technology, digital data chain, material research, and appropriate part geometries. Due to use of metal powder as a precursor material to generate solid structures, highly sophisticated, complex designs and repeating geometries as lattices or fluid media guiding channels can be formed in super alloy material, which was an impossible task until now. This enables applications in the energy sector, medical device applications, or spare parts business.

In this case study, we analyze an LBM repair technology where the final part itself is used as a base plate for directly melting powder on top of it.

Gas Turbine Burners

Industrial gas turbines provide shaft power in a range of 10 to 100 megawatts and are often deployed in remote areas as power supply, for example, on offshore oil rigs, or as a direct drive for large compressors, for example, for pressure increase in natural gas pipelines. Hence, the requirements on this equipment regarding reliability and availability are extremely high.

This case study is related to Siemens industrial gas turbines. The gas turbines are equipped with burners which mix hot compressed air and fuel (e.g., natural gas, liquid fuels, etc.) to provide a stable combustion with high efficiency and low emissions of volatile organic compounds, carbon monoxide, and...
nitrogen oxides. As Carnot efficiency determines the theoretical efficiency limit, the temperature of combustion needs to be very high (range of 1,400 to 1,650°C). Hence, the burner is a critical component in order to ensure reliable operations of gas turbines. The main body of the burners is made of thermal resistant stainless steel while the upper section of the burner tip is made of a high-temperature-resistant, nickel-based alloy material. At customer locations, burners from gas turbine units have to be exchanged regularly during standard service procedures. These burners are brought back to the Siemens manufacturing facility for refurbishment and for replacing the damaged tip section. Figure 1a shows a schematic of a typical Siemens gas turbine and figure 1b shows a single burner.

Figure 1 (a) Typical industrial gas turbine and (b) a single burner.

**Materials and Methods**

**Repair Process**

The gas turbine burner tip is made from nickel-based super alloy material as explained in the earlier section. Even though super alloys are designed to exhibit excellent mechanical strength and creep resistance at high temperatures, after about 20,000 to 30,000 hours the burner tip starts showing signs of damage (e.g., oxidation) due to extreme heat application over time. The repair of this burner tip cannot be performed on-site, but needs refurbishment at the workshop. Objective of the service repair is to replace the damaged parts with newly prefabricated metal parts of same function, geometry, and material as in the original burner in a short time.

**Conventional Repair Process**

When the burner is brought back to the repair facility, the first step during the conventional repair process is to remove the damaged burner tip by cutting it off. As previously mentioned, the burner tip is made from nickel-based super alloy designed for high-temperature application. Due to their high-strength properties, these materials can only undergo a very limited number of shaping processes, such as forging or casting, as opposed to materials like aluminum that allow for many more shaping processes, including extrusion. This is one of the main reasons why components manufactured from high-temperature super alloys have a low degree of material utilization. In addition to the material limitations, the conventional manufacturing process itself presents additional constraints. Since it is not possible to weld the new tip in the same location after removing the damaged tip in a conventional process, a very large portion of the burner needs to be removed, including parts that are not damaged. This causes additional consumption of material. Assembly is done stepwise by different welding technologies and a finishing process in the end.

**Additive Manufacturing Repair Process**

Unlike the conventional route, for the AM repair process it is possible to remove only the damaged part of the burner tip and avoid additional waste. Figure 2a illustrates the AM repair process where the powdered metal is laser beam fusion melted on top of a conventionally manufactured base.

First step of the AM repair process is removing the burner tip which is made of pure nickel based super alloy material, generating a perfect clean layer which is mounted into a customized LBM machine in perfect position and orientation, to be used as equivalent to the well-known LBM building plate. A CAD model of the new burner tip is digitally aligned to the surface of the used burner, so that all channels are positioned correctly by a software tool. The next step is the building process in which the building platform is coated with a fresh layer of metal powder. Outer edges and inner surfaces are selectively melted by a laser beam until the desired size and shape is obtained. Once the building process is finished, surplus metal powder is aspirated and all cavities are cleaned. Excess metal powder needs to be collected carefully without losses and to avoid contamination, which might decrease metal powder quality for reuse.

The repaired burner then can be removed from the LBM machine and taken through the final steps of the repair process of polishing the tip surface and finishing.

Siemens has developed this AM repair process through lab and field testing. In February 2016, an industrial shop floor was inaugurated at a Siemens facility where AM repair takes place, shown in figure 2b. Several machines from LBM machine manufacturer EOS are installed to perform this repair. Figure 2c shows the inside view of a customized "EOSINT M 280 Custom" powder bed fusion machine used for the AM repair process. The precisely cut burner can be transferred completely into the machine, perfectly horizontally oriented and directly used instead of an LBM building plate.

After closing the door, inert atmosphere needs to be created by rinsing the building chamber and other system parts with argon gas until a certain low-oxygen concentration is reached to start the laser welding process. The machine currently offers an increased inert gas flooding mode consuming roughly 1,200 to 1,400 standard liters in total, and a steady-state mode consuming roughly 10 to 12 liters per minute.

In order to measure the power consumption during the AM repair process, the load curve of the LBM machine (figure 3) was evaluated with a Hioki power meter (Hioki 3169-20); power and voltage values were recorded in 100-ms intervals on the three-phase power cable used for the EOSINT M 280 Custom machine. The argon consumption was estimated based on...
readings from two float-type flow meters and an internal state log file from the LBM machine. Data from the log file were obtained in 1-second intervals until the end of the build process. Based on these data, the electrical energy and argon consumption was calculated.

Figure 3 shows the time record of the building cycle with respect to power uptake and argon gas consumption. The process starts with the installation of the burner in the set-up phase. At \( t = 0 \), the LBM process starts with alternating argon flow for 2.5 hours to maintain a certain oxygen concentration in the chamber. After the desired threshold has been reached, argon is supplied with a low steady flow.

During the idle operation, the LBM machine has a power uptake of roughly 2 kW. Additional power for active laser operation only adds a surplus of 0.4 kW. Further review of the power uptake patterns allows the observation of laser beam operation in various modes, which clearly shows the difference in consumption during modes of repositioning of the building unit, powder recoating, and laser operation. It is even possible to distinguish between building heights of the burner from the power uptake values. Figure 3 also shows zoomed in views of 3-minute time intervals during typical operation. One can recognize the similarities in the power consumption patterns for the first two 3-minute interval sections based on similar building patterns of the upper part of the burner tip, which is cylinder shaped and contains and inner channel system. The similar patterns for both these operations with long laser power on times are caused by large outer and inner geometries over a period of several hours, whereas for a narrow conical part of the burner the laser operation phase gets shorter due to smaller outlines and inner surfaces and absence of internal channels. After around 16 hours, the build process is completed and the laser operation stops, but the machine remains in standby idle mode. Newly manufactured parts can cool down when manual powder removal starts and the finished burner is taken out of the building chamber.

Building process energy and argon demand were determined by integration of power uptake and argon flow over time. As the building process takes a long time, continuous consumption has a considerable effect. Total machining time is 23.5 hours, 18 hours required for building the tip, and 5.5 hours for machine setup and idle mode. Energy consumption for building the tip was 37 kilowatt-hours (kWh), while the processing consumed 50 kWh for a complete loop. The power consumption of the laser process does not vary much while building up the burner tip and oscillates in a 0.5-kW band depending on different laser modes. The base load can be attributed to consumption during the idle state of the laser unit, the inert gas ventilation system, internal computing units, energy distribution units, and, especially, the chilling unit. The chilling unit is in continuous
operation and consumes about 1 kW of power for cooling and 1.2 kW for operation of other components such as controls.

Argon consumption is dependent on the amount of entrapped oxygen in the enclosure, which diffuses from inaccessible corners of the chamber over several hours and is also prone to continuous leakage during a building process.

**Life Cycle Assessment**

The LCA was conducted according to the International Reference Life Cycle Data System (ILCD) Handbook for LCA (EC, JRC, and IES 2010). As a first step, the goal (i.e., the purpose) and scope (i.e., what to analyze and how) were identified. The goals of the LCA are to

(i) provide an understanding of the environmental impacts of state of the art (conventional) repair technologies for gas turbine burners;

(ii) compare these findings with the environmental impacts of repair processing based on LBM;

(iii) focus especially on resource efficiency gains between different repair process technologies; and

(iv) better understand and find points of improvement in the LBM process.

The intended audience for LCA results comprises customers using industrial gas turbine systems from Siemens and other interested parties, as well as the AM community.

**Product System and Functional Unit**

The functional unit, which reflects the primary function of the system, is the basis of the LCA and was defined as “repair of one burner tip after disassembly out of the gas turbine system at customer’s site and transport to the Siemens facility.”

All relevant life cycle stages for conventional burner tip repair and novel repair process based on LBM technology (AM) were taken into account, including extraction of raw materials and production of semifinished products and their assembly. According to International Organization for Standardization (ISO) 14044, system expansion is the preferred method of dealing with shared impacts between multiple co-products and allocation should be avoided whenever possible (ISO 2006). This principle has been applied during the waste treatment stage in this study.

The product system of this study also includes recycling of scrap, which leads to materials recovery, thus avoiding respective production from virgin sources. Transport of burners between customer sites as well as disassembly and reassembly of burner into the gas turbine system was out of scope of this study.

**Data Collection**

The inventory data were collected for each stage of the repair system’s life cycle. Primary data were internally collected by measurement in the Siemens facility in Finspång, Sweden, from material experts and manufacturing engineers and externally from suppliers.

For modeling the upstream processes, for example, extraction of materials, the study relied on generic data from ecoinvent v3.1 (Weidema et al. 2013). All production processes as well as end-of-life operations, such as sorting, pressing, and, finally, remelting of metal compounds in electric arc furnaces, were modeled using background data based on ecoinvent v3.1 with regional adjustments reflecting the country-specific grid mix of electricity used.
Figure 4  Sankey diagram showing energy and mass flows for the additive manufacturing burner tip repair process (measured) and individual primary energy ("P. energy") contributions (life cycle assessment calculation) for 95% equal quality recycling scenario. The value chain (from left to right) starts with raw material input and conversion to electrical energy ("E. energy") and ends with the repaired burner, metal scrap for recycling, and waste for disposal. In contrast to figure 4, this diagram shows a local closed metal powder loop at manufacturing site and upstream metal powder production. EU = European Union; kg = kilograms; kWh = kilowatt-hours; MJ = megajoules; Nm$^3$ = normal cubic meters; SLM = selective laser melting.

**Impact Categories**

The impact method used for this study is CML2001-Apr. 2015 as available in GaBi LCA software and database (Guinée et al. 2002). In addition to climate change, all ILCD recommended impact categories at midpoint level were evaluated. Environmental impact categories resource depletion and climate change were of particular interest with respect to the goal and scope of the study. In addition to these two categories, the total PED of the whole repair life cycle was also assessed. The systems were modeled in GaBi software version 6 (GaBi 2016).

**Results**

**Mass and Energy Flows in the Repair Process and Recycling Processes**

Sankey diagrams shown in figure 4 illustrate the measured mass and energy flow streams during the repair process from cradle to gate, the closed-loop recycling, and the LCA impact category of PED from renewable and nonrenewable resources (net caloric value, megajoule [MJ]) required for each process. The shaded gray box indicates the boundary limits of the Siemens internal repair process. The data used for LCA study were measured from the workshop processes, if possible, or taken from internal or external sources such as purchasing departments and literature.

**Conventional Repair Process**

The conventional repair process is illustrated by figure 5. The workshop receives premanufactured components and only performs cutting of the used burner, assembly of new parts, and finishing. Single component preparation is done at vendor locations. Combustion turbine parts are traditionally known to have a low degree of material utilization, as a high percentage of material needs to be removed and goes into scrap during the manufacturing of individual components. In the case of the burner tip repair process, the degree of material utilization for conventional machining equals 21% as compared to 83% for the LBM process. Power uptake for machining was measured on the shop floor level and also calculated from databases. Sourcing of parts is done globally and hence transport efforts are included in the primary energy footprint. PED from power generation was assigned to a country according to the location of the vendors for each part.

**Additive Manufacturing Repair Process**

The AM repair process uses a large quantity of nickel-based super alloy powder material, out of which more than 99% stays in the closed loop of the LBM machine. Sieving of the metal dust ensures the required quality of the powder is maintained and removes larger particles such as welding spatters. Only this removed off-spec material, and the material consumed as the new burner tip, have to be replaced.
Figure 5  Sankey diagram showing energy and mass flows for the conventional burner tip repair process (measured) and individual primary energy ("P energy") contributions (life cycle assessment calculation) for 95% equal quality recycling scenario. The value chain (from left to right) starts with raw material input and conversion to electrical energy ("E. energy") and ends with the repaired burner, metal scrap for recycling, and waste for disposal. The diagram also shows mass and energy needed for materials processing (rolling) and manufacturing of intermediate products (machining). kg = kilograms; kWh = kilowatt-hours; MJ = megajoules; Nm$^3$ = normal cubic meters; SLM = selective laser melting.

with fresh metal powder. Argon consumption of the process is calculated from the machine data recording as illustrated in figure 3.

The number of processes outside the workshop boundary during AM is much fewer as compared to the conventional process. The main upstream process is the powder production using a liquid smelter atomization process. Data for this process were generated from research facilities operating atomization setups (Wolf 2015). Due to business confidentiality reasons, no detailed data for metal powder distribution for hot gas liquid smelter atomization for nickel-based alloy were available and were taken from a similar process for copper alloys. Undersized particles from atomization processes representing about 20% weight in output on the lab-scale process were considered as secondary metallurgy feedstock, which should not be brought back into the atomization smelter due to contamination risk with oxides or other impurities. However, for large-scale processes, there would be a strong driver for finding marketable applications (e.g., in metal powder injection molding). Oversized particles representing about 27% weight in output are considered as a marketable by-product and hence are considered by performing physical weight-based allocation.

PED for power generation was assigned according to the location of the LBM factory, which is Sweden. Accordingly, the Swedish power mix was applied for all electrical power consuming processes performed in Sweden.

**Recycling Scenarios**

During a regular production cycle, there are several scrap waste streams in a metal manufacturing plant, which are collected separately. It is evident that even with high effort, a complete separation of different alloys is not possible. In order to get a good price for stainless steel waste, and an even better price for pure nickel-based super alloy scrap, cross-contamination of high-value scrap has to be avoided. Even with careful sorting, unknown super alloy metal residues will very likely end up in the general stainless steel waste, or even go to a lower value carbon steel waste. The same is true for small amounts of turning waste, which often get mixed with other qualities of waste materials. Also, parts with mixed alloy qualities, such as cut burner tip parts, cannot always be separated. The effort and meticulousness of the machining workshop is accounted for in the LCA model by considering the "recycling rate" variable. A range from 0% (no recycling, all metal scrap goes to landfill deposit) to theoretically 100% (all metal scrap back to metallurgy processes) is assumed for evaluating the pattern of environmental impact categories as shown in figure 6 and discussed in the next section.

Further, due to other losses in the metallurgic recycling process (losses due to slagging), a ratio of 110.5/100 (equals 90.5%) from recycling feedstock to finished product is assumed according to ecoinvent v3.1 (Weidema et al. 2013). This percentage (90.5%) is assumed constant and independent to the recycling rate for collecting scrap in the machining workshop.
Figure 6  Life cycle assessment impact categories for the conventional and the additive manufacturing (AM) repair process, depending on the share of scrap which goes to recycling (recycling rate), and on recycling mode (equal quality recycling or down-cycling) of (a) abiotic depletion potential (ADP elements), (b) global warming potential, and (c) primary energy demand. kg Sb-eq. = kilograms antimony equivalent; kg CO\(_2\)-eq. = kilograms carbon dioxide equivalent; MJ = megajoules; net cal. value = net calorific value; ren. and non ren. = renewable and nonrenewable.
To determine a recycling credit for these different alloy residues, we defined two theoretical recycling scenarios, viz., “equal quality recycling” and “down-cycling,” which span the range from best case to worst case regarding alloy quality.

**Equal Quality Recycling**

In equal quality recycling, scrap is collected and recycled separately for each alloy (nickel-based alloy, high and low thermal resistant stainless steel scrap), while maintaining 90.5% of the original material (metallurgical process efficiency). The goal of equal quality type of recycling is to recover the scrap in the original composition as far as possible. The LCA recycling credit is equal to the amount of new material, which was avoided assuming a 1:1 replacement ratio between recycled and new material (including savings in natural resources and upstream impacts).

In this case study, considerable amounts of pure nickel has to be used to gain the required high concentration of nickel used in nickel-based super alloy material, as the cheaper and easily accessible alloy of ferronickel does not have sufficient nickel content.

**Down-Cycling**

In this lower-quality recycling scenario, all types of scraps are collected in one vessel and cannot be separated. Hence, for this case study, the only option for a final product from this scrap mixture is stainless steel. A standard high-alloyed stainless steel (chromium nickel [CrNi] 18-8) was chosen as an example for the calculation of the recycling credit. The amount of CrNi 18-8 which could be produced based on nickel input was evaluated and was applied as credit for displaced raw material, as shown in figure 7a. Additionally, as the chromium and iron inputs are not sufficient for producing the required amount of CrNi18-8, some ferrochrome (Fe-Cr) and iron (Fe) scrap has to be added, reducing the credit given to displaced raw material. Figure 7b shows resulting down-cycling recycling credits for nickel-alloyed standard stainless steel production in Sankey diagram representation.

Figure 6 shows the final results for the three chosen LCA impact categories for the two recycling scenarios for conventional and additive manufacturing repair processes. The impact results are plotted for recycling rates ranging from 0 to 100%.

**Discussion**

A comparison of Sankey diagrams for conventional and AM repair processes (figures 4 and 5) demonstrates the difference in mass and energy flows between the two processes. Overall, much lower quantity of material moves through different production stages for the AM repair process and it comes closest to a near net neutral production in terms of mass. The AM process also requires fewer individual production steps. Additionally, the use of homogenous metal powder reduces the number of parts with differently shaped wrought material.

The selection of the repair process (conventional or AM), the recycling quality and the recycling rate have a strong influence on different LCA impact categories. However, this influence is not uniform for all categories considered here, as shown in figure 7.

Abiotic depletion potential (ADP elements), which is, in this case study, an indicator for mineral resource depletion, shows a strong dependence on the alloy mass required (the conventional process needs about a 3 times higher amount than the AM process for the 0% recycling rate), the recycling rate (steep slope for equal quality recycling), and the recycling quality (only equal quality recycling can reduce resource depletion, but only with high recycling rates). Abiotic depletion was found to be highly sensitive to whether material stays in the anthropogenic production loop or is lost to landfill deposit. The AM process has much lower ADP impacts than the conventional process since much less mass is involved.

Global warming potential (GWP) in this case study can be attributed mainly to carbon dioxide (CO\(_2\)) emissions from carbon-based fossil reduction of metal ores. Additional CO\(_2\) impacts are also produced from power generation. Hence, reduction in metal mass directly correlates to CO\(_2\) emission avoidance from metallurgy. Low recycling rates lead to increased primary metal production, which, in turn, increases the CO\(_2\) emissions dramatically. The carbon footprint of the metallurgical reduction process from mineral ore to metal is independent of the target alloy quality (nickel ore to pure nickel or ferronickel; iron ore to ferrochromium or pig iron), so there is no difference in CO\(_2\) emissions for the recycling quality (same for equal quality recycling or down-cycling). Similarly, using less metal in the AM process means much lower CO\(_2\) emissions due to mass reduction. The geographical location of the power generation is also crucial to impact calculations; as the LBM process is located in Sweden, the local power generation carbon footprint is allocated for Swedish power consumption. For premanufactured parts used in the conventional process that were sourced globally (Eurasia and Asia), each local power production footprint was allocated to the component according to location.

PED from renewable and nonrenewable resources demonstrates the energy intensity of the process, without differentiation of the origin and the type of primary energy (fossil, nuclear, renewable) or the use of primary energy (e.g., for reduction of metals, heat generation, or power production). In the case of a 100% recycling rate, the primary energy consumption of the conventional repair process is only about 30% higher as compared to the AM repair process, since at that rate the higher fossil energy consumption impact due to increased metal production in the conventional process is balanced by higher power consumption during the AM process. However, low recycling rates generate a need for a larger quantity of metal production from primary sources, which results in increased PED, especially from fossil sources. The PED for the AM process mainly traces back to the power supply for the LBM process and argon production, and hence has only minor influence from the recycling rate.
Generally, it is essential for an improved environmental footprint of the AM process not to waste any metal powder, especially super alloy powder material, since it has a considerably high ADP footprint. The environmental impacts of the AM process are dependent on many materials, as well as operational and energy variables. Through preliminary analysis, no significant differences were found as a result of altering many of these variables, although the authors suspect the electricity grid mix is likely to have some impact due to geographical location of power consumption. Swedish power generation is mainly based

Figure 7 (a) Balance sheet showing composition of scrap material from conventional burner repair: Input materials for down-cycling recycling (manufacturing scrap and additional primary materials) are shown in the left column. The middle column represents the amount and composition of secondary nickel-alloyed standard stainless steel while the right column calculated life cycle assessment credits for recovered primary resources are displayed. (b) Detailed section of Sankey diagram for conventional burner repair process showing resource flows based on material balance sheet (figure 7a) and credit for primary energy demand (PED). CrNi = chromium-nickel; Fe = iron; FeCr = iron-chromium; kg = kilograms; MJ = megajoules.
on nuclear and hydro power and hence has a very low GWP emission factor. If the LBM process was to be located in another country than Sweden with a higher GWP emission factor of the power grid mix, this would result in higher GWP impacts for AM. Since most of the critical data points used in this study come from primary sources, including measurements, we assume minimal uncertainty for primary data (Ashby 2012). However, for secondary data for metal powder production, data were obtained from a research setup instead of a large-scale production facility and likely introduce some uncertainty in the model.

The uncertainty introduced in the model due to lack of actual recycling rates and knowledge about the recycling procedure was addressed by performing a sensitivity analysis based on these two parameters in order to study the impact of the recycling rate and the choice of recycling scenario on the overall environmental impacts as shown in figure 6.

**Conclusion**

This article presents results of environmental impacts of AM/LBM technology. Comparison with conventional technology, including impacts of two different recycling scenarios, is also evaluated.

**Resource Consumption, Metal Alloy Quality, and Recycling Impact**

It is evident that recycling of metal scrap residues is important for lowering the environmental impact. Additionally, mono-fraction sorting and equal quality recycling provides significant benefits, especially for high-value alloy materials, which have a considerably high eco-footprint when produced from primary sources. Mixing individual scraps prevents the reuse of super alloy materials, and so down-cycling always means a loss of value and additional use of new virgin mineral resources for production of super alloy material can only be produced from very pure scrap of the same quality. From a resource point of view, the potential of near-net shape manufacturing makes LBM an effective method to manufacture parts if super alloy material is necessary, compared to conventional machining or welding. However, it is critical to minimize material losses in metal powder production as well as in the LBM powder cycle to minimize a financial impact, as metal powder is expensive to purchase and the waste is often categorized as hazardous waste that is expensive to dispose. It is also important to protect the purity of the metal powder and shield the users from contact with powder to avoid health and safety concerns.

**Logistics and Handling**

LBM simplifies handling and logistics during manufacturing. As metal powder in LBM can take any desired final geometry, delivery times for raw materials become shorter with no custom-shaped wrought material needed. Especially for super alloy, there is often an unsteady rate of production of certain bars and sheets wrought material, which can lead to long delivery times. For the same reason, inventory and storage can be reduced and much less national and international transport logistics are needed for the specific parts.
The reduction in transport logistics also provides the opportunity to set up distributed workshops for remote AM manufacturing, to reduce logistics of target good, making use of reduced material and machine inventory. Manufacturing concepts can be kept flexible until the final CAD file is sent to the AM machine. Expanded future analysis might also consider the viability of on-site metal powder production for AM.

**Primary Energy and Carbon Footprint**

As shown by the results, primary energy consumption and greenhouse gas (GHG) emissions can be reduced by LBM technology if the right approach is used. Therefore, industrialization of LBM might have a significant future contribution to decarbonization of manufacturing. Even if the power consumption of the LBM process contributes to some environmental impact, primary energy and GHG emissions can be reduced upstream, especially if LBM will substitute a manufacturing process with a low degree of material utilization far from near-net shape manufacturing. Further, LBM energy impact occurs mainly from electricity use, whereas conventional machining impact originates from upstream carbon-based processes. Hence, for scenarios with increased use of renewable fuel in the power generation mix, the GHG footprint of LBM manufactured parts could decrease further, whereas that of conventional manufacturing will stay constant. Figure 8 shows the contribution of various life cycle stages to the PED for conventional and AM repair processes for equal quality recycling scenario with a 50% collection rate. The conventional repair process has significantly higher PED than the AM repair process, especially in the material stage, regardless of the high footprint of argon used for the LBM process.

**Laser Beam Melting Machine Technology**

Today’s LBM machine technology demonstrates promising capability for future manufacturing. For an increased industrialization of LBM, there are several opportunities to reduce the environmental impact further. Efficiency gains are possible through machine control systems, which reduce consumption during idle/standby modes. Until now, LBM machines were designed as stand-alone units, which provide all utilities internally. For cooling duty, a considerable energy saving potential in industrialization can be obtained by a connection to a plant factory cooling water system instead of an air-cooled chiller compressor unit. Also, argon inert gas consumption has a considerable impact, which might be reduced by an gas-tight design with smooth surfaces and less hidden chambers and cavities, or a design with a continuously inert gas building chamber and a locker system. Current developments have already taken this into account; as an example, the next-generation machine from the same manufacturer, EOSINT M 290, has already reduced continuous argon consumption by around 50% as well as standby electric energy consumption to 35% to 70% (depending on machine settings) compared to the previous generation (Knoch 2015).

**Environmental Potential of Laser Beam Melting Technology**

Even with all the positive impacts mentioned in the previous sections, LBM does not have environmental advantages in competing with processes which use already near-net shape optimized material, such as injection molding or casting. Further, LBM does not provide an opportunity for building large pieces of super alloy material, especially when the design requires large amount of support structures which use material, time, and energy for building and for removal without any added value. This is often the case when LBM is wrongly considered as a “digital parts copy machine.”

In contrast, LBM shows high potential when it is understood as a new manufacturing philosophy alongside and complementing existing manufacturing technologies. A smart combination with existing processes, that is, by avoiding support structures by design or by process, by minimizing postprocessing such as cutting and welding, and by near-net shape manufacturing, AM becomes an environmentally and economically attractive methodology. It can further increase manufacturing value by materializing sophisticated structures and geometries for hard machinable alloys and materials, and through parts and complexity bundling into the “3D printed” part.

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