Quantifying the overall impact of additive manufacturing on energy demand: the case of selective laser-sintering processes for automotive and aircraft components

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Abstract
The general consensus is that 3D-printing technologies can help to render industrial production more sustainable, e.g. by shortening process chains, by allowing more efficient production processes or by providing benefits resulting from light-weight construction. In this paper, we aim to quantify the impact of additive manufacturing processes on energy demand by taking the example of selective laser-sintering (SLS). For this purpose, we suggest and apply a model that distinguishes three important phases in the life-cycle of additively manufactured components and which allows to compare them to conventional manufacturing processes. The three phases under consideration include the production of the required raw material, the actual manufacturing process of specific components as well as their utilization. The analysis focuses on the automotive and aircraft industries. In the paper, we analyze and discuss main factors influencing energy demand and estimate the impact of additive manufacturing on a national level, taking Germany as an example. The analysis indicates that despite replacing only a small component, substantial energy savings can be achieved. Furthermore, the utilization phase appears to be very relevant for achieving energy savings in the considered industries as compared to the other two phases.

Introduction
Additive manufacturing is generally considered to hold a disruptive potential to partially substitute conventional subtractive manufacturing processes due to a large degree of liberty in terms of design and the economic production of small series (Hopkinson et al. 2006). Due to these advantages as well as improvements in product and process quality, the market for additive manufacturing has been growing with double-digit growth rates during the last decade (Wohlers Associates 2012). As a consequence of the considerable potential that this technology may yield, its influence on production has already been the subject of many scientific studies. These studies mostly focus on the economic impact of the additive manufacturing process. Energy is usually not investigated in detail because it is reported to only constitute less than one percent of the final costs for additive manufacturing (Hopkinson und Dickens 2003). Yet additive manufacturing technologies could potentially yield considerable energy savings as compared to conventional manufacturing processes (Morrow et al. 2007). Due to its increasing relevance, quantifying the impact of additive manufacturing on energy demand thus seems to be very important.

To help understand the role of additive manufacturing technologies, the aim of this study is thus to quantify the impact of additive manufacturing processes on energy demand taking the example of selective laser-sintering (SLS) for industrial applications. This could help to gain better insights into the quantitative impact of additive manufacturing processes on a national level and thus allows to frame its possible future role in future policy action to reduce energy demand. Furthermore, the analysis could help to pinpoint which phases of the overall life-cycle are especially relevant with regard to improving energy efficiency.

In the remainder of this paper, we will first give a brief background description of additive manufacturing which will help to further refine our research questions. We will then outline our overall methodology which addresses three phases that appear to be very relevant for the life-cycle impact of the SLS process in selected industries. Thereafter, we address each of these phases and combine their results. This is accompanied by a sensitivity analysis to identify the most relevant factors of influence on the overall results. We then discuss our results before finally providing some final conclusions.

Background

ADDITIVE VS. CONVENTIONAL MANUFACTURING PROCESSES

Additive manufacturing describes a family of manufacturing processes in which objects are produced by layerwise joining of material based on digital data (according to ISO ASTM F2792-12a) (ASTM 2012). The development of additive manufacturing and similar methods can be traced back to the 1950s (Meindl 2006). With developments in the late 1980s and through the commercialization of stereo lithography in the early 1990s, generative manufacturing processes became part of R&D departments of entire industries and were known as Rapid Prototyping. Since then, a variety of processes have been patented and developed in terms of accuracy, speed and range of materials (Levy et al. 2003).

On the contrary, however, manufacturing processes which are based on removing material, i.e. processes where an object is shaped by a selective removal of the base material (e.g. by milling or cutting), are referred to as subtractive manufacturing processes (Marquardt 2014). As compared to subtractive methods, additive manufacturing usually allows a high degree of freedom in terms of design. At the same time, certain process steps such as assembly may become superfluous and the need for costly tools is reduced (Roland Berger 2013). Material is also only required where it is actually needed to fulfil the design specification. Depending on the produced object, the resulting savings in material and weight can sometimes exceed 70 % (Wohlers Associates 2012). Furthermore, the unused base material can often be recycled and reused in all the subsequent processes, so that a generative production gets by with almost no waste (Tuck und Hague 2006). Thus, the increased use of lightweight components can have a positive impact on the need for materials and energy demand. Yet there are also limitations to additive manufacturing processes which concern the relatively long processing time or certain physical properties.

The decision which additive manufacturing technology is used depends on the material properties of the desired product such as tensile strength, stiffness, colour, transparency, hardness or conductivity. While many additive manufacturing technologies are able to produce objects made of plastic, only relatively few technologies like powder bed fusion including the selective laser-sintering processes, binder jetting, sheet lamination processes and directed energy deposition processes are suitable for the production of metallic objects (VDI 2014) which are especially relevant for industrial applications.

MARKET SITUATION

According to market projections until 2020, the overall market for additive manufacturing will further grow by about 20 % annually in the five core industries for additively manufactured products, i.e. aviation, automotive industrial machines, medical products and consumer products (Markets and Markets 2014). With regard to industrial applications, the aviation and automotive industry not only reveal a high annual growth rate, furthermore, the two industries offer the highest potential for change in energy consumption of the listed industries (Gebler et al. 2014). Furthermore, the final products also have a great impact on the energy demand during their use. Against the background of this paper, these two industries therefore are of major interest for our analysis.

In the automotive sector mainly the additive manufacturing process of stereo lithography and laser sintering are used. The main reasons for using additive processes are, among others, savings in terms of weight while realizing high quality products. The reduced weight affects the performance of a vehicle's energy demand (Müller 2014). However, the use of additive manufacturing in this sector is still largely limited to the rapid prototyping of components with small numbers and large complexity and less common for the production of end products of mass production.

Similar advantages are also seen in the aviation industry, namely by reducing the energy consumption in production and in use as well as in noise pollution. The use of additive manufacturing processes in the field of direct manufacturing in the aviation industry is particularly well suitable because of the small numbers produced. Exemplary components are turbine parts, special interior parts for jets and helicopters and injectors (Gausemeier et al. 2011). Should additive manufacturing prevail in the near future, this could have a significant impact on the business models and value chains of a number of other industries (Bopp 2010) The increasing use of additive manufacturing may lead to disruptive changes in logistics and production (Grassl 2015). In terms of energy, the important driving factors are on the one hand the possibility of waste-free production, as for example about 60 % of metal waste occurs in the production of the automotive industry. On the other hand, there is the possibility for reducing energy demand by altered production processes compared to conventional processes (Fraunhofer IWU 2008).

A market breakdown for 2013 by sales shows that almost 55 % of the turnover of the raw materials used in additive manufacturing have been achieved by plastic-based and about 35 % by metal-based materials (Markets and Markets 2014). With about 16 % of the total market volume, laser-sintering holds the largest market share among the processes for processing metallic products (Markets and Markets 2014).

LASER SINTERING

Laser sintering is based on selectively fusing metallic powder to shape an object. The process setup mainly consists of a laser as an energy source, a mirror system, a powder bed which is stored on a movable platform and a levelling roller. To create an object, the levelling roller moves a thin film of metallic power onto the movable platform and the laser beam, guided by the mirror system, smelts selected areas of the power bed. Where heated sufficiently, the particles fuse together. After cooling down, the heated area forms a first layer of an object. Then the movable platform is slightly lowered, the levelling roller adds a new layer of power onto the power bed and the process starts anew. When heating the material, part of the currently processed layer as well as the layer below is smelted together, thus the individual layers are linked to each other. By successively adding layers with varying shapes to the previous layers, a solid body can be generated (for a more elaborate technological description, see for example (Gebhardt 2013)). Thereby the resulting energy demand depends on a wide variety of material- and machinery specific factors of influence (Le Bourhis et al. 2013).

IMPLICATIONS FOR THE ANALYSIS

The analysis of energy demand of additive manufacturing technologies is complex given the large number of potential applications and the many factors affecting energy demand. A restriction to specific technological and market segments and an exclusion of minor factors of influence can help to reduce the complexity. In view of the previously discussed aspects, a focus on selective laser-sintering processes as used in the automotive and aircraft industry seems reasonable because of high shares in market volume and growth rates. Furthermore, the utilization of products from these industries seems to be also very relevant as light-weight construction in cars, trucks and planes is a very promising area to save energy.

Methodology

The focus of our analysis is on the energy input for automotive and aircraft components produced by a selective laser sintering process as compared to conventional subtractive methods. The literature on life-cycle analysis (LCA) has provided a range of different methods for analyzing the life-cycle impact of product and services based on input and output factors. The LCA method allows for a systematic analysis to quantify the environmental impact associated with the production and use of a product. To do so, the objective and scope of the analysis are defined and the life-cycle of the system is divided into several phases. The input and output mass and energy flows are analyzed for each phase. Using this information, important parameters to reduce the environmental impact can be determined.

PRIOR STUDIES RELATING TO ENERGY-EFFICIENCY OF ADDITIVE MANUFACTURING PROCESSES

In recent years, various studies on energy efficiency of additive manufacturing processes have been published (see Table 1; for a closer description of studies, see also (Huang et al. 2015)). Though associating these studies to specific phases of a life-cycle is not always easy and accurate, a few general remarks can be made: Studies dealing specifically with the energy demand of additive processes tend to focus on the demand for the preparation of raw materials or pre-products, or they focus on the manufacturing process itself. While they tend to focus on one or more specific life-cycle phases, the overall impact of additive manufacturing on energy consumption over a whole supply chain and different phases of the life-cycle and especially the consequent large scale effect is not the focus of most studies and only addressed in a few. Such a cross-examination of the phases is also quite difficult due to the numerous factors of influence.

Among the various available LCA methods, the Cumulative Energy Demand (CED) and Material Input Per Service Unit (MIPS) seem to be the most relevant methods for our purpose as they focus on inputs instead of analysing outputs like for example downstream emissions. CED takes the primary energy effort of all inputs into account for the assessment of the product or service. In MIPS mass inputs are recorded based on pre-defined categories documenting all incoming materials, including energy. Given the limited availability of data for discussing additive manufacturing, it is challenging to apply either method for the given purpose.

Like many of the other studies, we therefore chose to rely on a less rigorous approach and to focus on some of the most relevant areas as depicted in Figure 1. In line with the aim of the paper, this focus is on energy demand and it does not take other input or output factors into consideration. Furthermore, our paper concentrates on differences in the energy demand of additive and subtractive manufacturing processes. Given this focus, some phases seem to be of minor importance and can thus be omitted. Accordingly, the energy required for the extraction of the raw material is for both manufacturing processes the same or only slightly different and therefore negligible. This also applies to the assembly of the final product, if the final component is supposed to have similar properties. Furthermore, the distribution of the raw materials and the final products as well as recycling and disposal are supposedly relatively similar though minor differences may exist. In sum, we thus focus on energy demand to produce pre-products, products and utilization.

FACTORS AFFECTING ENERGY DEMAND

There is a wide range of factors that affect differences in energy demand across the three considered phases. The energy demand for producing metallic pre-products depends on the technology and layout of the process chain as well as material properties as illustrated in Figure 2. A decisive factor with regard to energy demand for this phase is evidently the level of process integration, i.e. how many times the material needs melting. For the production of components, the material properties are important, as well, as they are closely linked to the properties of the production process. For example, the required exposure time for the laser sintering process depends on them. A third category affecting the energy demand when manufacturing the components are evidently the properties of the manufactured components such as their shape and quality. Important factors during the utilization phase are the properties of the components. Firstly, they might affect tribological properties or aerodynamics. Secondly, weight savings can be achieved by more complex but therefore lighter structures. This could be reached, for example, by eliminating joining elements like screws or rivets or by using other materials with a lower density. In addition to the component-related factors, there are other properties related to the utilization of products using the additively manufactured components. Such factor include for example the intensity of use.

With this broad range of factors affecting energy demand on the one hand and often scarce information on the other hand, it is challenging to conduct a detailed analysis. For our purpose, the parameterisation of the factors for the calculation is therefore based on mean or aggregated values and examples from literature. This inaccuracy seems acceptable because the model focuses on the overall effects. Furthermore, if adequate data becomes available, omitted or aggregated factors can be used to extend and enhance the model.

Table 1. Studies related to the energy-demand of additive manufacturing processes.

Publication	Title	Phase: Raw material	Pre-products	Final components	Assembly	Distribution	Utilization	Disposal/recycling
(Baumers et al. 2010)	A comparative study of metallic additive manufacturing power consumption			x				
(Baumers et al. 2011)	Energy inputs to additive manufacturing: does capacity utilization matter?			x				
(Le Bourhis et al. 2013)	Evaluation and modeling of environmental impacts in additive manufacturing			x				
(Gebler et al. 2014)	A global sustainability perspective on 3D printing technologies	x	x	x	x	x	x	x
(Kellens 2013)	Environmental aspects of laser-based and conventional tool and die manufacturing			x				
(McAlister und Wood 2014)*	The potential of 3D printing to reduce the environmental impacts of production	x	x	x		x	x	x
(Mognol et al. 2006)	Rapid prototyping: energy and environment in the spotlight			x				
(McCullough et al. 2016)	Additive Manufacturing Power Consumption Measurement System			x				
(Huang et al. 2015)	Energy and emissions saving potential of additive manufacturing	x	x	x	x	x	x	
(Luo et al. 1999)	Environmental performance analysis of solid freeform fabrication processes			x				
(Morrow et al. 2007)	Environmental aspects of laser-based and conventional tool and die manufacturing		x	x			x	x
(Sreenivasan et al. 2010)	Sustainability issues in laser-based additive manufacturing			x				
(Telenko und Seepersad 2011)	A comparative evaluation of energy consumption of selective laser sintering and injection molding of nylon parts		x	x				
(Yoon et al. 2014)	A comparison of energy consumption in bulk forming, subtractive, and additive processes			x				

** Predominantly discussed in a qualitative manner.*

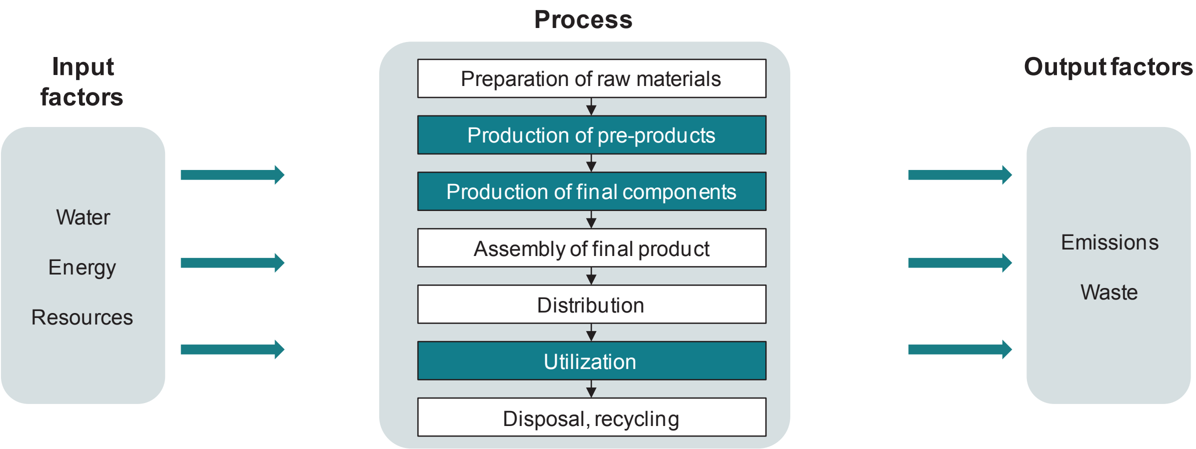

Figure 1. General life-cycle approach and focus of this study (based on Owens 1997).

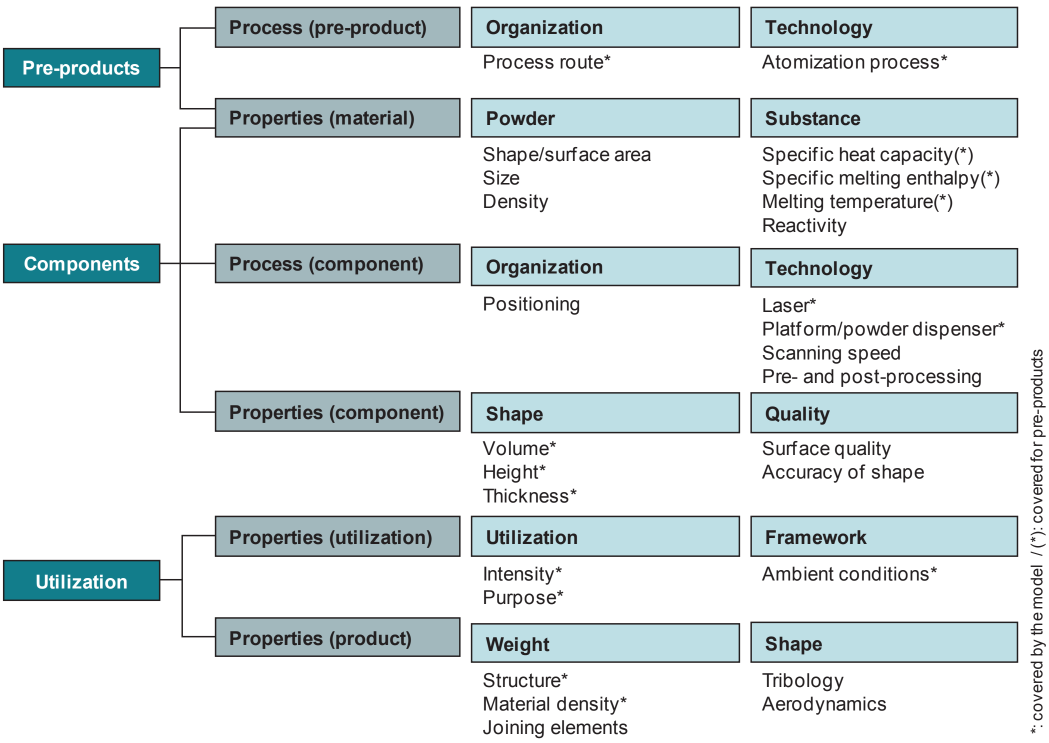

Figure 2. Important factors affecting the energy demand of additively manufacturing processes.

Our overall approach for analyzing these three phases covers two essential steps. First, we describe the main assumptions for each phase, e.g. the essential process steps that are considered in the analysis. Second, we use the factors to establish a simple calculation model for energy demand. While many factors have an important influence, we cannot build a detailed model due to a lack of data. We therefore only select such factors that can either be calculated using simple physical laws or that have been investigated in other studies. Finally, we apply the model and compare the results for the additive and subtractive processes.

Production of pre-products

ASSUMPTIONS

This section deals with the process routes for preparing the pre-products for both conventional and additive manufacturing processes. In the case of the conventional route, a block of material is a typical pre-product for the process. In the case of additive manufacturing based on SLS, the corresponding material is a metallic powder. The basic production routes for the pre-products are similar; both start with a metal refining process. For the purpose of our analysis, we chose steelmaking based on an Electric Arc Furnace (EAF) as the basic production process. The major difference between both production routes is the melting process (Figure 3). For the additive route, there are two ways of producing the metallic powder: either a direct route where metal is processed directly after the melting process or an indirect route based on casting and processing the metal to obtain metal blocks first which are then molten again. Obviously, the direct route is less energy-intensive as it saves one of the smelting processes. For the additive route, we furthermore assume that both powders are produced by gas atomization.

In terms of additive materials, we focus on aluminium and titanium. Aluminium is one of the most widely used metals in global production and well-suited for light-weight construction in the automotive sector due to its low density (Schubert und Weissgärber 2015). Today the aluminium share of curb weight is already around 10.4 % and expected to grow further (Ducker Worldwide 2014).While titanium is too expensive for mass-production, the material is increasingly used in the aviation industry as its responds well to the extreme operating condition of planes while also fulfilling the requirement of light-weight construction. The bad buy-to-fly ratio, the amount of material that has to be bought and which finally is really used for the final product is thereby a steady obstacle which can be overcome by the use of additive manufacturing technologies (Gebler et al. 2014). While the share of titanium in the Boing 777 was about 7 % it increased to 15 % in the Boing 787 while the share of aluminium dropped from 70 % to 20 % (Smith 2003; Boing 2006). In terms of specific alloys, we chose AlSi10MG and Ti6Al4V because they are broadly used in the automotive and aviation industry for additive manufacturing applications (Kempen et al. 2012).

CALCULATION MODEL

The first process steps are the melting and refining processes which are carried out in the same way for both routes. (Morrow et al. 2007) identified an average specific energy consumption e_1 for these processes. Additional energy is required for the melting processes. In line with the previous process description, there is one melting process for the conventionally manu-

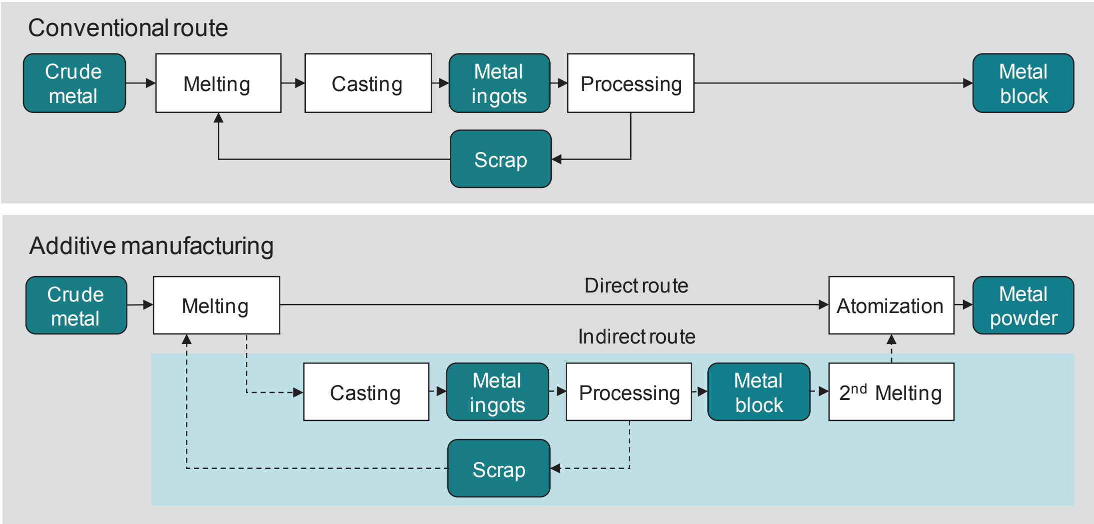

Figure 3. Production routes for conventional and additive material as assumed in this paper.

factured product and there are two for the metallic powder. The energy demand for a smelting process e_2 can be approximated using the specific heat capacity c_i, the temperature difference between the melting point and ambient condition (assumption: 15 °C), the specific melting enthalpy δ_i and a markup-factor factor α on this theoretical value. The mark-up factor α allows to adjust the theoretical value to the actual real-world demand ((Morrow et al. 2007); (Schifo und Radia 2004); (Kruzhanov und Arnhold 2013). A value of two to five has been suggested (Schifo und Radia 2004); here we chose $\alpha = 4$. As a result, a minimum energy requirement of 0.89 MJ/kg for the aluminium alloy and 1.28 MJ/kg for the titanium alloy can be derived (AZO Materials 2014; EOS 2014).

The subsequent operations mainly comprise mechanical activities in casting and processing, which is necessary for both the metal powder production via the indirect route and for the production of the metal block. The energy demand e_3 can be approximated by a value of 5.5 MJ/kg (see (Morrow et al. 2007)). The energy demand of the atomizing processes depends on whether gas or water atomization is used. Due to limited data availability, we use the measured values of the investigations of (Morrow et al. 2007) for the gas atomization $e_{4,gas}$ of 1 MJ/kg (waster atomization: 1.4 MJ/kg).

In sum, the specific overall energy demand for the pre-products for the conventional route e_{conv} as well as the direct additive route $e_{add,dir}$ and the indirect additive route $e_{add,ind}$ are estimated as follows:

$$e_1 = 6.6 \text{ MJ/kg} \quad (1.1)$$

$$e_2 = (c_i \cdot \Delta T_i \cdot \delta_i) \times \alpha \quad (1.2)$$

$$e_3 = 5.5 \text{ MJ/kg} \quad (1.3)$$

$$e_{4,gas} = 1 \text{ MJ/kg} \quad (1.4)$$

$$e_{conv} = e_1 + e_2 + e_3 \quad (1.5)$$

$$e_{add,dir} = e_1 + e_2 + e_{4,gas} \quad (1.6)$$

$$e_{add,ind} = e_1 + 2e_2 + e_{4,gas} \quad (1.7)$$

Production of components

ASSUMPTIONS

This section deals with the production of the components from the previously provided pre-products. In terms of components, parts from the automotive and aerospace industry are used as sample components. More specifically, a turbine part is selected for both industries. To allow for a better comparison of the impact in the utilization phase, the volume of the components for both industries is identical, yet the materials differ to reflect typical materials used in these industries. The starting point for the conventional process is a metal block with a volume of approximately 82 cm³. The amount of material removed is the difference between the block and the volume of the component, which means roughly 61 cm³. The volume of the turbine wheel is taken from (Baumers 2012).

The energy requirements for the use of additive manufacturing processes are very specific to the actually used process and system. In this case, the calculation is based on the example of EOSINT M270 as actual measured values of the energy requirement are available for this machine. As corresponding material processing volume rates, the following values are used: 5 mm³/s for Ti6Al4V, 7.4 mm³/s for AlSi10Mg and 2 mm³/s for steel (EOSINT M270). The maximum power of the system is 5.5 kW (EOS 2014); Baumers (2012) determined an average value of about 2.3 kW using different components (Baumers 2012). The average value which is less than half the specified maximum power, is also detectable within other models in the series, so that a value of 2.3 kW is used for the estimation. It was possible to measure the time for distributing a new layer of powder from digital recordings of the production process and it takes 12 seconds. The desired layer thickness is variable and assumed to be 0.02 mm for our case (Baumers 2012). Since the volume rate is considered as pure sintering time and does not consider other time-intensive factors, a deviation factor $\beta = 1.4$is used in this paper.

CALCULATION MODEL

The total energy requirements for producing a component with a subtractive process can be divided into four components (Balogun und Mativenga 2013): the energy consumption required by the system while it is switched on, the mechanical consumption for the moving platform on which material is processed, the consumption for removing material by the spindle and the machine-specific consumption used for coolant or tool change. Yet these terms are very system and material-specific and difficult to determine. As an alternative used in our case, the energetic analysis is based on the removed material volume and the specific cutting performance taken from the literature (ASM International Handbook Committee 1989). Knowing the specific metal removal rate per volume p_{sub}, the block volume V_{block} and the component volume V, the specific energy consumption $e_{sub,2}$ can be determined.

For the additive process, the construction time depends mainly on two elements, namely the time for the distribution of new powder layer t_{layer} and on the number of layers, determined by the height and the layer thickness. The total time t_{mech} is described by the time for the mechanical movement of the lifting table and the powder distributor. The construction time of the component t_{constr} can be determined if the volume of the component and the material-specific volume rate are given. Since this construction time is only the theoretically possible construction speed at the volume rate, the deviation from the actual value is taken into account by the mark-up factor β. With knowledge of the specific system power p_{Add}, according to the technical data or on the basis of own measurements, the energy consumption of any component can be estimated depending on material-specific to e_{add}.

$$e_{sub} = (V_{block} - V) \cdot p_{sub} \quad (2.1)$$

$$e_{add} = (t_{Layer} \cdot \frac{h}{Layer\ thickness} + \beta \cdot \frac{V}{r_{add}}) \cdot p_{Add} \quad (2.2)$$

$$t_{mechs} = t_{Layer} \cdot \frac{h}{Layer\ thickness} \quad (2.3)$$

$$t_{constr} = \frac{V}{r_{add}} \quad (2.4)$$

Utilization phase

ASSUMPTIONS

After the production of the components, we now address their utilization phase. The objective is to analyse the effect on energy demand if the additively manufactured component is used instead of a conventionally manufactured good. In the utilization phase, the long-term impact of the final product over its lifetime is considered in terms of relative, but not absolute change as compared to the component based on subtractive manufacturing.

To connect with the previous phases, the analysis relies upon an additive manufactured component with the volume of the turbine wheel. Thus, it is examined how the energy demand changes in the utilization phase, when a vehicle or an aircraft is equipped with an additive manufactured part of the same volume as the turbine wheel. It is assumed that the component in the conventional case is made of steel and is replaced by the additive component made from aluminium or from titanium alloy. Replacing steel is justified by its frequent use in the automotive and aerospace industries. By using the additively manufactured component, weight reduction and thus a reduction of energy demand can be achieved. For the analysis, it is assumed that the average life of the components corresponds to the average life of the final product.

In the case of the automotive industry, energetic effects which are possible during vehicle usage are examined, if a suggested component made of an additive aluminium alloy with the equivalent volume of the turbine wheel from the previous section is used, instead of a conventional part made of steel. With a density of 7.85 g/cm³ and the given volume of the components, the steel part weighs 162 g. The component made of an aluminium alloy AlSi10Mg weighs 57 g, so that a reduction in weight of 105 g can be achieved. To find out which energy impact is caused by the mass reduction in the utilization phase, a further segmentation of the vehicle group is necessary to consider the different final product properties of vehicles. Significant differences in the product life and in the usage, a high relevance given by the large market share can be found in the segments of passenger vehicles (cars) and lorries (trucks). In examining the trucks segment, the tractor unit or semi-trailer tractor (STT)) can be considered specifically. The reason is that they play an important role in the context of energy efficiency with nearly 10 % of global energy demand in the transport sector (Baumers 2012).

Helms and Lambrecht (2007) have examined the potential savings of vehicles, if the total weight is reduced. Their research states a potential saving for passenger vehicles of 1.1 J per saved kg and km (Helms und Lambrecht 2007). On average, the annual mileage of passenger cars in Germany in the year 2015 was 14,259 km (Kraftfahrt-Bundesamt 2015a) with a lifetime of nine years (Kraftfahrt-Bundesamt 2015b). Based on the subsequently shown equations, the impact on energy demand by using the 105 g lighter, additive manufactured part can be determined to a saving of 1.65 MJ/year. Over its lifetime, this equals about 14.8 MJ. In the case of the tractor unit, energy consumption can be reduced by 2.27 MJ/year (Table 2).

When considering the effect on energy demand on the basis of the total traffic in Germany with about 44 million cars and 188,000 tractor units (Kraftfahrt-Bundesamt 2016), an energetic impact of nearly 72.5 TJ/year for vehicles and 0.43 TJ/year for tractor units is possible, if all vehicles in Germany were equipped with the additive manufactured component.

In the aviation industry the energetic impact is estimated in case of an additive manufactured titanium component. The focus is on commercially used aircrafts, this is due to the available data bases. The calculation is once again performed based on the example of a component with a volume comparable to the one of the turbine wheel. Furthermore, it is assumed that the component in the conventional processes is made of steel and made of the titanium alloy Ti6Al4V in the case of the additive manufactured component, which is used often in the aircraft industry. While the steel component weighs about 162 g, the component of the titanium alloy has a weight of 90 g, so that in this example, a weight reduction of 72 g can be obtained. The determination of the energy demand for aircrafts is very complex because the energy need during a flight is not constant. The main reason for this is the greatly decreasing weight during the lift-off and flight due to the heavy weight of the aircraft fuel. Because long-haul aircrafts (LHA) perform a higher number of flight hours during their lifetime, the energy saving potential is higher compared to short-haul aircrafts (SHA). Therefore, the

Table 2. Energy-related effects by additively manufactured components in vehicles.

	Specific energy saving potentials	Annual travel distance	Annual energy savings	Lifetime	Energy savings over lifetime
Unit	[MJ/(km·kg)]	[km/year]	[MJ/year]	[years]	[MJ]
Passenger car	0.00110	14,259	1.65	9.0	14.82
Tractor unit	0.00021	102,832	2.27	4.2	9.52

Table 3. Energy-related effects by additively manufactured components in aircrafts.

	Energy saving potentials	Annual energy savings	Lifetime	Energy savings over lifetimes
Unit	[GJ/kg]	[GJ/year]	[years]	[GJ]
SHA	5.00	0.36	26	9.36
LHA	6.67	0.48	26	12.49

segmentation of the example calculation in short-haul aircrafts (SHA) and long-haul aircrafts (LHA) is carried out. Helms and Lambrecht (2007) state annual savings of 5 GJ per kg saved in a SHA and 6.67 GJ per kg saved in a LHA. (Helms und Lambrecht 2007). With the knowledge of an average age of 26 years for a commercial aircraft (Forsberg 2015), the energy savings for short-haul aircrafts and for long-haul aircrafts by titanium components, which are lighter by 72 g, can be estimated. The savings through the use of the additive manufactured components account for 9.36 GJ in a short-haul aircraft and for 12.49 GJ in a long range aircraft.

CALCULATION MODEL

To determine the energy consumption of products with conventionally produced components e_{sub}, the knowledge of the product lifetime as well as the usage behaviour is sufficient. The component-specific factors weight and shape concern the energetic change through the use of additive manufactured components, which is why the elements can be omitted when considering conventional methods. Accordingly, the fluctuations caused by abrasion or repair are not registered separately in the calculation. For the utilization phase, the following equation indicates the energy consumption of the product over its entire lifetime. The factor e_{Usage} corresponds to the application-specific energy demand during the use of the product, per unit time or distance, while γ indicates the average product lifetime.

When using additively manufactured components, the shape and weight of the product can be changed. The equation to determine e_{Add} describes a simplified estimate of the energy demand in connection with the component properties. The energetic effect by the altered form is taken into account by the pre-factor θ. The pre-factor refers to the impact on the entire energy demand $e_{Consumption}$ by changing the aerodynamics or tribology. The factor $\Delta g \cdot e_{Weight}$ reflects the change in energy demand, due to the weight change Δg compared to conventionally manufactured components. The last term γ is also regarded as the average lifetime of the product as in equation (3.1). If the shape of the component has no influence on the energy demand, the pre-factor θ takes the value 1. When only the change in energy consumption is considered for the evaluation, the calculation based on equation (3.3) is sufficient, which provides the energy savings due to the lower weight.

$$e_{sub} = e_{Usage} \cdot \gamma \quad (3.1)$$

$$e_{Add} = (\theta \cdot e_{Consumption} - \Delta g \cdot e_{Weight}) \cdot \gamma \quad (3.2)$$

$$e_{Difference} = \Delta g \cdot e_{Weight} \cdot \gamma \quad (3.3)$$

The equations are used in the next section to determine the energy demand taking the example of the end products automobile and aircraft and to evaluate the energy impact through the use of additive manufacturing processes. The pre-factor θ will take the value 1 in the course of the calculations, due to the currently limited available data for shape-based energetic effects.

Overall results

The previous sections dealt with the separate analysis of the energy impact in the individual life cycle phases. This section describes the overall analysis across the different phases.

The assessment along all phases is considered for two different cases. In the first case, the subtractive method will only be replaced by the additive method, without using a different material. In the first case the impact on energy demand is only relevant for the first two phases, i.e. the production of the raw material and the production of components. The utilization phase is irrelevant because the component properties are retained and therefore have no effect on the end products. In the second case, a hypothetical conventionally manufactured steel component is replaced by an additive component made of aluminium or titanium alloy. In this case, the energy requirements change for all considered phases of the life-cycle.

Figure 4 shows the energy impact in the various phases for the first case, in which the additive manufacturing processes are only used as an alternative to the subtractive methods. The values show the difference in energy consumption between the subtractive and additive methods. The values correspond to the amount of energy saved by the use of additive manufacturing processes. The raw material preparation only has a minor effect. In the automotive industry, it makes up about 10 % of the total energy difference or approximately 3 MJ. In the aviation industry, the difference is about 5 MJ as compared to a total of

270 MJ and thus very low (2 %). Furthermore, the high overall value of the aviation industry is striking. The main reason is the high energy consumption in the subtractive processing of the titanium alloy.

An aggregated examination of the impact on Germany shows a different picture. In Germany approximately 5.7 million passenger cars (VDA 2015) and 260 short and medium-haul aircrafts were produced for commercial purposes (Airbus 2015) in 2015. The production of tractor units and long-haul aircrafts takes place outside Germany, so these are irrelevant for the first case. The significantly higher production volume in the automotive industry offsets the initially higher impact of aircrafts (Table 4). In sum, annual energy savings of about 184 TJ/a could be possible through the use of an additive manufactured component.

The change of the energy demand in the second case, in which the subtractive produced steel component is replaced by the additive manufactured aluminium or titanium component, is shown in Figure 5. The energy demand in the utilization phase refers to the annual demand, to meet the different average lifetime of vehicles and aircrafts. Unlike the first case, the energetic impact in the production process of both industries differs only slightly from each other. Rather conspicuous is the major change in the demand for energy in the utilization phase of the aircraft, which exceeds the changes in all other phases. For a single vehicle only minor changes can be seen in the utilization phase.

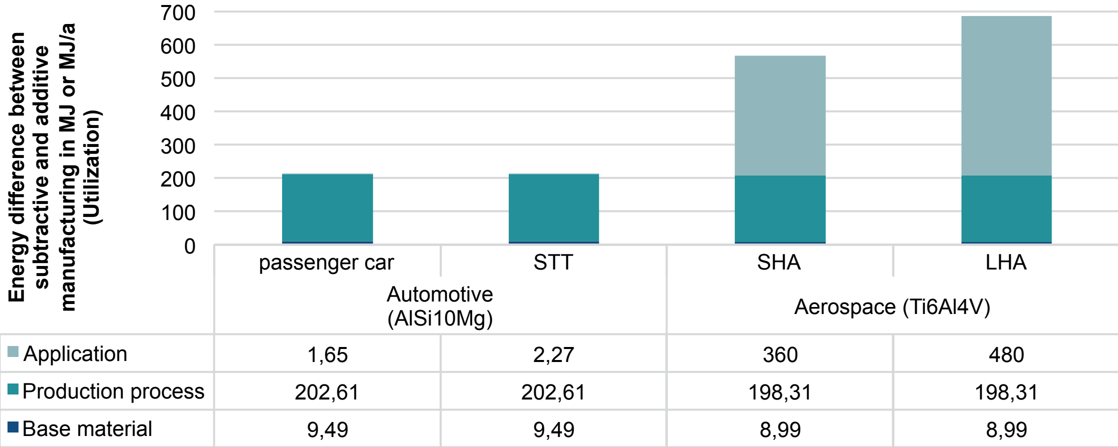

Figure 4. Impact per vehicle and aircraft per component in "Case 1: Changing the procedure".

Table 4. Annual energy savings per component in Germany in "Case 1: Changing the procedure".

	Number of passenger cars	Annual energy savings	Number of SHA	Annual energy savings
Unit	[units]	[TJ/a]	[units]	[TJ/a]
Base material	5,700,000	16.68	260	0.0013
Production process	5,700,000	166.93	260	0.0687
Total	–	**183.61**	–	**0.07**

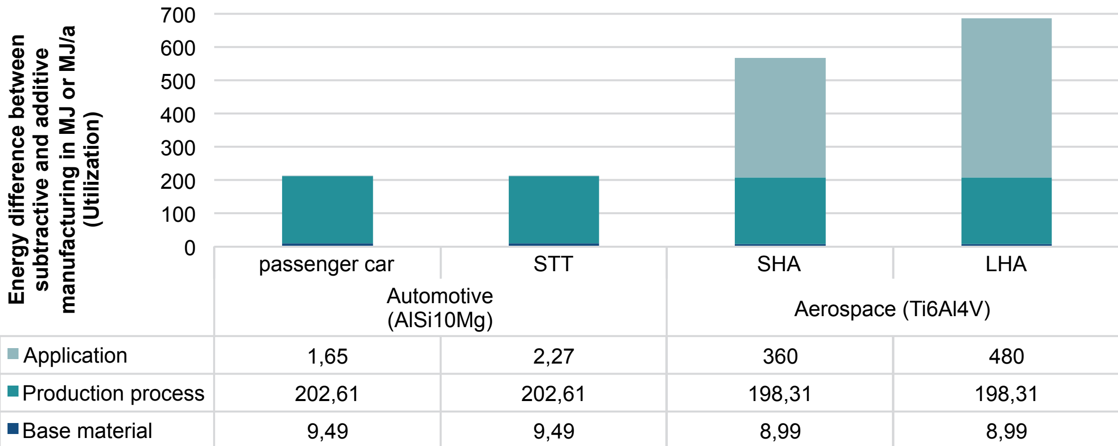

Figure 5. Annual impact per vehicle and aircraft per component in "Case 2: Changing the material".

Table 5. Annual overall energy savings in Germany in "Case 2: Changing the material".

	Number of STTs	Annual Energy Savings	Number of LHAs	Annual Energy Savings
Unit	[units]	[TJ]	[units]	[TJ]
	188,000	0.43	125	0.0600
	Number of passenger cars	**Annual energy savings**	**Number of SHAs**	**Annual Energy Savings**
Base material	5,700,000	54	260	0.0023
Production process	5,700,000	1,155	260	0.0516
Usage	44,000,000	72	501	0.1804
Total	**–**	**1,281.43**	**–**	**0.295**

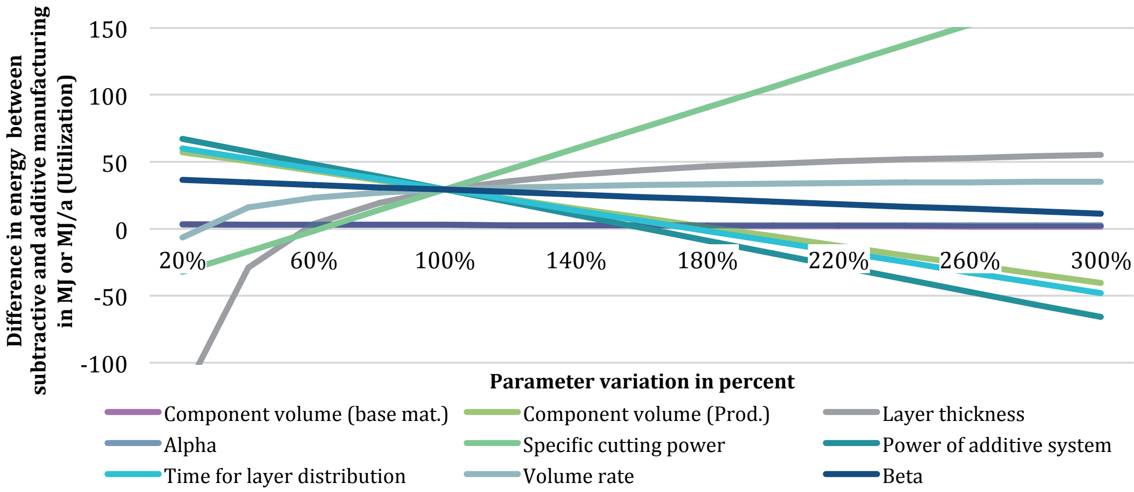

Figure 6. Sensitivity analysis of the energy difference because of the use of additive manufacturing processes (on base of Case 1).

The possible overall impact on the energy consumption of Germany, by the use of an additively manufactured component in vehicles and aircrafts, with an equal volume as the previously described turbine wheel, is summarized in Table 5. The quantitative assessment of the energetic impact over the life cycle phases shows that the use of additive manufacturing processes as an alternative to the conventional method has energetically a differently strong influence in the individual phases. While the effect in the preparation of the base material in the two industries is very low compared to the overall impact, the relevance of the other phases varies: In the automotive industry, the largest difference occurs in the phase of the production process, while in the aviation industry, the largest difference can be detected in the utilization phase. In terms of productions and stocks in Germany, the largest energy impact when used in the automotive industry is determined essentially by the high numbers of vehicles. The widespread use of additive manufacturing processes, using the example of a single component for the automotive and aerospace industries, can change about 0.05 % of the total final energy consumption in the German transport sector, which had a overall consumption of 2,630 PJ in the year 2014 (AGEB 2015).

A sensitivity analysis of specific factors shows how strongly the energetic impact reacts to changes in the key factors. Figure 6 shows all the parameters that were examined in the sensitivity analysis. The parameters are changed in percentage terms. The figure illustrates what factors have a particularly large impact on the energy difference between the use of the subtractive and the use of the additive manufacturing process. Particularly noteworthy are the changes caused by the specific metal removal rate and the performance of the additive manufacturing systems. While the effect of the parameter variation usually varies linearly, it responds exponentially in the variation of the factors volume rate and layer thickness. Furthermore, the component volume has a greater effect on the demand for energy in the production phase than in the phase of preparing the base material.

Discussion

As shown earlier, there are numerous factors affecting the performance of additive manufacturing processes in terms of energy demand. The results for the selected examples need to be considered with care and considering the simplifying assumptions and limitations in terms of data quality. The calculation model includes terms, such as physically required minimum amounts of energy or possible construction times, under optimal conditions, which only reflect the theoretical values. Despite the use of markup-factors to take the differences between the theoretical and practical values into account, the results can only be seen as approximate estimates of the energetic impact. In addition, the analysis includes only a part of the complex interactions of factors. Under the ceteris paribus condition and the reduced complexity, the determination of the energetic impact is feasible.

To counter this limitation, the result values were checked against available reference values and documented measurement data. To gain a better insight regarding the inaccuracy which accompany these limitations the calculated energy consumption to produce the aforementioned turbine wheel was compared to real world measurement results of Baumers (2012). The parameters of his investigation were therefore put into the model. The comparison showed a deviation of 1.2 %. Although the comparison is made to the phase of production, the number of influencing factors and therefore the possibility for a high deviation appears especially in this phase to be very high. Further direct comparisons with other studies as listed in Table 1, seem little helpful because either the given data is insufficient for a comparison or different assumptions (e.g. the used additive manufacturing technology or the material) were made. Although not all the factors and interactions are included, the analysis results reveal insightful findings, about how the use of additive manufacturing processes, as alternatives to conventional methods, may affect the energy consumption in different phases of the life-cycle. Furthermore, the influencing factors give an insight into the extent to which factors affect the energy consumption. In addition, estimates can be made, in which specific phases the change in energy consumption resulting from the use of additive manufacturing is greatest (such as the production process in the example of the automotive industry). The need for further research exists regarding the level of detail of the process chains and the influencing factors. In addition, further measurements of the actual energy consumption of individual process steps can improve the data base for the assumptions made.

Conclusions

In this paper, we conducted a quantification of the overall impact of an additively manufactured component using SLS on the energy demand in Germany. The analysis reveals that the use of additive manufacturing processes can have different effects on the energy consumption in the various life-cycle phases of the component used in the automotive and aircraft industry. In the preparation phase of the base material, the energy consumption of the material preparation for the additive manufacturing method may be higher or lower than demand for the conventional method, depending on whether the base material is manufactured directly after the first melting process or indirectly from a metal block. However, the energetic impact of the first phase is negligibly small compared to the impact of the subsequent phases of production and use. In the production phase, the energetic effect is very high, whereby the detailed extent depends on the material used. As the energy consumption for additive manufacturing of different materials only differs slightly from each other, the differences in the subtractive production are substantial. Finally, additive manufactured components also allow for possible energy savings during the utilization phase due to weight savings. The exemplary assessment of a component produced and used in the German automobile and aircraft stock, revealed an overall saving potential of several TJ or 0.05 % of the total final energy consumption in the German transport sector, solely by this one component. Thus, on the one hand this study points out that there are very relevant applications for additively manufactured products with a high energy efficiency potential such as in aeroplanes. This insight confirms the findings also indicated for example by (Huang et al. 2015). On the other hand this study reveals the large scale potential accompanying a diffusion of additive manufactured products such as in the automotive industry. So while the energy saving potential by additive manufacturing technologies in the automotive industry during the utilization phase, appears rather small at first glance, it actually bears a non-negligible potential.

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