Value chain-wide energy efficiency potentials of additive manufacturing with metals – some preliminary hypotheses

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Abstract
For some time, 3D printing has been a major buzzword of innovation in industrial production. It was considered a game changer concerning the way industrial goods are produced. There were early expectations that it might reduce the material, energy and transport intensity of value chains.

However for quite a while, the main real world applications of additive manufacturing (AM) have been some rapid prototyping and the home-based production of toys made from plastics. On this limited basis, any hypotheses regarding likely impacts on industrial energy efficiency appeared to be premature.

Notwithstanding the stark contrast between early hype and practical use, the diffusion of AM has evolved to an extent that at least for some applications allows for a preliminary assessment of its likely implications for energy efficiency.

Unlike many cross-cutting energy efficiency technologies, energy use of AM may vary substantially depending on industry considered and material used for processing. Moreover, AM may have much greater repercussions on other stages of value chains than conventional cross-cutting energy efficiency technologies.

In case of AM with metals the following potential determinants of energy efficiency come to mind:

- A reduction of material required per unit of product and used during processing;
- Changes in the total number and spatial allocation of certain stages of the value chain; and
- End-use energy efficiency of final products.

At the same time, these various streams of impact on energy efficiency may be important drivers for the diffusion of AM with metals.

This contribution takes stock of AM with metals concerning applications and processes used as well as early evidence on impacts on energy efficiency and combine this into a systematic overview. It builds on relevant literature and a case study on Wire Arc Additive Manufacturing performed within the REINVENT project.

Introduction
Steel, aluminum and titanium, the metals referred to in this contribution, are important materials for industrial production. At the same time, the production and processing of these metals are highly energy intensive. Energy use for current metal production and processing is associated with large volumes of GHG and will need to be rendered carbon neutral, if ambitious climate policy objectives are to be met by 2050.

For instance, the decarbonisation of the steel industry is largely about how steel is being produced, and the carbon intensity of related upstream production technologies. Conventional primary steel production requires carbon as the main reduction agent to convert iron ore into iron and steel. This technology is currently based on the use of coking coal in a blast furnace as the main reduction agent, and most emissions of greenhouse gases from the steel industry are caused by this. Options which may allow for an almost complete decarbonisation of the production of primary steel are direct reduction of iron ore (DRI) based on hydrogen as an alternative reduction agent with first implementation going on or electrolysis of iron ore with somewhat lower technology readiness (Fischedick et al. 2014, Weigel et al. 2016).

Secondary steel production is based on the conversion of iron and steel scrap in electric arc or induction furnaces which requires no reduction agent. While some CO_2 may still result from the inevitable burning of some of the graphite from the electrodes in an electric arc furnace, the decarbonisation of secondary steel production primarily proceeds simultaneous to the electric utility sector that provides the electricity used.

In a potential future world with a complete decarbonisation of primary and secondary steel production, emissions related to logistics and downstream processing of steel will ultimately gain importance for total carbon emissions. At the same time, steel processing will be significant along the pathway to such a state of complete decarbonisation. Even once complete decarbonisation of steel production will have been achieved, steel processing will remain to be important for energy and resource efficiency and the volume of energy namely electricity and material resources required.

Thus given today's dominant role of primary and secondary steel production for decarbonising the steel industry, it makes sense to take a closer look at downstream technologies for further processing and how those and the use of the goods produced for final demand impact on lifecycle-wide emissions of greenhouse gases (GHG) as well as other Sustainable Development Goals (SDGs). Similar to steel, aluminum and titanium processing will also need to be made more material and energy efficient.

Additive Manufacturing with Metals – State of the Art

One important innovation in downstream technologies for the processing of metal products is Additive Manufacturing (AM) which is still in its early stages of implementation. This is even more true for Wire Arc Additive Manufacturing (WAAM) for steel processing which is even newer and the focus of the case study.

AM is often also called 3D printing, additive fabrication or free-form fabrication (US Department of Energy 2015). Generally, AM is an advancing technology with various techniques, materials and applications (Brooks 2016). Over the next ten years, AM is expected to experience significant growth and to play an important role in various manufacturing industries. A lot of current AM is about producing objects using plastic materials. However, AM also allows for innovative designs and processing of objects made from various metals like steel, aluminum and titanium.

AM has initially been developed for rapid prototyping in order to reduce time to market (Bauer et al. n.d.) and had a focus on creating objects that previously had to be crafted from wood or plastics from full. With plastic materials, the similarities to the 2D printing process of documents are straightforward. However, for AM with metals, partial or full melting is often required which differentiates these processes from conventional printing technologies in terms of the high temperatures and hence energy required for processing. Notwithstanding this, the term 3D printing is often also used for AM with metals.

Table 1 provides an overview on current AM technologies with a focus on those that can be used with metals. Powder Bed-Fusion (PBF) as an AM technology has evolved to a greater degree of maturity but is still substantially limited in terms of the size of the objects that can be produced. However, further upscaling is imaginable also in terms of numbers of workpieces processed simultaneously using several laser or electron beams which might result in an increasing potential for mass production.

AM processes based on aluminum and titanium powders are already substantially being used for lightweight objects, components and structures for space and aviation applications. The reason for this is that utilisation of AM with aluminum and titanium has been driven by the enormous reductions in energy

Table 1. Properties of AM technologies that can be used with metals.

Starting Material	Process	Material Preparation	Layer Creation	Phase Change	Materials	Applications
Powder	Selective Laser Sintering (SLS)	Powder in Bed	Laser Scanning	Partial Melting	Thermoplastics, Waxes, Metal, Ceramic	Prototypes, Casting Patterns, Metal and Ceramic Preforms
	Selective Laser Melting (SLM)	Powder in Bed	Laser Scanning	Full Melting	Metal	Tooling, Functional Parts
	Electron Beam Melting (EBM)	Powder in Bed	Electron Beam Scanning	Full Melting	Metal	Tooling, Functional Parts
	Laser Metal Deposition (LMD)	Powder Injection through Nozzle	Powder Injection/ Melting by Laser	Full Melting	Metal	Tooling, Functional Part Repair
	3D Printing (3DP)	Powder in Bed	Drop-on-Demand Binder Printing	–	Polymer, Metal, Ceramic, Other Powders	Prototypes, Casting Shells, Tooling
Solid Sheet	Laminated Objective Manufacturing (LOM)	Laser Cutting	Feeding/ Binding of Sheets – with Adhesives	–	Paper, Plastic, Metal	Prototypes, Casting Models
Wire	Wire Arc Additive Manufacturing (WAAM)	Wire	Welding	Full Melting	Metal	Prototypes, Sculptures, Structures, Functional Parts, on-site Repair

Source: Partly adapted from US Department of Energy (2015).

Table 2. Use of metals for industrial production and properties with AM.

	Steel	Aluminum	Titanium
Metal Specification for AM	Stainless steel, tool steel	Aluminum alloys	Titanium, Ti-6Al-4V
Density	7.8 t/m^3	2.7 t/m^3	4.5 t/m^3
Energy Intensity per t input	Benchmark for primary crude steel: 18.1 GJ/t (Fischedick et al. 2014) global average 20 GJ/t (2017) (World Steel Association 2019a); For austentic stainless steel: 79 GJ/t for primary production, 26 GJ/t for secondary, 53/t for average (Johnson et al. 2008)	Primary production: 138 GJ/t (Wang 2013), no information for special grades.	Primary production: 1,300 GJ/t (Toho 2015)
GHG Intensity in CO_2eq per t input	Primary crude steel: 2 t/t q in EU (Material Economics 2019) Austentic stainless steel: 5.3 t/t for primary production, 1.6 t/t for secondary, 3.6 t/t in average (Johnson et al. 2008)	8.9 t/t in USA (Wang 2013)	
Global Primary Production (t per y)	1,250 Mt (2018) of crude steel (World Steel Association 2019b); 17 Mt (2004) of austentic stainless steel (Johnson et al. 2008)	64.3 Mt (2018) (World Aluminium 2020)	0.192 Mt (2018) (Gambogi 2020)
AM Processes	PBF, WAAM	PBF	PBF
Applications	Prototypes and art, lightweight structures, ground vehicle and machinery components, tools for casting	Prototypes and art, lightweight aerospace components	Prototypes and art, lightweight aerospace components, desalination facilities, medical implants
Main Drivers of R&D/ Diffusion	Specific designs, on-site repair, lightweight design, end use energy efficiency	Specific designs, lightweight design, end use energy efficiency	Specific designs, lightweight design, end use energy efficiency
Potential Drivers of Cost Reduction	Material lean design and processing, logistics and end use energy efficiency of ground vehicle/machinery components	Material lean design and processing, logistics and end use energy efficiency of ground vehicle/machinery components and aerospace components	Material lean design and processing, logistics and end use energy efficiency of aerospace components
GHG Driver Material	Energy-intensive powder versus wire	Energy-intensive powder versus wire	Energy-intensive powder versus wire
GHG Driver Processing	Electricity use per t output, shielding gas	Electricity use per t output, shielding gas	Electricity use per t output, shielding gas
GHG Driver Logistics	SC material intensity, warehousing, global transport distances	SC material intensity, warehousing, global transport distances	SC material intensity, warehousing, global transport distances
GHG Driver End-use	Mass moved per ground vehicle or machinery component	Mass moved per ground vehicle or machinery or aerospace component	Mass moved per aerospace component

use and related cost that can be achieved during the use phase of products of highly lightweight metal designs for space and aviation applications. This allows to combine the particularly low specific weights of aluminum or titanium with the lightweight structures of AM designs. Another important area of application is AM with titanium for medical implants, owing to the individual design options and non-allergenic properties of titanium.

Opposed to this, steel-based AM is just starting and might in future be of growing importance for components of machinery as well as of vehicles operating at the ground level and for immobile structures build by the construction industry. For such applications, weight savings are also important but not to such an extent that may justify the use of relatively costly materials like aluminum or namely titanium as compared to steel.

Regarding AM with metals, the currently most common technologies are selective laser melting and sintering. Subsequently, electron beam melting was developed, which is a relatively similar technique, but uses an electron beam instead of lasers.

Applications of metal AM can be found in the aerospace, automotive, tooling and healthcare industries. Aerospace applications are focused on complex lightweight components in limited numbers that have to comply with particularly high safety standards, pushing the boundaries of AM in terms of producing homogenous high-quality microstructures. Application of AM with metals in the automotive industry are also focused on complex lightweight structural components. In the tooling industry reduced production times, reduction of tooling metal scrap and unique designs of cooling channels with molds play an important role for utilising AM. In the healthcare industry application of metal AM is comprised of precise dental components and implants according to individual scans (Yakout et al. 2018).

Review of metal AM energy and GHG intensities

There is evidence from the literature that a simple comparison of energy use of steel processing techniques is particularly insufficient in case of AM. Instead of restricting such analyses to the processing step in the value chain, spillovers to upstream or downstream stages of the value chain need to be taken into account. The main reason for this is that as further explained in this section AM may have substantial repercussions on the required output of upstream metal production processes as well as downstream during the use phase of products (Baumers 2012).

Resulting from the use of WAAM, the respective supply chain and relevant features of the product might be entirely altered which requires a broader perspective in order to fully encompass all relevant impacts along the value chain. At the same time, the bridge is just one example aiming at the construction sector which might not be telling us too much about other – still to be developed – future applications of WAAM with steel.

Based on evidence from the literature on the utilisation of AM with metals and the WAAM Case Study, there is a sufficient basis that suggests what the most important drivers of effects of AM on decarbonising metal processing and whole metal value chains might be. However it needs to be kept in mind that any such effects may vary greatly depending on the specifics of products under consideration. With the manufacturing of products that to a substantial extent are comprised of metal, the significance of downstream production processes and technologies like AM or more specifically WAAM for decarbonisation is primarily based on the following and to some extent interrelated pillars (see Figure 1):

- Energy efficiency as compared to the respective conventional processing technology – if available – that allows to manufacture similar products;
- Scrap intensity of processing and the related amount of energy that has been lost up to the respective step in the value chain;
- Transport intensity and related energy use and GHG emissions required for logistics related to production, maintenance, repair and (re-) distribution (Pastowski et al. 2014, Bauer et al. n.d.); and
- Longevity and end-use carbon intensity (Bauer et al. n.d.) of the utilization of final products.

Energy efficiency of metal AM compared to the respective conventional processing technology that allows to manufacture similar products is the core area of direct effects on the carbon intensity.

It is straightforward that it will heavily depend on the product category and conventional processing technologies deployed to which extent using AM may result in higher energy efficiency. One of the main strengths of AM with metals is that only the volume of material required per unit of product will need to be produced and processed. This means less scrap at the processing stage of the value chain.

Normally, primary structures for aircraft that are made of steel, aluminum or titanium, are machined from very large blocks of metal. Starting from 20, 30 or even 50 times more material than actually needed for a particular workpiece because the most of it has to be removed to achieve the final shape is very inefficient from both an environmental and a cost point of view. Opposed to this, using AM for producing the same part almost only deploys the volume of material that is ultimately required. (Bauer et al. n.d.)

Considering the various conventional metal processing technologies, the material efficiency of AM is similar to casting while milling might require substantially more material to be processed. In the end, it is the energy required for processing the respective volumes of material per unit of product that can make a decisive difference. Beyond this the material intensity hints at further potentials for increasing energy efficiency that are based on scrap intensity and transport intensity along the supply chain as well as carbon intensity of end use of the respective products made of metal. This means that any comparison of metal AM with conventional processing technologies would be too narrow if it failed to include the material and transport intensity implications along the value chain as well as related changes in energy efficiency of metal processing arising from the use of AM.

Scrap intensity of production along the supply chain not only refers to product that fails to meet quality standards at a certain stage of the value chain in the metal processing industry. Beyond this, subtractive manufacturing in metal processing regularly results in a substantial volume of metal which has been produced but does not make it to the final product stage. All such yield losses need to be recycled either in-house of the processing plant (e.g. using ovens in casting plants) or externally via electric furnaces in secondary metal production.

There are estimates that roughly one quarter of all liquid metal is turned into scrap during downstream processes. Globally in 2008, for steel alone there was 1,040 million tonnes of demand for steel products. In the course of downstream processes, 98 million tonnes of liquid steel ended up as forming scrap while 236 million tonnes of scrap resulted from other subtractive fabrication. In the event that all such yield losses could be eliminated, liquid steel production might be reduced by 26 % (Allwood et al. 2011).

These figures hint at the enormous potential for reducing scrap at the processing stage alone, some of which might in future be achieved through the use of AM. However it remains to be seen to which extent metal AM can eliminate subtractive manufacturing and how the utilisation of AM will interfere with the achievement of quality objectives and related volumes of scrap from processing.

Opposed to the scrap intensity of conventional metal processing, AM promises to solely use the volume of material that is ultimately required for the final product. Therefore, AM as a processing technology might allow for substantial reductions in the volumes of materials required per unit of product and result in less related energy consumption during downstream and upstream processes (Huang et al. 2018; Tang et al. 2016).

Thus provided that scrap sorting out as a result of quality control might be eliminated and all subtractive processing can instead be done by additive manufacturing, the volume of scrap resulting from steel processing might greatly be reduced.

The transport intensity of production along the supply chain is another trigger of emissions of GHG and the attainment of other SDG. Generally, the transport intensity of a supply chain is greatly influenced by the expectations of final users, production and logistics concepts as well as technologies used for the respective products and in production and logistics operations. More focused on the context of this contribution, decisive factors are the overall volume of material required per unit of final product, the various locations involved in the value chain and the distances between those locations (Pastowski 1997).

Thus, it is clear that scrap intensity and transport intensity are somewhat interrelated. The more scrap is produced at a certain location that cannot be recycled there, the more of it needs to be transported to other locations where recycling can be done. Likewise, greater volumes of semi-finished product need to be transported from steel production plants to processing plants. However, the general material intensity per unit of final product stretches well beyond the impact of processing technologies on the scrap intensity and starts with design considerations, which however is not the focus of this contribution.

Unfortunately, there is limited evidence with regard to the energy intensities of metal AM. The direct impact of AM and namely WAAM on the energy and carbon intensities of steel processing e.g. per kilogram of product as compared to conventional processing technologies may vary substantially depending on the type of product and which conventional technology would otherwise need to be deployed. The individual steps for PBF display substantially different energy demands as compared to WAAM, as wire production is more energy-intensive than powder production. At the same time, energy consumption for deposition is much higher for powder, roughly balancing the two approaches (Jackson et al. 2016).

Direct energy use at the steel processing stage is primarily determined by the volumes of electricity or natural gas required. Further to this at the processing stage, the use of argon as a shielding gas contributes to the energy intensity of WAAM which is not required with conventional processing technologies. The use of argon as a shielding gas increases the indirect energy use for WAAM and switching to another shielding gas might contribute to reducing it. Unlike the PBF technologies, the raw material used by WAAM is steel wire that can be produced at significantly lower cost and most likely also energy use than metal powders. Thus, it is not straightforward whether the use of AM or more specifically WAAM at the processing stage alone including relevant direct inputs will result in higher or lower energy efficiency of production.

It is inherently difficult to assess the carbon impact of a manufacturing technique like WAAM, as the functional unit to be compared is hard to define (Bauer et al. n.d.). If only material output (e.g. 1 kg of manufactured steel product) is used as the functional unit, WAAM fares poorly as compared to other steel processing technologies. Producing bulk-shaped steel objects will always be more energy-efficient when using conventional techniques, but WAAM is capable to produce complex and delicate 3D objects that can serve the same envisioned purposes with substantially less material. WAAM's strength is therefore rather to be found in its potential to produce more lightweight and material-efficient structures and components than possible using conventional steel processing technologies. However, competing technologies also evolve further and become more material efficient.

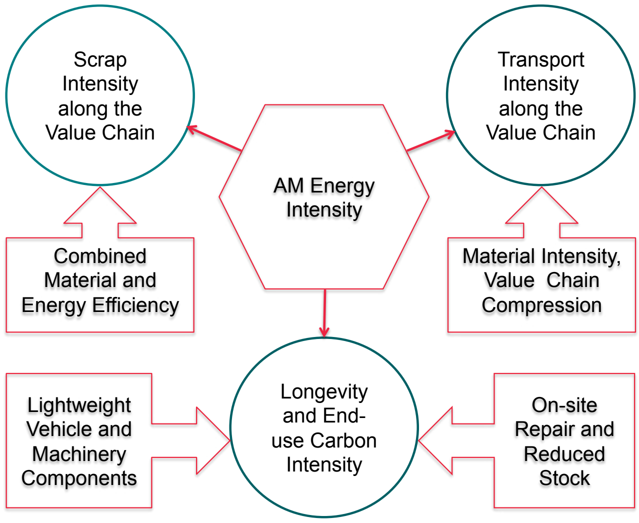

Figure 1. Potential streams and drivers for reducing the energy and carbon intensity through AM in metal processing along the value chain.

Due to the early stage and visionary nature of the technology, it is difficult to estimate its carbon significance (Bekker et al. 2016). The relevant carbon significance depends on the specific manufacturing process to be replaced. In terms of absolute emission reductions, printing and adjusting components on site would reduce emissions from logistics, overproduction and material waste handling.

Less than in terms of the quantitative numbers for specific parts produced, the potential of WAAM is based on qualitatively altering the production process and enabling both the manufacturing of uniquely shaped and therefore less comparable functional units and the repair and alteration of existing components, machines and installations. Thus WAAM needs to be considered more from a strategic point, especially in the light of how far such a technology might help to retrofit the existing industrial infrastructure for future, low carbon-oriented production processes.

In terms of the geographical allocation of various stages of steel value chains, it is deemed possible that some degree of reshoring might occur, so that the wires used for steel AM and simple conventionally produced structures that can then be assembled via WAAM can be produced within the region of final use and the actual manufacturing process occurs on or near the site where the product is required (Bauer et al. n.d.). Therefore, steel production will most likely be influenced to a lesser extent than the manufacturing of steel components. This might go hand in hand with a further shift from large-scale production plants (like those of the basic steel industry) to smaller facilities.

The unique appeal of a technology to quickly manufacture consecutive innovative prototypes and "produce personalised high quality products with the batch size of one" (Griffiths et al. 2016), for example for new machinery, might well increase the speed by which other new technologies are developed and

Table 3. Value chain-wide energy intensities of various products.

	Aerospace Components	Ground Vehicle Components	Stationary Machinery Components	Construction Components	Onsite Production	Onsite Repair
Processing Energy Efficiency	++ Titanium, aluminum	++ Aluminum, steel	++ Steel	++ Steel	– Steel	+++ Steel
Supply Chain Material Efficiency	+++	+++	+++	+++	+++	+++
Supply Chain Transport Efficiency	+	+	+	+	++	+++
End Use Energy Efficiency	+++	++	+	–	–	–

introduced. Such an effect can either be ecologically highly beneficial or devastating, depending on the resulting growth effects and the replacement potential for older technologies. The political and economic framework can have strong influences on these.

Case Study: Development and Properties of WAAM

PBF as an AM technology with metals has so far been rolled out in particular by aerospace industries and for medical implants. However until recently, this has happened only for relatively small structures, owing to the limitations of the necessary size of the required sealed building chambers. So far, owing to the substantial economic incentives for ultimate weight reduction with aerospace applications, the focus has been on the use with aluminum or, in particular, titanium. Thus, aerospace applications have been an important driver for the increasing development and application of AM with metals.

As a recently introduced innovative steel processing technology, WAAM is the focus of one of the Steel Case Studies within the REINVENT Project (Bauer et al. n.d.). The objective of the REINVENT Project which started in December 2016 and that will end in November 2020 is to focus on the decarbonisation of the meat and dairy, paper, plastic and steel sectors for which decarbonisation has been explored to a somewhat lesser extent. The particular interdisciplinary approach deals with the respective entire value-chains and non-technological factors of relevant innovations.

WAAM is basically an innovative combination of industrial welding robots and wires optimised for WAAM as the mechanical hardware, with computers and software that translate three-dimensional CAD designs into movement of such machines.

WAAM is a comparatively simple method that uses well-established welding as a technology to deposit metal droplets, which are then allowed to cool down, before another layer of droplets is deposited. Via WAAM technology, metal layers are continuously welded on top of each other by a six-axis robot arm controlled by special software (Bekker and Verlinden 2018). For the welding, big volumes of inert shielding gas like argon are necessary to provide the protective atmosphere required. In terms of mass, the use of argon is roughly similar or even larger than the steel that is being deposited. This makes the production process about twice as energy intensive as conventional methods for producing steel parts (Bekker and Verlinden 2018).

WAAM allows to manufacture structures of almost any shape and size making production very individualized and flexible. The WAAM technology is particularly interesting in terms of the associated freedom to design and produce large structures with high material efficiency (Camacho et al. 2017).

WAAM amongst others is used by the technology company MX3D for producing medium-sized lightweight steel structures, like the pedestrian bridge made from stainless steel for final installation in the City of Amsterdam (Joosten 2015). MX3D is a Dutch start-up company that co-operates with the steel industry but is independent in developing the technology. Therefore, this endeavour provides valuable insights about innovative entrepreneurial activities in a more established industry. Although MX3D amongst others works together with ArcelorMittal, it is so far entirely owned by its founders and employees. This is unusual in the manufacturing and basic materials industries, where technical innovations are usually created by the R&D departments of large companies (Glossner and Leupold 2016).

The development impulse for the WAAM bridge project did not emerge from one of the large steel producers or manufacturing companies, but from an art and design studio (Joris Laarman Lab) and its cooperation with the software-focused start-up MX3D.

The pedestrian bridge made of stainless steel for the City of Amsterdam by MX3D is 12 m long and 6.3 m wide, consisting of 4.5 tons of welded stainless steel (Rodrigues et al. 2019). It took 6–7 months to manufacture the bridge, and it was also meant to demonstrate the leap in skills that the start-up MX3D had achieved.

As there is still a lot of material research that needs to be done, and the technology still needs to be further developed, it was deemed premature to demonstrate the technology's potential to build the most light-weight bridge (Bauer et al. n.d.). Instead, a design was chosen that showcases all the design liberties the technology offers. The bridge was manufactured as individual pieces of one meter in length that were subsequently welded together.

The bridge by MX3D demonstrates that for applications like construction, suitably high surface and structural qualities can be obtained. The look of the unprocessed welded surfaces may even add some artistic appearance. For other applications like machinery components, the surface roughness is too harsh and some subtractive post processing is inevitable. However, this will result in substantially less scrap metal than conventional subtractive processing from full.

The main innovation of WAAM does not rest with the well-established industrial welding robots and only to some extent with the metal wires used. Rather, the translation of CAD designs into the movement of such welding robots makes up the innovative core of WAAM. So far, software used for WAAM appears to be somewhat 'hand-made' and one decisive challenge is to turn this into an automated process that requires as little human intervention as possible (Bauer et al. n.d.).

As compared to other AM technologies, WAAM has been assessed to be superior in terms of platform flexibility, workpiece size and mechanical properties as well as cost. However, the achievable workpiece complexity and accuracy may be higher using other AM techniques (Bauer et al. n.d.).

As compared to other additive manufacturing technologies, operating costs are lower because stainless steel wire is ten times cheaper than stainless steel powder. However, the technology has yet to be rolled out and tested on a large scale (Bekker et al. 2016). With regard to production cost at the processing stage, there is evidence that depending on feedstock prices utilising WAAM tends to be cheaper than machining from solid. Likewise, using WAAM is cheaper than PBF given that the latter are more expensive than machining from solid due to high capital and feedstock cost (Martina and Williams 2015). Further to this, a switch away from argon to a less energy intensive shielding gas like CO_2 might alter the balance more in favour of WAAM.

The main advantages of WAAM over the various PBF technologies include the non-existence of boundaries to the size of objects, which results from no need to use a sealed building chamber. Besides, the deposition rate (build speed) is significantly higher than with PBF technologies at lower investment and consumables costs, because steel wire is much cheaper than powder. Moreover, WAAM may solve problems with structural designs that are out of reach with conventional production technologies (e.g. for aircraft), creating a value that was previously impossible (Bauer et al. n.d.).

The potential for the diffusion of WAAM to different industries, companies and purposes seems to be high (Ashraf et al. 2018). There are no known limits to the size or geometric properties of the welded structure, thus it can be used for a multitude of different applications. The software can be adapted in such a way that no special training or expertise is required to utilise it. The welding robots are relatively small and flexible and can be operated with different types of steel or other metals. Initial tests show no significant disadvantages in the strength or ductility of the welded material.

WAAM opens both a door towards more creative use of steel in construction applications and to replace less recyclable materials like concrete. Besides, it offers options for on-site construction of complex metal structures by combining simpler processed metal parts that have been pre-built using conventional processing. Another potential application for this technology is on-site repair of existing metal structures like bridges or industrial installations, which allows to reduce the need for replacing these, thus extending the lifetime. However, this has so far been more of theoretical than practical significance as it has not been explored sufficiently (Rodrigues et al. 2019).

Beyond the construction industry, some of the market potential of WAAM is about spare parts and repair demand. This means in-house full-fledged or temporary repair of components of machinery and installations using WAAM instead of replacing them with stocked spare parts. In the steel or railway industry or with offshore installations, production standstills are very costly. Generally, where equipment is utilized 24/7,

Figure 2. Quality control on the MX3D stainless steel pedestrian bridge depicting features of the design as well as patterns of welding layers reminding of structures shown in some science fiction movies (source: MX3D).

huge numbers of spare parts are stocked to prevent a standstill of production in case of any breakdown. However, some of those parts might never be used (Bauer et al. n.d.).

WAAM with steel is mentioned in the literature as an application that allows to manufacture parts at low cost, even though some authors regard its core area of application for large parts and complex geometries (Rodrigues et al. 2019). For certain applications, hybrid concepts of components produced by different production technologies are likely where each component is produced using the most adequate production technology. (Bauer et al. n.d.)

It can be concluded that there may at least be niche markets in steel processing in the machinery production and construction industries where AM, and in particular WAAM, might be game changers and result in disruptive transformations of particular value chains. However there are authors who are more optimistic expecting that WAAM may become the most widely used AM technology (Rodrigues et al. 2019). Notwithstanding this, the overall impacts of this innovation are yet unclear and might only become apparent within the next 2–3 decades.

Conclusions

While the specific global utilisation of titanium, aluminum and steel varies substantially, it can be argued that in absolute numbers steel processing is much more important to be made more material and energy efficient by AM than that of aluminum and namely titanium. However the particular properties of aluminum and titanium create immediate incentives to use AM and to further develop its applicability. R&D efforts, increased utilisation and the resulting economies of scale that were initially focused on aerospace applications with titanium for maximising weight reduction of components or on medical implants might horizontally trickle to AM applications with aluminum or steel. Likewise owing to the initial strength of WAAM application with steel, some horizontal trickling is conceivable towards processing of aluminum and titanium. However based on the current state of AM with metals, it remains to be seen how this will unfold.

Additive Manufacturing (AM) with metals has primarily evolved as PBF, where objects can be formed out of metal powders using laser or electron beams. However these processing technologies have their limitations in terms of minor deposition rate and limited size of object resulting from the size of the building chambers required. Nevertheless it has greatly evolved using aluminum and titanium for maximum weight reductions with components for aviation and space missions.

Wire Arc Additive Manufacturing (WAAM) combines industrial welding robots, wires for welding and software that translates CAD designs of objects into the movement of welding robots to overcome these limitations. At the same time, wires for welding are cheaper than metal powders. What makes the WAAM technology particularly interesting is the associated freedom to manufacture relatively big and uniquely designed structures that previously were impossible using conventional steel processing technologies combined with a higher level of material efficiency along the supply chain over subtractive manufacturing techniques (Camacho et al. 2017, Tang et al. 2016).

The carbon significance of using AM with metals depends on the specific product considered and manufacturing process to be replaced and the resulting comparative savings in metal use for a specific product. The main drivers of impacts of AM on the carbon intensity beyond direct energy use of metal processing reside with material use, geographical supply chain characteristics and the energy intensity of final product usage.

Summing up the aforementioned, an assessment of the potential carbon impacts of AM and WAAM involve particular methodological difficulties with metal structures which were impossible to be produced using conventional processing technologies. Moreover the mentioned spillovers to carbon emissions during other phases of metal value chains increase the complexity of lifecycle-wide analyses and deserve additional projects that are sufficiently focused on such assessments. This mainly refers to the material efficiency of processing as such in terms of energy intensity and logistics related to material efficiency and geographical properties of value chains. Moreover reducing the weight of metal structures may have substantial impacts during the use phase. However at its current state of development, the carbon impacts of WAAM can not sufficiently be assessed.

Taking account of the early development stage of additive metal manufacturing, the exact extent to which subtractive processing of steel might in future be substituted for by AM is still unclear. Thus it will require further research and development and diffusion of this technology in order to figure out what the full potential of AM might be.

It remains to be unclear whether AM technologies will help to decrease the total socioecological metabolism of metal value chains. It might as well be that AM with metals will cause significant increases in total metal consumption, thus a cautious and ongoing monitoring and assessment appears advisable. AM is a typical case of a Collingridge dilemma (Liebert and Schmidt 2010) in technology assessment: Effects are difficult to predict as long as the technology is insufficiently developed or widespread. However, the more widespread the technology has become, the more difficult it is to change its further development or even alter the path altogether.

The MX3D Case Study of the utilisation of WAAM with steel and literature on AM with metals in general hint at the significance of a system-wide perspective that takes interrelations between various stages of the value chain into account. Focusing on energy intensive upstream basic industries is important for the vast volumes of carbon emissions concentrated at single plants. However such plants do not produce for final demand. Primary and secondary steel production is undertaken as a matter of derived demand, depending on the product mix of final demand and related consumer preferences and properties of products as well as changing processing technologies. Thus decarbonisation does not only depend on upstream processes.

While the stage of development of AM in general is still too premature for drawing any final conclusions, AM has the potential to transform the processing of certain metal products in a way that may reduce the need for metals and increase the energy efficiency of some products during the use phase.

Thus due to the early stage of implementation and visionary nature of the technology as well as the mentioned complexity of its interplay with the carbon intensities of other stages of metal value chains, it is difficult to estimate the total carbon significance of AM or WAAM (Bekker et al. 2016). This means that there is a substantial knowledge gap regarding these aspects that will require further applications of AM and related life cycle analyses to be performed.

Nevertheless it can be expected, that the contribution of AM to decarbonisation of metal value chains can be very substantial in cases where it may allow to combine:

- Higher material efficiency during the processing stage over conventional subtractive manufacturing;
- A geographical compression of value chains by reshoring certain steps of them; and
- Increased energy efficiency during the end use phase of the respective products by reducing their weight.

Even if not all of the mentioned positive effects can be achieved simultaneously, there could still be a significant contribution of AM to decarbonisation.

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