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The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach

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ABSTRACT

The effect of disruptive technologies unrelated to the energy sector, such as additive manufacturing (AM), tends to be overlooked in energy scenarios. The present research assessed the potential effect of AM on the global energy demand in four energy scenarios for 2050 with extended versus limited globalisation and limited versus extensive adoption of AM. These scenarios were developed and applied for two cases, namely the aerospace sector and the construction sector, analysing the effect of AM on each phase in the value chain. In the aerospace sector, energy savings of 5–25% can be made, with the largest effect in the use phase because of weight reduction. In the construction sector, energy savings of 4–21% are achievable, with the largest effects in the feedstock, transport and use phases. Extrapolated to the global energy demand in 2050, a reduction of 26–138 EJ/yr, equivalent to 5–27% of global demand is achievable. It is recommended that energy policymakers should consider integrating AM and other disruptive technologies, such as robotics and the Internet of Things, into their long-term energy planning, policies and programmes, including Nationally Determined Contributions under the Paris Agreement on climate change.

1. Introduction

1.1. Disruptive technologies and future energy demand

The future of energy is widely studied and discussed in business, academia and politics, and scenario building is often used in these studies and discussions. However, the effect of emerging technologies – such as additive manufacturing (AM), big data, robotics, the Internet of Things and autonomous driving – on the future energy consumption is often overlooked. Even long-term energy scenarios and normative visions are usually based on familiar technologies, directly related to the energy industry. This gap may result in energy policymakers stimulating only traditional sectors rather than also looking at adjacent areas of innovation that can be extremely effective in reducing energy demand while matching important co-benefits (Nagji and Tuff, 2012).

In an effort to close this gap, this article presents a bottom-up assessment of the potential effect of one such disruptive technology, namely AM, on the global energy demand in 2050. AM was chosen because it is disruptive and paradigm changing for manufacturing, logistics, product design, intellectual property, local production and mass customisation.

1.2. Additive manufacturing

Additive manufacturing, popularly known as 3D printing, is the process of building objects bottom-up, one layer at a time. AM is an umbrella term for a group of technologies (Cotteleer, 2014). Table 1 and Fig. 1 present overviews of AM processes along with the related technologies and the materials used. As can be seen, the range of techniques and materials is extensive. Traditional subtractive manufacturing techniques build objects by cutting or machining raw materials into the desired shape, after which several objects are assembled to form the final product. Other mass production techniques, such as injection moulding and metal stamping, produce less waste but require large production volumes.

3D printing involves three essential phases (Campbell et al., 2011). First, a digital 3D model is designed and converted into a standard AM format file. Second, this file is sent to the 3D printer, where it is

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Table 1
Overview of additive manufacturing processes, the materials used and the technologies involved (Manyika et al., 2013; DOE, 2015).

AM process type	Brief description	Materials used	Technologies
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed	Metals, polymers	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), direct metal laser sintering (DMLS)
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Metals	Laser metal deposition (LMD)
Material extrusion	Material is selectively dispensed through a nozzle or orifice	Polymers	Fused deposition modelling (FDM)
Vat photo polymerisation	Liquid photopolymer in a vat is selectively cured by light-activated polymerisation	Photopolymers	Stereolithography, digital light processing (DLP)
Binder jetting	A liquid bonding agent is selectively deposited to join powder materials	Polymers, foundry sand, metals	Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)
Material jetting	Droplets of build material are selectively deposited	Polymers, waxes	Multi-jet modelling (MJM)
Sheet lamination	Sheets of material are bonded to form an object	Paper, metals	Laminated object manufacturing (LOM), ultrasonic consolidation (UC)
Inkjet-bioprinting	A nozzle deposits tiny dots of a combination of scaffolding material (e.g. hydrogel) and living cells	Biomaterials, human cells	Inkjet-bioprinting

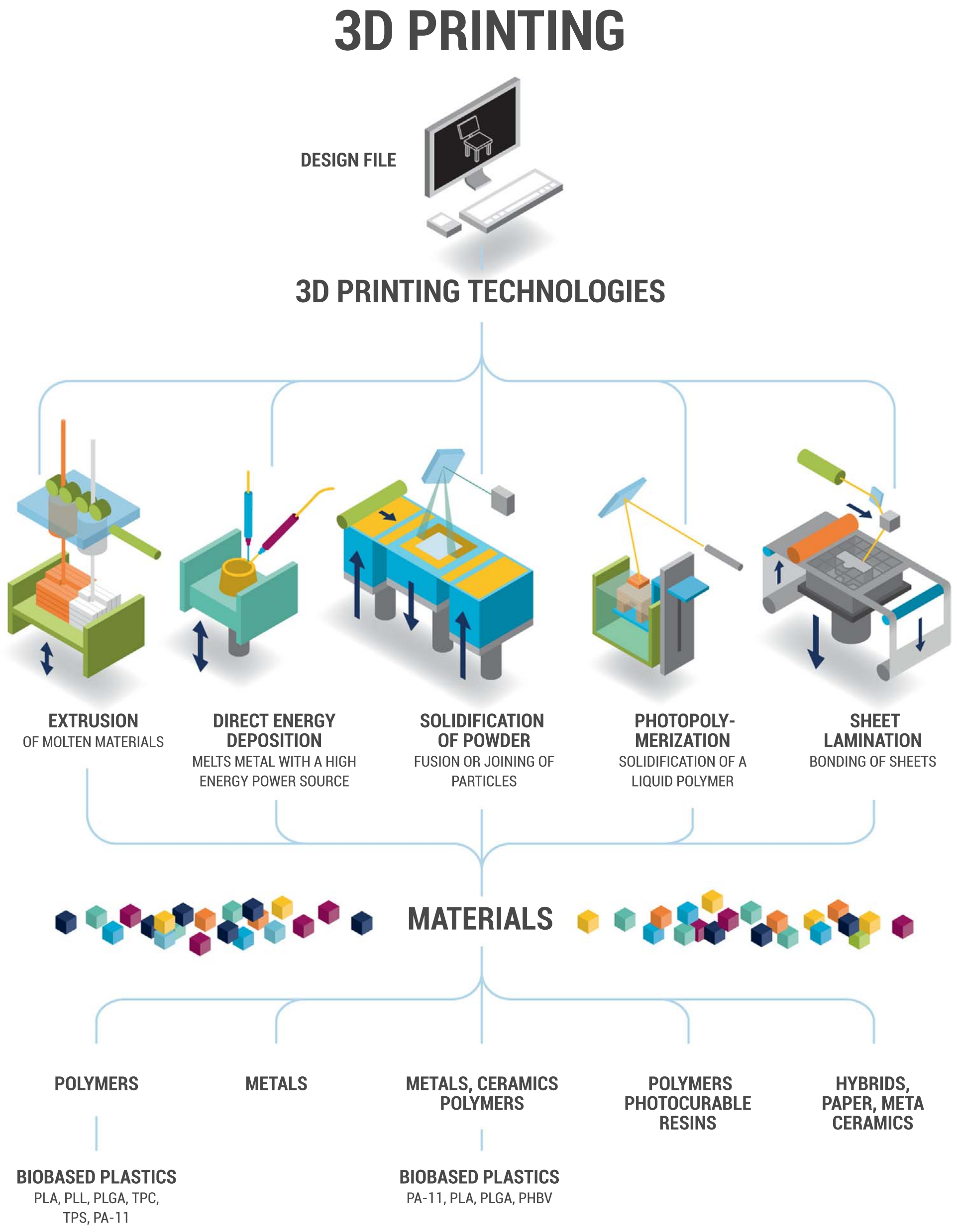

Fig. 1. Overview of additive manufacturing (*3D Printing*) technologies and the materials used, displaying the wide range of techniques and materials.

adjusted to the desired shape, position, orientation and scaling. Third, the object is built using a layer-by-layer mechanism.

AM has a unique selling point over subtractive manufacturing: it enables the production of complex products and small series. Other advantages include low potential energy consumption during production, reduction of waste material, reduced time to market, strong opportunity for innovation, and great potential for customisation, part consolidation and a final product with less weight (DOE, 2015). In energy terms, AM can be more responsive to demand management with concentration of high-energy production during hours where renewable and/or low-cost sources are available.

The weight reduction achieved through AM can have a significant effect on the transport sector, as lighter components generally reduce fuel consumption. The enhanced design freedom can lead to radical changes in a product and a significant improvement of its performance. For example, GE's LEAP fuel nozzle (a crucial part of an aeroplane's engine) is 25% lighter and five times more durable when printed in one piece using AM instead of being assembled from 20 different components (GE, 2013; Kellner, 2014). Thought is also being given to deploying AM for full biomaterials-based production of, for example, houses (van Wijk and van Wijk, 2015).

1.3. Markets for additive manufacturing

3D printing, as AM was originally called, was conceived in the 1980s as a means for rapid prototyping. It has since gained enormous popularity, and in the last five years both market size and applications areas have exploded. AM is growing by 33% a year and is starting to cover all sectors of industry (Wohlers, 2014). The market size is huge: more than USD 20 billion in 2020, according to a compilation by Columbus (2015) (see Fig. 2). Fig. 3 shows the percentage of printing revenues of the end-market in 2014, showing the widespread application of 3D printing. The largest segments are consumer products and electronics (22%), motor vehicles (19%), medical/dental (16%) and industrial machines (13%). The aerospace sector accounts for 10% of the revenues (Wohlers, 2014). Various reports conclude that mass adoption of AM is expected within the next 10 years (Deutscher et al., 2013; Manyika et al., 2013). The Economist (2012) referred to AM as ‘the third industrial revolution’.

Top-down approaches have been used to develop sustainability perspectives of AM for the mid term by, for example, Gebler et al. (2014). An extensive literature review of AM forecasts (Campbell et al., 2011; Columbus, 2015; Cotteleer and Joyce, 2014; Cotteleer, 2014; Deutscher et al., 2013; DOE, 2015; Gebler et al., 2014; Heller, 2014; Manyika et al., 2013; PriceWaterhouseCoopers, 2014; Roland Berger, 2013) revealed that there are two fundamental types of effects that AM can have on the energy demand in industry:

1. Simplification of the supply chain. Supply chains can be improved by eliminating the need to produce components at different sites. With AM, the final product can be manufactured in proximity to the end-user. The length of the supply chain can be shortened, reducing energy consumption during transport. The establishment of local manufacturing centres enables on-demand production and faster shipping, and thus reduces overall delivery times. The inventories needed in operation & maintenance services, such as the spare parts market and other aftermarket services, are also reduced. On-demand production also enhances flexibility. Finally, AM reduces the waste material in the production process, lowering the amount of raw materials needed and the energy consumption associated with its extraction.

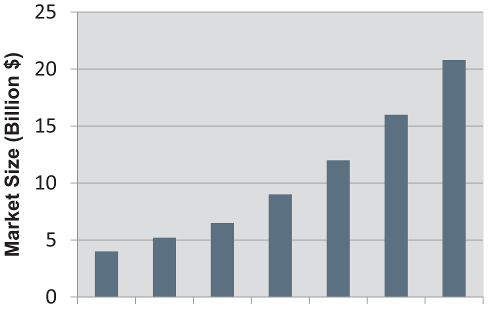

Fig. 2. Additive manufacturing market size and forecast to 2020 (Wohlers, 2014), predicting a market size of USD 20 billion by 2020.

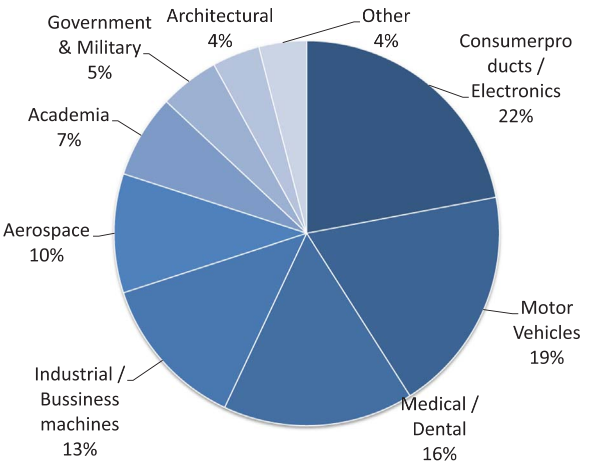

Fig. 3. Distribution of additive manufacturing revenues over business sectors showing the widespread application (Wohlers, 2014).

2. Unlocking ways of developing new products that demand less energy over their lifetime. Examples of product evolution can be found in new product designs that give rise to better energy efficiency; for example, lighter aeroplane parts, which reduce fuel consumption.

The combination of the supply chain evolution and the product evolution opportunities provided by AM holds the potential to reduce energy consumption, shorten lead times and simplify supply chains.

1.4. Research question and aim

The key question addressed by the present research was: *What is the potential effect of additive manufacturing (AM) on the global energy consumption?* The aim of this article is to encourage researchers, business leaders and policymakers to reflect on how the implementation of technological breakthroughs might influence global efforts to fight climate change.

The effect of AM on future global energy consumption was investigated by working with two of Shell's (2008b) energy scenarios for 2050 in two variants, namely limited and extensive adoption of AM. These scenarios were then implemented for the aerospace and the construction sector. For these sectors, the effect of AM on each phase in the value chain was carefully analysed.

2. Methodology

2.1. Deductive exploratory scenario building

Exploring the effect of an emerging technology is a challenge for which traditional forecasting or backcasting approaches are inadequate. Forecasting is not appropriate, as it is mostly based on dominant trends (Dreborg, 1996) and does not facilitate disruptive technologies. Backcasting is also inappropriate, as it starts by defining a desirable future vision or normative scenario and then looks back at how this desirable future could be achieved (Quist and Vergragt, 2006);

however, a ‘desirable future’ is hard to define with disruptive technologies and there is a risk of making biased choices.

This study used deductive explorative scenarios (Shell, 2008a, 2008b; Van der Heijden, 1996). Well-designed scenarios are used to explore different future alternatives, broadening the perspective of evaluation and improving the robustness of relevant decisions. Usually two critical uncertainties are selected and four scenarios are based on the extremes of each of these uncertainties.

This study deviated slightly from that approach. As supply chain effects and globalisation/localisation are core assets of AM, the socio-political atmosphere in the world is an important uncertainty and a main key driver that could affect AM. That made the Shell Energy Scenarios for 2050 *Blueprints* and *Scramble* (Shell, 2008b) very useful, as they represent more versus less global cooperation. These different amounts of global cooperation influence the innovation sharing and innovation drivers, which are key to the penetration of disruptive technologies, such as AM:

- Innovation sharing: how well will nations and companies collaborate or share technology advancements? Will open-source technologies flourish under these conditions?
- Innovation drivers: will decisions be market driven, or will governments use mandates to implement different technologies in the search for a different objective, such as energy security?

Four scenarios were built as presented in Fig. 4. Two are based on the *Scramble* scenario, with high and low degree of penetration and effect of AM (scenarios SH and SL); the other two are based on the *Blueprints* scenarios, also with high and low degree of penetration and effect of AM (scenarios BH and BL).

2.2. Cases and extrapolation to other sectors

Two cases, each involving an entire global economic sector, were worked out: the aerospace sector and the construction sector. These sectors are quite distinct from each other, as they have significantly different technological bases and the expected implications of AM are also significantly different. Five steps (see Fig. 5) led to the results of this study:

1. The energy use in each phase in the value chain of the sector was analysed for 2015 and projected to 2050 for the *Scramble* and *Blueprints* scenarios, giving two base cases.
2. The maximum effect that AM can have on the energy consumption was calculated for the *Scramble* scenario and the *Blueprints* scenario based on references and assumptions.
3. Two sets of AM penetration and effect (high and low degree) for each phase in the value chain were overlaid on the maxima as determined in step 2.
4. The absolute reduction in the energy demand compared to the base case was calculated, as was the relative reduction. The case results were used to estimate the reduction in energy demand in other industry sectors and in the global final energy demand in two ways:
   - First, by averaging the energy savings (in %) from the aerospace sector case and the construction sector case and assuming this average is representative of the total global energy demand in 2050.
   - Second, by using the value chain analysis of both cases and assigning the relevant elements to other economic sectors, followed by calculating the energy savings (EJ/yr) per sector and summing the savings of all sector to the global energy demand savings, followed by dividing by global demand without AM to the corresponding scenarios.

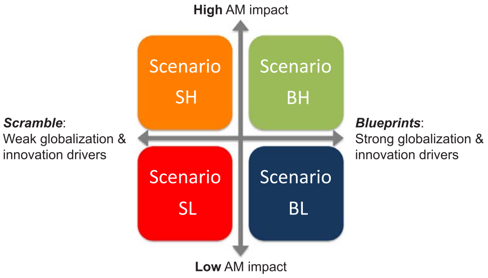

Fig. 4. Scenarios developed in this study, according to two dimensions: global cooperation – *Scramble* versus *Blueprints* scenarios (Shell, 2008b), and penetration/effect of additive manufacturing (high or low).

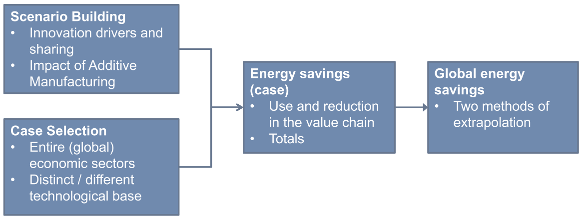

Fig. 5. Methodology used in this study: four scenarios are built using innovation drivers and effect of AM. In parallel, two global economic sectors are selected as cases. Subsequently energy use and reduction potential is calculated for each case for all four scenarios, and these savings are extrapolated to all global economic sectors.

These calculations are rather crude and simplified, leaving the task of integrating and embedding them in more detailed models to specialists in other sectors.

Note: throughout this article, total final demand rather than primary energy is used.

3. Scenarios and case descriptions

Four scenarios were developed. They are described below and briefly summarised in Fig. 6.

3.1. Scenarios

The main points of the socio-political atmosphere of Shell's *Scramble* and *Blueprints* are:

- *Scramble* represents a world of deep geopolitical distrust and a clear focus on national energy security. Decision makers are driven by immediate pressures to secure their own and their allies’ energy supply. Real action towards climate change and energy efficiency is postponed until the moment that major climate events necessitate change. The competition between national governments – the principal actors in *Scramble* – is focused on securing favourable terms of supply and access for their energy companies. Although there is a strong rivalry among governments, they align with each

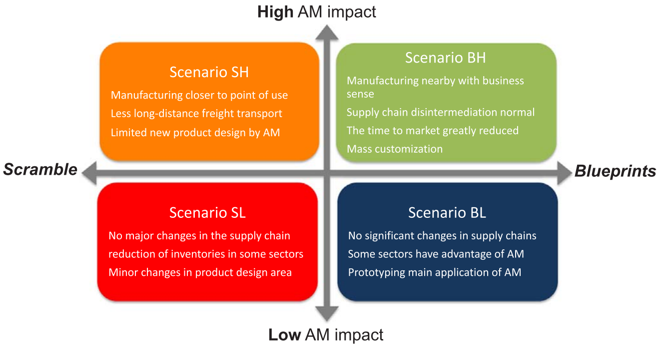

Fig. 6. Summary of the characteristics of the four scenarios.

Table 2
Global primary energy use in 2050 for six economic sectors, in *Scramble* and *Blueprints* scenarios (Shell, 2008b).

Economic sector	Global primary energy use (EJ/yr)	
	Scramble	Blueprints
Transport	176	140
Residential	122	117
Agriculture & other industries	85	84
Heavy industry	80	79
Services	40	39
Non-energy use	54	55
TOTAL	**557**	**513**

other wherever their interests coincide.

- *Blueprints* represents a world in which new coalitions are formed based on market interests. These do not necessarily reflect common interests, but build on a combination of supply concerns, environmental interests and associated entrepreneurial opportunities. A broader fear about lifestyle deterioration and economic growth forges new alliances that promote action in both developed and developing countries, with energy efficiency playing a major role.

The associated energy demand in 2050 over six economic sectors according to the Shell scenarios is given in Table 2. The *Scramble* scenario has a total primary energy use of 557 EJ/yr, which is 10% higher than the 513 EJ/yr in the *Blueprints* scenario. In both scenarios, the transport sector and the residential sector are the largest energy consuming sectors, consuming 176 and 122 EJ/yr (32% and 22% of the total), respectively, in the *Scramble* scenario and 140 and 117 EJ/yr (27% and 23% of the total), respectively, in the *Blueprint* scenario.

3.1.1. Scenario SH – Scramble with a high degree of AM

In an international atmosphere of diminishing cooperation and major asset holders accumulating increasing amounts of power, the governments of developed countries see AM as a way to restore independence and safeguard national security. Governmental decisions override the free market and create artificial markets in which the full potential of AM is achieved and the supply chain effects of AM can flourish:

- Manufacturing is brought closer to the point of use, especially in Western countries, which results in reduced dependence on Southeast Asia and the creation of new jobs.
- As a consequence, transport of freight over long distances is reduced. Supply chains are streamlined, raw materials are shipped directly to the point of use and the outsourcing of production to cheap-labour countries is avoided whenever possible.
- Once the AM market reaches maturity, other benefits in the supply chain arise, for example increased responsiveness and flexibility, the on-demand production of spare parts and the associated reduction of inventories in operation & maintenance businesses, and the possibility to exploit economies of scope as opposed to economies of scale.
- On the product evolution side, the effect of AM is not equally felt: whereas reduced lead times benefit most industries, the focus of governments and businesses remains on reducing their dependence on other countries and global sources of energy. Therefore, the potential of AM in the area of radically new product designs is not fully exploited and remains the niche of highly specialised sectors, such as the aerospace and medical sectors.
- AM develops into a technology that can deliver performance, quality and production quantities and fulfils key performance indicators in a satisfactory manner in most industrial sectors. The emerging applications of AM in, for example, the aerospace industry indicates that this level of development is potentially achievable.

3.1.2. Scenario SL – Scramble with a low degree of AM

Under this scenario, the full potential of AM is not achieved. Although high-end niche applications benefit from some characteristics of AM, the lack of interest in collaborative and open-source development among low-end users eventually prevents AM from reaching mass market applications. All in all, the technology does not lead to major changes:

- There are no major changes in the supply chain, although the reduction of inventories is achieved in some sectors.
- Minor changes are achieved in the product design area: rapid prototyping is widely used but the optimisation of geometrically complex structures improves only a limited range of applications.

3.1.3. Scenario BH – Blueprints with a high degree of AM

Industries worldwide quickly identify the advantages and the potential of AM. The initial hype that led to the new possibilities opened up by AM in highly specialised industries is quickly translated into major research schemes in the automotive and construction sectors and into the manufacturing of industrial and consumer products all over the world. Overall, the combined effect of AM on supply chains and on the evolution of new products gives rise to completely new business models.

- Manufacturing is brought closer to the point of use only when it makes business sense, with most decisions being driven by the market (i.e. AM making it cheaper to produce certain products nearby).
- Supply chain disintermediation, bypassing wholesalers and distributors, becomes the norm, with the features of AM now favouring the vertical integration of some businesses.
- The time to market is greatly reduced in many sectors. This market responsiveness allows for a closer alignment with user preferences. Combined with the possibility of mass customisation, customers become increasingly empowered.
- AM develops into a technology that can deliver performance, quality and production quantities and key performance indicators in a satisfactory manner in most industrial sectors.

3.1.4. Scenario BL – Blueprints with a low degree of AM

The awareness of global issues and the increase in mutually beneficial collaborative efforts quickly leads to the development of an ecosystem in which innovative technologies thrive. Renewable energy systems, autonomous vehicles, AM, advanced robotics and the automation of knowledge work receive considerable attention and a large economic stimulus during the 2020s. The hype that surrounded AM during its development stage fades away as other disruptive technologies prove to be more valuable substitutions in many areas and the expectations surrounding AM are not met. Accordingly, interest in AM slowly disappears.

- No significant changes are achieved in supply chains. Increasing globalisation is the norm, with companies outsourcing a larger part of their production chains.
- Only certain sectors continue to take advantage of AM and they do so much in the same way as they were doing in the 2010s, that is, they use AM for the small-scale production of complex components.
- Prototyping remains the main niche of AM in most sectors, effectively cutting lead times and allowing companies to economically iterate their products before launching them.

3.2. Case I: aerospace sector

Here, the aerospace sector is defined as the manufacturing, use and

Fig. 7. The value chain of the aerospace sector, from feedstock to end of life.

dismantling of all commercial aeroplanes worldwide. This includes the collection of raw materials, transport and manufacturing activities as well as the use (e.g. fuel requirements) and dismantling of aeroplanes. The value chain of the sector, in particular the aircraft market, is presented in Fig. 7. In the processing phase of the value chain, new manufacturing possibilities emerge that lead to the production of complex designs that cannot be achieved using traditional manufacturing techniques. This leads to more efficient designs and reduces energy consumption during the manufacturing process.

The following assumptions were made in order to construct the case for the year 2050, a year for which we assume that all currently potential applications (such as printing aircraft wings, complex engine parts, etc.) are indeed performed by AM.

3.2.1. *Feedstock*

- Aluminium, steel and titanium alloys make up 81% of all materials used as feedstock (Michaels, 2013). The weight-specific energy required to produce these feedstocks is provided by the Global Energy Assessment (GEA, 2012).
- Literature suggests that it is possible to reduce the weight of components by up to 64% when AM is used (Coykendall et al., 2014). When the aircraft is taken into consideration, one third of that 64% (i.e. 21.3%) was considered feasible in this study for the empty weight.
- Buy-to-fly ratios are usually in the range of 6:1–33:1 (Coykendall et al., 2014; GEA, 2012), implying that 83–97% of the feedstock needed to produce a component for an aeroplane is wasted. Airbus claims an average buy-to-fly ratio of 10:1 (Richter, 2016). As AM allows for zero waste production, it is assumed that AM will result in feedstock materials savings of 90% in the entire fleet by 2050, with the same proportion of metals as in current production (Galgani et al., 2014). The 21.3% reduction in component weight is included in that 90%.
- It is assumed that the energy required to produce each ton of feedstock will be reduced by 30% in 2050. Considering this 30% reduction, the embedded energy in aluminium, steel and titanium alloys in 2050 is 52, 12 and 286 GJ/ton, respectively.
- It is assumed that metal use (aluminium, steel and titanium alloys) will grow proportionally to fleet growth.

3.2.2. *Transport*

- The energy for shipment is assumed to be 65 J/(kg*km) for both 2015 and 2050 (Galgani et al., 2014).

3.2.3. *Processing*

- It is assumed that 35% of the energy needed for processing can be saved by AM, based on the comparison of energy costs of AM by Baumers et al. (2011) using EBM (electron beam melting), a commonly used process for making metal components.

3.2.4. *Use*

- An average annual traffic growth of 5.2% has been predicted until 2036 (Forsberg, 2014). An annual fleet growth of 4% for 2036–2050 is assumed, leading to an aircraft fleet that is five times as large by 2050.
- The Airbus A320 was chosen as the representative product of the aerospace industry.
- The aircraft's fuel efficiency (in litres per kg per km), operational range and payload weight (11,700 kg) remain unchanged.
- In the case of the Airbus A320, which has an empty weight of 42,400 kg, the 21.3% empty weight reduction (see Assumption 2 in the Section 4.1.1) equates to 9031 kg.
- Fuel use is directly proportional to aircraft weight, and weight reduction leads to fuel reduction. According to American Airlines (Lyons, 2011), reducing the weight of an aeroplane by 1 kg reduces the annual fuel consumption by 114 kg.

3.2.5. *Maintenance*

- Maintenance, repair and services account for 6.9% of the money spent in the industry, and this 6.9% is assumed to be the share of energy use for maintenance (IATA, 2011).
- It is assumed that AM could reduce the energy required for maintenance by 30% up to 2050, based on the reductions found in other phases in the value chain, such as processing.

3.3. *Case II: construction sector*

Here, the construction sector is defined as embracing the entire lifecycle of residential and commercial buildings, including the collection of building materials, the transport and construction of buildings, the use of buildings (e.g. heating and cooling) and their demolition. Fig. 8 shows the phases in the value chain, from feedstock to end of life. Space heating and cooling needs are included in the *Use* phase of the value chain, whereas other phases such as lighting and non-heat/cold-related electrical appliances of buildings are omitted.

The variety of buildings and construction materials around the world make it challenging to build a case based on an average building. For an educated estimation, the analysis by van Wijk and van Wijk (2015), who compared a 3D printed house and its traditional equivalent, was extended. The 3D printed house is considered a zigzag pattern of concrete, which saves raw material and increases insulation because of the air between the concrete layers. The respective assumptions for the calculations are as follows:

3.3.1. *Feedstock*

- Feedstock, transport and construction account for one quarter of the energy use in the construction sector (including the use of the building) (Nässén et al., 2007). One eighth of the energy used by the construction industry is used in feedstock and transport and one eighth is used in the construction phase itself (i.e. bricklaying and other activities performed at the construction site) (GEA, 2012).

- It is assumed that a 40% saving in materials can be achieved, as already demonstrated by a Chinese manufacturer of 3D printed houses (Sevenson, 2015). This is in line with van Wijk and van Wijk (2015), where 41–64% is assumed.

3.3.2. *Transport & construction*

- Transport energy is assumed to correspond to 5% of the total energy use in this sector.
- Transport energy is directly proportional to material weight.

3.3.3. *Use – heating and cooling*

- The use of the building accounts for 43% of the energy used in this

Fig. 8. Value chain of the construction industry, from feedstock to end of life.

Table 3
Material use, embedded energy in feedstock and 90% material savings by AM, together leading to energy savings for feedstock production in the aerospace sector in 2050.

Material	Projected material use in 2050 (1000 t/yr)	Material savings by AM (1000 t/yr)	Embedded energy in feedstock (GJ/ton)	Energy savings (EJ/yr)
Aluminium alloys	1335	1200	52	0.0624
Steel alloys	625	563	12	0.0068
Titanium alloys	245	220	286	0.063
Other[a]	515			
Total	2720			0.132

[a] Non-metal materials not evaluated in this study.

Table 4
Transport energy in 2050 for the aerospace sector and resulting energy savings. Transport energy calculate by specific shipment energy consumption of 65 J/kg/km (Galgani et al., 2014).

	Trajectory	Distance (km)	Weight (million kg)	Transport energy (PJ)
Without AM	Pittsburgh – Taiwan	12,400	2720	2.19
	Taiwan – Pittsburgh	10,300	272	0.18
Total				*2.37*
With AM	Pittsburgh – Toulouse	6500	272	1.15
Energy savings				*1.22*

value chain (GEA, 2012). Due to the new structure of the wall, the heating and cooling energy requirements will change. Using thermal conductivity and convection calculations, the higher thermal resistivity of the 3D printed walls resulting from the air pockets formed in the zigzag 3D printed structures, the walls are estimated to result in 32% less energy losses.

4. Results

The following subsections present the calculations of the base case for 2050 of the *Scramble* scenario. Similar calculations are made for the *Blueprints* scenario.

4.1. Aerospace

4.1.1. Feedstock

The 545 million kg of feedstock used by the aerospace industry today will have risen fivefold to 2.72 billion kg of feedstock by 2050. Of this feedstock, 81% are metals: 1335, 625 and 245 kt of aluminium, steel and titanium alloys, respectively (see Table 3). Using the assumed 90% raw material savings in metals in 2050: 1200, 563 and 220 kt of raw aluminium, steel and titanium alloys, respectively, can be saved. The embedded energy, using the assumption that 30% energy savings is achieved in 2050, in aluminium, steel and titanium alloys is 52, 12 and 286 GJ/ton, respectively (GEA, 2012). The energy saved in the feedstock process can be calculated by summing the products of material savings:

Σ[(feedstock saving) × (embedded energy)] = 0.132 EJ/yr.

4.1.2. Transport

The Airbus A320 is currently manufactured in various locations and finally assembled in Toulouse, France. The transport energy use was calculated for a typical supply chain, and then extrapolated to the whole sector. The shipment energy use is 65 J/kg/km (Galgani et al., 2014).

For an Airbus 320, the raw aluminium is obtained from Alcoa in Pittsburgh, USA (Alcoa, 2016), and transported 12,400 km to Taiwan, where the Aerospace Industrial Development Corporation produces all the composite panels as Tier 1 supplier (Chiu, 2014), whereby 90% of materials are discarded or taken up in other economic sectors. The panels are then transported 10,300 km to Toulouse (Airbus, 2016), where the final product is assembled. It is assumed that by using AM technology, the transport to Taiwan is eliminated, reducing the transport distance to 6500 km.

The amount of total raw material that was shipped in 2012 was 545 million kg. This will have grown to 2720 million kg in 2050. The total energy consumed in transporting the raw material from the USA to France via Taiwan in 2050 was computed as follows: 2720 (million kg) × 12,400 km (Pittsburgh–Taiwan) × 65 J/kg/km + 2720 (million kg) × 10% (weight reduction after processing in Taiwan) × 10,300 km (Taiwan–Toulouse) × 65 J/kg/km = 2.37 PJ/yr. In 2050, by application of AM and eliminating the routing through Taiwan, the energy used for the transport of raw materials from the mining site to Toulouse was calculated as follows: 2.72 (billion kg) × 10% (reduction of material consumption due to AM) × 6500 km (Pittsburgh–Toulouse) × 65 J/kg/km = 1.15 PJ/yr, a reduction of 1.22 PJ/yr compared to 2.37 PJ/yr without AM, see also Table 4.

4.1.3. Processing

The energy consumed in the production of the aircraft components was calculated as follows. The consumption of electricity, on average, was 0.32 kWh per USD of value added (Fabrication, 2000). The ratio between the gross value added (GBP 9.4 billion) and total turnover (GBP 24.7 billion) for a number of businesses in the aerospace industry was calculated to be 9.4/24.7 = 0.38 (Rhodes et al., 2015). This ratio was then used to calculate the gross value added for the aerospace industry based on its market size of USD 3182 billion by 2050 (PricewaterhouseCoopers, 2015): USD 3182 billion/yr × 0.38 = USD 1209 billion/yr. This was multiplied by the specific consumption per USD value added: USD 1209 billion/y × 0.32 kWh/USD × 3.6 million J/kWh = 1.39 EJ/yr that would be consumed by the manufacturing of aerospace components by 2050. With the assumption that 35% of the energy can be saved in processing, the potential savings are 1.39 EJ/yr × 35% = 0.49 EJ/yr.

4.1.4. Use

A lighter aircraft requires less fuel to cover the same distance assuming the same fuel efficiency (l/kg/km). We calculated that a 16.7% reduction in fuel weight (29,860 l kerosene at 0.8 kg/l × 16.7% = 3988 kg) does not change the fuel efficiency for the total airplane weight (empty weight + fuel + payload). The total weight reduction per aircraft is 9031 kg (reduction in empty weight) + 3988 kg (reduction in fuel weight) = 13,019 kg.

The assumption that a weight reduction of 1 kg saves 114 kg fuel/yr leads to a reduction in fuel use of 13,019 × 114 = 1,485,000 kg fuel per year per aircraft. With an energy content of 43.2 MJ/kg for kerosene type BP Jet A-1 (Lackner et al., 2010), the energy consumption per aeroplane would decrease by 64.1 TJ/yr. In 2013, the world jet airliner fleet comprised 23,000 aircraft (Forsberg, 2014). By 2050, this figure will increase fivefold to 115,000. Using the assumption that the Airbus A320 is a representative aircraft of the aerospace industry, the energy savings in the aerospace industry by 2050 would amount to 115,000 × 64.1 TJ/yr = 7.37 EJ/yr for the world fleet.

4.1.5. Maintenance

The total amount spent on maintenance, repair and services in 2015 was USD 50.1 billion (IATA, 2011). With a total market size of USD 729 billion, this corresponds to 6.9% and the other phases to 93.1%. With the assumptions that money spent is proportional to energy in the

Table 5
Effect and penetration percentages of additive manufacturing in value chain steps of the aerospace sector. The SL and BL scenarios have the lowest penetration percentages (20–40%). The SH scenario has higher penetration percentages (60–100%). For scenario BH, full penetration (100%) over all steps in the chain is assumed.

Scenario	Feedstock	Transport	Processing	Use	Maintenance
SL (Scramble – low AM)	20%	40%	20%	20%	40%
SH (Scramble – high AM)	75%	100%	60%	80%	100%
BL (Blueprint – low AM)	40%	20%	40%	40%	20%
BH (Blueprint – high AM)	100%	100%	100%	100%	100%

sector and that AM could reduce the energy required for maintenance by 30% up to 2050, one can calculate the energy use in maintenance, using the sum of energy in the other phases of the value chain (0.14 + 0.0024 + 1.394 + 31.4) × 6.9%/91.3% = 2.48 EJ/yr for *Scramble*, and 1.41 EJ/yr for baseline *Blueprints*. The maximum savings by AM would be 30% of this, i.e. 0.746 EJ/yr for *Scramble*, and 0.424 EJ/yr for *Blueprints*.

4.1.6. End-of-life

Decommissioning an aircraft at the end of its life leads to the reuse or recycling of 85% of its components (Asmatulu et al., 2013). The energy savings related to the recycling of metals can be significant, with 95% in the case of aluminium and 70% in the case of steel (Asmatulu et al., 2013). The effect of AM on the energy consumed in recycling aeroplanes is difficult to estimate at this stage. Consequently, no calculations are presented for the end-of-life of aircraft.

4.1.7. Scenarios

For each of the four scenarios, a certain fraction of the aforementioned savings can be achieved. The amount of energy reduction for each scenario and the extent to which AM penetrates was determined (see Table 5). In the SL and BL scenarios, the lowest penetration percentages were used (20–40%). The SH scenario has higher penetration percentages (60–100%). For scenario BH, full penetration (100%) over all phases in the chain was assumed.

4.1.8. Total

Using the calculations above, the energy use forecast for the aerospace sector is 35.4 EJ/yr in the *Scramble* scenario when AM is not included. An overview of all the potential savings in the base case (100% penetration of AM) for *Scramble* and *Blueprints* is given in Table 6, rows 1 and 4. Using the penetration degrees of Table 5 for the four scenarios, the energy savings for each phase in the value chain can be calculated, as given in Table 6, rows 2, 3, 5 and 6. For instance, the *Use* part of the aerospace sector value chain (see Table 5, column *Use*), the energy savings in the four scenarios are a penetration of 20% and 80% of 7.37 EJ/yr for SL and SH, respectively, leading to 1.47 and 5.90 EJ/yr (SL and SH), and 40% and 100% of 4.18 EJ/yr for BL and BH, respectively, leading to 1.67 and 4.18 EJ/yr (BL and BH). Summing the savings in the value chain phases leads to a reduction of 7.03 EJ/yr in the SH scenario and 4.96 EJ/yr in the BH scenario.

Table 7
Energy saving (in EJ/yr) and relative to total (in %) in the aerospace sector by AM in four scenarios: Scramble scenario and Blueprint scenario combined with low respectively high penetration of additive manufacturing.

	Low AM	High AM
Scramble	SL 1.90 (5%)	SH 7.03 (20%)
Blueprint	BL 1.90 (9%)	BH 4.96 (25%)

The cumulative effect of AM technology in the various phases of the value chain leads to a saving of 7.03 EJ/yr in the SH and 1.90 EJ/yr in the SL scenario, or a 20% and 5.4% reduction, respectively, compared to the forecast without any AM (see Table 7). In the *Blueprints* scenario without any application of AM, an energy consumption of 20.1 EJ/yr is forecasted. The cumulative effect of AM penetration leads to a reduction of 4.96 EJ/yr in the BH and 1.90 EJ/yr in the BL scenario, corresponding to a 25% and 9% reduction, respectively, compared to the 20.1 EJ/yr forecast without any AM (see Table 7). In all four scenarios, the highest reduction in energy use is in the *Use* phase of the value chain, as lighter aeroplanes lead to lower fuel consumption, and the *Use* phase accounts for more than 75% of the savings in all scenarios (see Fig. 9).

4.2. Case II: construction sector

A similar approach was chosen to compute the effect of AM in the construction industry.

4.2.1. Feedstock

The starting point for these calculations was the forecasted global final energy consumption by 2050, namely 513 EJ/yr for *Blueprints* and 557 EJ/yr for *Scramble*, based on Shell (2008a, 2008b) (see Table 2). Using the 31% share of global energy in the construction sector (GEA, 2012), the energy demand in the sector was calculated to be 557 EJ/yr × 31% = 173 EJ/yr in the *Scramble* scenario without the influence of AM technology and 513 EJ/yr × 31% = 159 EJ/yr in the *Blueprints* scenario (Shell, 2008a, 2008b). Using the assumption that one quarter of energy use in this sector is accounted for by feedstock, transport and construction, the expected energy demand for feedstock, transport and construction by 2050 is 159 (EJ/yr)/4 = 39.8 EJ/yr for *Blueprints* and 173 (EJ/yr)/4 = 43.3 EJ/yr for *Scramble*.

Nässén et al. (2007) posit that half of these energy consumptions are associated with the raw materials (thus 39.8/2 = 19.9 EJ/yr for *Blueprints* and 43.3/2 = 21.6 EJ/yr for *Scramble*), and the other half with transport and construction. With the assumption that AM technologies will consume 40% less raw materials, energy savings are 19.9 × 40% = 8.0 EJ/yr for *Blueprints* and 21.6 × 40% = 8.6 EJ/yr for *Scramble*.

Table 6
Energy savings (EJ/yr) in value chain steps for the aerospace sector, calculated using the maximum savings and the penetration percentages for each scenario in Table 4.

	Feedstock	Transport	Processing	Use	Maintenance	Total
Scramble						
Maximum savings by AM	*0.132*	*0.00122*	*0.487*	*7.37*	*0.746*	*8.74*
Energy savings SL	0.026	0.00049	0.097	1.47	0.299	1.90
Energy savings SH	0.099	0.00122	0.292	5.90	0.746	7.03
Blueprints						
Maximum savings by AM	*0.075*	*0.00069*	*0.276*	*4.18*	*0.424*	*4.96*
Energy savings BL	0.030	0.00014	0.111	1.67	0.085	1.90
Energy savings BH	0.075	0.00069	0.276	4.18	0.424	4.96

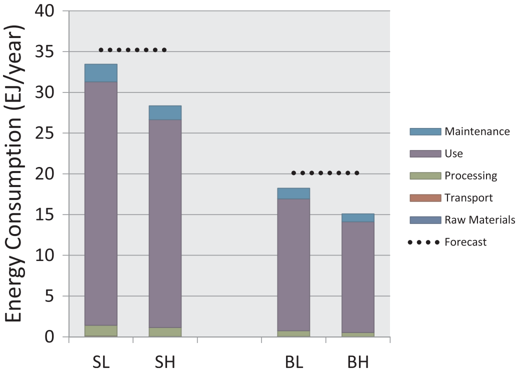

Fig. 9. The energy use in the aerospace sector for each scenario in 2050. The dashed line represents the forecast, without any savings through additive manufacturing.

4.2.2. *Transport & construction*

As stated above, half of the energy demand for feedstock, transport and construction is for transport and construction: 21.6 EJ/yr for *Scramble* and 19.9 EJ/yr for *Blueprints*. Using the assumption that 40% of energy use corresponds to *transport* energy, leads to 21.6 × 40% = 8.6 and 19.9 × 40% = 8.0 EJ/yr, respectively. Using the assumptions (40% maximum feedstock weight reduction by AM) and the direct relation between weight and transport energy, yields maximum savings of 40% × 8.6 EJ/yr = 3.44 EJ/yr for *Scramble* and 40% × 8.0 = 3.2 EJ/yr for *Blueprints*.

4.2.3. *Use – heating and cooling*

Knowing that heating and cooling accounts for 43% (GEA, 2012) of the total buildings' demand of 159 EJ/yr for *Blueprints* and 173 EJ/yr for *Scramble* by 2050 (Shell, 2008a, 2008b), and using the assumption that improved insulation results in 32% energy savings, 159 × 43% × 32% = 21.9 EJ/yr for *Blueprints* and 173 × 43% × 32% = 23.8 EJ/yr for *Scramble* could be saved.

4.2.4. *Other*

'Other' includes lighting, non-heat related electric appliances and other energy demand components associated with the use and demolition/recycling of buildings. Although electricity use makes a significant contribution to the total energy consumption in the use phase, the effect of AM was not evaluated. Nor was the demolition of buildings evaluated, as also here AM is expected to have a less significant effect in terms of energy reduction, and other technologies – such as robotics, waste processing innovations and/or circular economy management – are thought to be more responsible for energy gains here.

4.2.5. *Scenarios*

The degree of penetration of AM per phase in the value chain is given in Table 8. All scenarios have a 100% penetration in the construction phase. In the other phases, the SL scenario has the lowest penetration percentages (20–50%). The BL scenario has a somewhat higher penetration (30–40%), except for *Other*, which is set at 100%. The SH scenario has higher penetration percentages (50–100%). For scenario BH, full penetration (100%) over all phases in the chain was assumed.

4.2.6. *Total energy savings*

An overview of all the potential savings in the base case (100% penetration of AM) for *Scramble* and *Blueprints* is given in Table 9, rows 1 and 4. Using the penetration degrees of Table 8 for the four scenarios, the energy savings for each phase in the value chain was calculated, as given in Table 9, rows 2, 3, 5 and 6. For instance, the transport part of the construction sector (see Table 8, column *Transport*), the energy savings in the four scenarios are 20% and 80% of 3.45 EJ/yr for SL and SH, respectively, and 30% and 100% of 3.18 EJ/yr for BL and BH, respectively, or 0.69 EJ/yr and 2.76 EJ/yr (SL and SH, respectively) and 0.95 EJ/yr and 3.18 EJ/yr (BL and BH, respectively). Summing the savings in the value chain phases leads to a reduction of 28.7 EJ/yr in the SH scenario and 33 EJ/yr in the BH scenario. Compared to the 2050 forecast of 173 EJ/yr and 159 EJ/yr, this corresponds to a saving of 17% and 21%, respectively (see Table 10). Doing the summation for the other two scenarios, the reduction comes to 7.7 EJ/yr (4%) in the SL and 12.1 EJ/yr (8%) in the BL scenario (see Table 10). Fig. 10 represents the energy consumption in the four scenarios with various divisions in the value chain. The *Raw materials* and the *Use* phase of the value chain are the phases most affected by AM: approximately one quarter and two-thirds, respectively, of the total savings are in those phases.

Table 8
Effect and penetration of additive manufacturing in value chain steps of the construction sector. All scenarios have a 100% penetration in the construction step. In the other steps, the SL scenario has the lowest penetration percentages (20–50%). The BL scenario has a somewhat higher penetration (30–40%), except for 'other', which is set at 100%. The SH scenario has higher penetration percentages (50–100%). For scenario BH, full penetration (100%) over all steps in the chain is assumed.

Scenario	**Raw materials**	**Transport**	**Construction**	**Use**	**Other**
SL (Scramble – low AM)	20%	20%	100%	20%	50%
SH (Scramble – high AM)	80%	80%	100%	80%	50%
BL (Blueprint – low AM)	30%	30%	100%	40%	100%
BH (Blueprint – high AM)	100%	100%	100%	100%	100%

Table 9
Energy savings (EJ/yr) in value chain steps for construction sector, calculated using the maximum savings and the penetration percentages for each scenario in Table 6.

	Feedstock	Transport	Construction	Use	Other	Total
Scramble						
Maximum savings by AM	*8.63*	*3.45*	*0.00*	*23.8*	*0.00*	*35.8*
Energy savings scenario SL	1.73	0.69	0.00	4.75	0.00	7.2
Energy savings scenario SH	6.91	2.76	0.00	19.0	0.00	28.7
Blueprints						
Maximum savings by AM	*7.95*	*3.18*	*0.00*	*21.9*	*0.00*	*33.0*
Energy savings scenario BL	2.39	0.95	0.00	8.75	0.00	12.1
Energy savings scenario BH	7.95	3.18	0.00	21.9	0.00	33.0

4.3. *Extrapolation to other sectors and global energy demand*

Two methods for assessing the global energy demand were employed.

In the second extrapolation method, for each industrial sector, selected energy reduction (in %) results from the value chain phases in

Table 10
Energy saving (in EJ/yr) and relative to total (in %) in the construction sector by AM in four scenarios. Scramble scenario and Blueprint scenario combined with low respectively high penetration of additive manufacturing.

	Low AM	**High AM**
Scramble	SL 7.2 (4%)	SH 28.7 (17%)
Blueprint	BL 12.1 (8%)	BH 33.0 (21%)

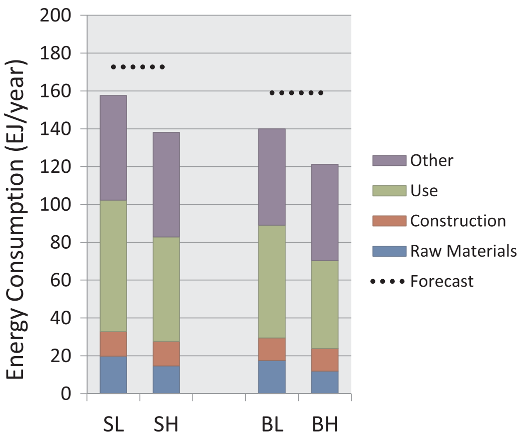

Fig. 10. Energy use in the construction industry in 2050, for all steps in the value chain, and the 2050 forecast without any penetration and effect of additive manufacturing (dashed lines).

Table 12
Global energy demand saving (in EJ/yr and/or relative to total demand in each scenario) by AM, summed over all economic sectors, by two methods of extrapolating the case studies. Straight extrapolation is an average of the percentage savings of both cases studied. The more detailed extrapolation is by using Tables 2 and 11. Both methods give similar results: *Scramble* scenarios have lower savings potential and *Blueprints* scenarios have higher savings potential.

	Low AM	High AM
Method 1: straight averaging		
Scramble	5%	18%
Blueprint	9%	23%
Method 2: more detailed extrapolation		
Scramble	36 (6%)	121 (22%)
Blueprint	47 (9%)	138 (27%)

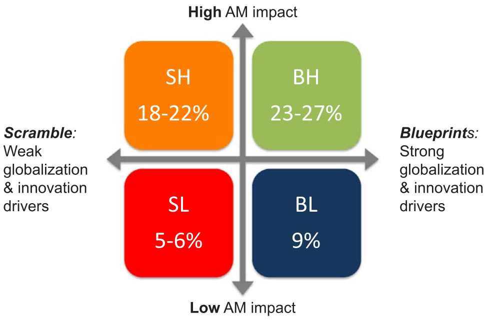

Fig. 11. Energy reduction potential of AM on the global final energy demand for four scenarios: 5–27% depending on scenario.

the aerospace sector and the construction sector were used. The figures from the construction and aerospace sector used in this extrapolation are explained in Table 11. For instance, for the transport sector in the BH scenario, the energy reduction of the value chain phases *Transport* and *Use* of the aerospace sector (51.5% and 23.5%) plus the value chain phase *Transport* of the construction sector (40%) were averaged, yielding 38%.

The global energy savings were calculated by summing up the energy savings of all sectors in one scenario (by multiplying the savings percentages shown in Table 11 by the energy use given in Table 2). As an example, in the BH scenario, 140 EJ/yr × 38% + 117 × 14% + 84 × 18% + 79 × 67% + 39 × 0% + 55 × 0% = 138 EJ/yr, which is 138 EJ/yr/513 EJ/yr = 27%. Similarly, savings on global energy demand are 36 EJ/yr (6%) for SL, 121 EJ/yr (22%) for SH and 47 EJ/yr (9%) for BL.

The first, straight averaging method yields the following results. For example, averaging the percentage savings for the aerospace and the construction sector in the SL scenario, namely 5% and 4%, respectively, leads to 5%. For the other scenarios, savings of 18% for SH, 9% for BL and 23% for BH were calculated; these results are shown in Table 12.

In Fig. 11 the results of both extrapolations are presented, indicating that total energy savings are 5–6% for SL and 18–22% for SH, and 9% for BL and 23–27% for BH. Regardless of whether a *Blueprints* or *Scramble* socio-political atmosphere unfolds, the potential effect of AM on the energy demand is rather large. Low penetration of AM saves 26–47 EJ/yr, whereas high penetration saves 102–138 EJ/yr.

5. Discussion

The energy savings achievable by AM are considerable, namely 5–27% of the world energy consumption, depending on the scenarios. The subject therefore deserves further study and policymaking. To our knowledge, this is the first time that the effect of a non-energy related disruptive technology – in this case AM – on global energy demand has been analysed, bottom-up, for 2050. The effect was studied by a straightforward analysis of the effect on two sectors: aerospace and building construction. The results were extrapolated to other sectors. There is a need to elaborate this analysis in a more sophisticated way. Improvement issues are:

- Assumptions were made on the energy savings due to material savings, transport savings, production savings, savings in the use phase and in operation & maintenance. These need to be compared and validated using more field data.
- Although the averaging method and the more extensive extrapolation method gave almost the same results, detailed analysis of other sectors using actual value chain data will provide insight into the energy saving potential of AM in other sectors and substantiate the findings.
- A more sophisticated sector analysis is not simply a matter of adding up all numbers, because of interaction between sectors. For example, with less transport, fewer ships, trucks and planes are needed, reducing material and energy demand. On the other hand, if all products were made by AM, more computing power, data storage and more extensive internet connections worldwide would be required, costing material and energy.

The long-term perspective (to 2050) and the full development of AM led to AM having much larger effects – namely energy savings of between 26 and 138 EJ/yr – than those found by other studies; for

Table 11
Energy demand reduction for all economic sectors in each of the four scenarios, and the value chain steps results which were used from the two cases (Construction and Aerospace).

Sector	Value chain steps results from cases used for calculation	SH	BH	SL	BL
Transport	Average of 'Transport' and 'Use' in aerospace case and 'Transport 'in the construction case	34%	38%	11%	11%
Residential	'Use' step in construction sector	9%	14%	2%	6%
Agriculture & other industries	Average of 'Processing' from aerospace case and 'Construction' from construction case	11%	18%	4%	7%
Heavy industry	Average of 'Raw materials' from aerospace sector and 'Raw materials' from construction sector	51%	67%	13%	25%
Services	AM is assumed to have no effect on services	0%	0%	0%	0%
Non-energy use	Zero	0%	0%	0%	0%

example, Gebler et al. (2014) found a primary energy supply reduction of 2.5–9.3 EJ/yr in 2025. This difference stems from the longer time horizon, the further development of AM technology, confidence in the penetration of AM in most economic sectors and a more detailed bottom-up assessment.

The scenarios presented in this article were built on the assumption that AM will develop incrementally. For instance, AM technologies with a larger variety of materials were included in scenarios SH and BH, but revolutionary AM techniques were not. It is nearly impossible to forecast such breakthroughs. The analysis performed in this research should therefore be regularly updated to take into account new breakthrough technologies.

The effect of AM on energy demand was investigated using a linear effect model, evaluating each phase in the value chain separately. Second-order effects and negative behavioural effects – such as rebound effects, additional weight increases or the relocation of production to low energy cost countries – could counteract the energy savings. Positive feedback loops, such as additional material savings by other geometries, and circular economy implementation could lead to higher savings.

Insight into the effect of AM and other disruptive technologies on global energy demand will be a powerful tool for advanced energy planning and energy policies. For example:

- In energy planning, local AM production may require increased local power capacity and thus increased electricity grid capacity or additional solar or wind energy systems. Matching AM production with moments of high solar electricity production may be a way to avoid having to increase the capacity of the electricity grid. Electricity distribution and production companies need to take these developments into account in order to be able to proactively anticipate.
- Energy policies include regulations and standards related to the energy consumption of buildings, cars and appliances. It would also make sense to impose standards for energy and material use in the manufacturing of buildings, cars and appliances, as well as standards for and limits on transport energy for the construction of buildings, cars and appliances.

This article presented an analysis of the effect on energy demand of one disruptive technology. However, there are many more disruptive technologies, such as robotics, drones, autonomous driving, cloud computing, the Internet of Things, circular material use, nanomaterials, and so on. All these disruptive technologies will have an effect on energy demand. Whereas some of them, for example drones, will almost certainly increase energy consumption, the majority will tend to reduce global energy demand. For example, autonomous driving could lead to energy savings, as cars can drive closer to each other, thus reducing air resistance. It could also boost car-sharing, thus reducing the number of cars and the materials needed. A comprehensive analysis of the effects on energy and material use for all these disruptive technologies and their interrelations is certainly needed to get a better understanding of and insight into energy demand development.

The aerospace case results are dependent on the assumption that, for example, the Airbus 320 is a representative aircraft. The largest reduction in energy consumption is in the use phase. This reduction is based on three main assumptions: the five times larger aircraft fleet by 2050, fuel use directly proportional to aircraft weight (114 l of kerosene per year per kg of reduction) and that the use of AM can bring about a empty weight reduction of 21.3% and fuel weight reduction of 16.7%. These assumptions, by virtue of the predominant proportion of the use phase in the energy savings, are almost linearly correlated to the energy savings compared to the base case. Material savings achieved by technologies other than AM would yield equivalent energy savings.

In the construction case, material savings (40%) and improved insulation (32%) assumptions result in less energy use in the raw materials and use phases. These again reflect the direct effect of the assumptions on the results, and are also proportional to the energy saving potential of AM. This article presented an initial assessment of the potential *direct* effects of AM on global energy demand: no or less waste in manufacturing processes (reducing feedstock consumption), less material use in products designed for AM, production of products and spare parts close to where they will be used, and better and lighter products. The *indirect* effects related to the lifecycle of products were not investigated during this research. To name a few indirect effects: production on demand; not for demand, products personalised according to size, preference and style; repair of products on demand and on site; product lifetime extension by replacing and upgrading old parts; and products reuse via updates, redesign and restyling. Both the direct and indirect effects of AM also contribute to other environmental issues, such as material savings, water use and emissions. In this broader perspective, AM could become a key technology in realising a circular economy.

6. Conclusion and policy implications

6.1. Conclusions

The objective of this research was to assess the potential effect of additive manufacturing (AM) on the global energy demand by 2050. The most important conclusions are:

- AM can have a considerable effect on the global energy demand, as it potentially decreases energy demand by at least 5% and as much as 27%. It is evident that a widespread implementation of AM technologies would lead to a larger effect.
- For the aerospace sector, most energy would be saved in the use phase because of weight reduction. Between 5% and 25% can be saved in comparison to the base cases in 2050. In the construction sector, the largest savings are expected in feedstock and the use phase; savings of between 4% and 21% are achievable.
- Even with a low degree of penetration of AM, the potential for energy demand reduction is large and warrants more attention, adoption in energy scenarios, and activation in energy & innovation policies. Conversely, AM specialists are advised to emphasise their energy-saving impacts.
- The global energy demand in the four scenarios for all economic sectors by 2050 was extrapolated from two case studies covering two sectors with totally different value chains, material use and supply chains. In both sectors, both extrapolation methods yielded comparable results, with the detailed extrapolation leading to higher estimated savings. Study of one more sector will solidify the outcomes and validate the extrapolation methods used.
- The aim of this research was to make an initial assessment of the potential effects of a new wave of technological disruptions in the global energy demand. AM was chosen as illustrative of the effects of disruptive technologies. Although it is still an emerging technology, its application range, penetration and market size are large enough to study its effects on value chains. Other emerging technologies such as robotics, drones and the Internet of Things are rapidly being introduced in a wide range of applications and their market size is growing fast. It is therefore recommended to evaluate the energy effect of other disruptive technologies that fulfil these criteria, such as robotics, autonomous driving, drones and the Internet of Things.

6.2. Policy implications

It is evident that the energy demand reduction potential calculated in this research can best be achieved when energy policies take into account AM as a group of technologies that affect energy demand. Some of the possible energy policy measures related to energy demand in combination with AM are:

- Develop guidelines or standards for no or minimal material waste during manufacturing.
- Develop energy efficiency standards for products and appliances in the use phase, based on best practice AM.
- Develop energy use standards for the transport of products and goods based on AM transport and logistics.
- Arrange free access to AM design files for spare parts, repair and reuse.
- Encourage transition from ownership of to access to products and goods.
- Develop guidelines, best practices and standards for AM machines.
- Include AM support in the revisited Nationally Determined Contribution under the Paris Agreement for the deepest possible decarbonisation of the economy, with a view to limiting global warming to 1.5 °C.

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