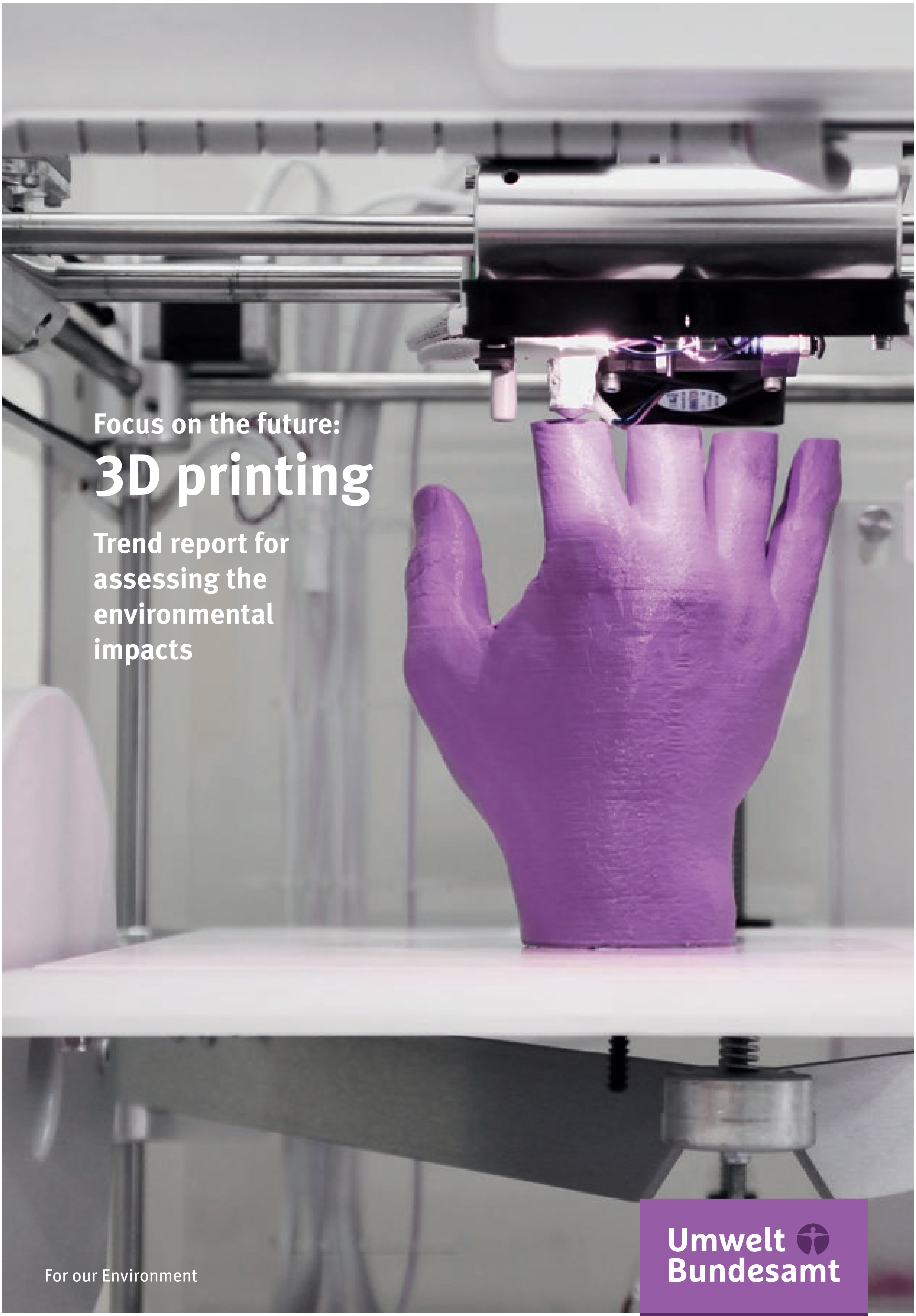

Focus on the future:

3D printing

Trend report for assessing the environmental impacts

For our Environment

Umwelt Bundesamt

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1 Introduction

1.1 Background

3D printing will not only redefine the power structures in industrial manufacturing but shake the economic world as a whole. (Michler 2014)

Be it a 3D printed bionic ear…, 3D printed cake toppings… or 3D printing your dream house… 3D printing is revolutionizing every walk of life. (Banerjee 2016)

"We're on the eve of a new disruption; 3D printing will revolutionize the way we think about manufacturing." (Ruth 2016)

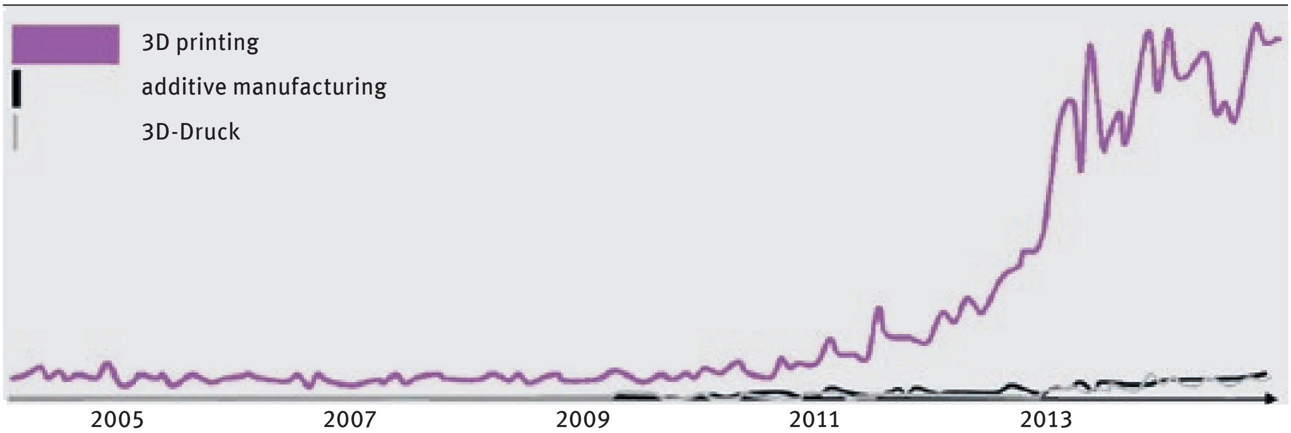
According to current debate, high expectations are placed on 3D printing. The technology is seen as a possible trigger for a new industrial revolution (Berman 2012; Gershenfeld 2012) potentially leading to changes as far reaching as those brought by the steam engine, nuclear energy, the microchip or the Internet (Campbell 2011). The characteristics of 3D printing bring a completely new freedom to design and the possibility of quickly and simply manufacturing individually tailored products. In this way, 3D printing could enable innovations and help realise ideas more quickly.

With 3D printing it is possible to create very complex geometries and internal structures which would be impossible to produce using classical subtractive (such as turning or milling) or formative manufacturing processes (such as casting or forging) without joining technologies (gluing, welding, screwing etc.) (Harhoff and Schnitzer 2015; stratasys Direct Manufacturing 2015). In addition to the process advantages, 3D printing is particularly interesting due to the great diversity of useable materials (plastics, metals, ceramics, concrete, tissue cells etc.) and their wide range of mechanical, physical, chemical and(in some cases) physiological properties. Technically, 3D printing is therefore applicable in many different fields.

There are high hopes for 3D printing also from the environmental perspective. The procedure is expected to contribute to more ecologically sustainable production in the future through savings in material input, waste avoidance and new recycling ideas (Petrovic et al. 2011; Atkins 2007). In 3D printing, products are built on a layer-by-layer basis. In contrast to subtractive processes, there is hardly any waste generated from milled material.[3] Based on new construction possibilities, innovative lightweight structures can be implemented e.g. in the automotive sector, resulting in a lower fuel consumption of cars and aircraft (Petschow 2014). For plastic materials, waste recycling (such as municipal waste or commercial waste) may be a source of new printing material. In addition, 3D printing devices are quite flexible in terms of location. This could result in a further globalisation of production sites (cf. e.g. Gao et al. 2015). By purchasing a 3D print template, anyone can produce goods where they are immediately needed. As a result, the volume of goods needing transportation can be reduced, which

Figure 1:

Google trend search queries[1] for the terms "additive manufacturing", "3D printing", and "3D-Druck"[2]



Source: Chart generated by the authors (after Google 2010)

[1] The chart "does not represent any absolute search volume figures since the data are normalised and shown on a scale from 0 to 100" (translated from Google 2010).
[2] 3D-Druck is German for '3D Print'

will consequently lead to a decrease in CO_2 emissions. Also potential impacts on spatial development (rural areas) may occur in the wake of increasing flexible on-site production.

It still remains to be seen whether such expectations and hopes will be fulfilled. So far, positive effects have often been emphasised in the debate without systematically analysing the trend of 3D printing (Campbell et al. 2011; Berman 2012).[4] What is missing is a synoptic presentation of direct environmental impacts, which are being discussed only partially at present. The indirect effects that have so far been identified mainly concern their social or economic significance, and are still poorly reflected with respect to their environmental relevance. The innovation potential of this future technology has so far been discussed with a focus on technological, economic and social opportunities without comprehensively considering possible impacts on the environment. This trend report contributes to closing this gap.

1.2 Scope and objectives

The future environmental impacts of 3D printing will depend on many different factors. These include, among others: 3D printer type and the printing material; type of use, e.g. industrial or private applications; and supporting services required for 3D printing, e.g. transport of printing materials. This trend report takes into account these different elements of 3D printing and analyses to what extent they could lead to environmental burdens or benefits. The innovative characteristics of 3D printing are also considered in a subchapter of the report (Chapter 3.3) in order to analyse their potential environmental implications in the future. What are referred to as innovative characteristics are those new elements of a trend which are "a major source of potential strategic surprises" (Liebl and Schwarz 2009) e.g. because they imply a completely new paradigm.

In this way, this trend report contributes to an early identification of both the positive and negative environmental impacts of 3D printing to be expected in the future. It also includes impacts that can already be observed today. The report is based on the current state of scientific knowledge and comes to a conclusion in terms of the action needs for environmental policy and

further research. The report does not replace integrated environmental and economic accounting, scenario analyses or quantitative modelling of all the phenomena associated with 3D printing in the future but nevertheless, makes an important contribution.

The aim of this report to identify the fields that environmental policy should pay more attention to in the future. Furthermore, it is intended to reveal areas where there are major uncertainties in the development of 3D printing and the related implications for environmental policy and therefore, where further research is required. This report is meant to constitute a first inventory with regard to the environmental impacts of 3D printing already observed and those to be expected in the future. It is a result of a strategic foresight for environmental policy.

In this report, only the environmental impacts presumed relevant are identified and described. Other effects of 3D printing, e.g. those on the economy or society, are only examined insofar as they affect the environment. Minor effects on the environment, such as the consumption of electricity during the production of CAD software, are not discussed in detail.

This report focuses on both the direct and indirect environmental impacts. Direct environmental impacts are those environmental burdens and benefits immediately (in temporal and spatial terms) arising from the printing processes, materials and the behaviour of actors involved (e.g. pollution from particulate matter due to printing). Indirect environmental impacts occur only via intermediate steps (in spatial and temporal terms), e.g. if lifestyle changes are triggered by 3D printing.

[3] Waste may, however, be generated from support structures.
[4] In the proper sense, what can be seen as a trend is the increasing use of 3D printing (in certain fields), not 3D printing in itself. Nevertheless, this report refers to the "3D printing trend", for simplification purposes.

1.3 Methodology

The methodology applied in this report serves the above-mentioned objective to early identify and describe in detail the future problem areas potentially arising for environmental policy.[5] Simultaneously, it takes account the basic methodical problem that there is no reliable way to predict the future. However, the various approaches selected and the resulting different perspectives allow the range of possible developments to be determined and described. This methodology is aimed at an early identification of potential problems rather than predicting probabilities or making precise forecasts for the future.

The assessment of environmental burdens and benefits from 3D printing is based on three different methodical approaches:

1. Trend description;

2. Criteria-based identification of direct and indirect environmental impacts (assessment);

3. Identification of other potential environmental impacts (ICC procedure).

The first two approaches described below are in part based on preliminary methodical works (e.g. horizon scanning processes and environmental impact assessment). The third approach, the ICC procedure (see below under 3) was specifically developed for this project. For this trend report, these three approaches were for the first time applied jointly and in an integrated way in order to include as many facets as possible of the environmental impacts of 3D printing. The three methods differ as to their objectives:

1) The first method serves to outline the objective of the study: aiming to identify, describe and analyse in the form of trend hypotheses all developments of 3D printing that are relevant in environmental terms. In the context of a literature analysis, 987 passages from 46 references on 3D printing were recorded, classified and evaluated by means of a qualitative content analysis software.[6] Relevant text passages were tagged with codes. The codes reflect internal and external factors of 3D printing and were arranged in a morphological box. The authors used a coding scheme for horizon scanning processes developed by the Institute for Innovation and Technology (IIT) comprising of 311 codes, of which 122 were assigned in the context of the analysis of the trend of 3D printing. Through this method, specific trend hypotheses can be identified and analysed, i.e. assumptions can be made on possible developments and manifestations of factors influencing 3D printing.

2) By means of the second method, the environmental impact assessment, it is possible to identify potential direct and indirect burdens and benefits in some aspects of 3D printing. The analytical instrument of the assessment procedure consists of the cause-effect chain. The cause-effect chain provides the fundamental heuristics for analysing the environmental impacts of 3D printing. In a systematic way, different categories of the trend are subjected to an analytical examination of its environmental impacts. Such approach is based on direct and indirect impact categories.

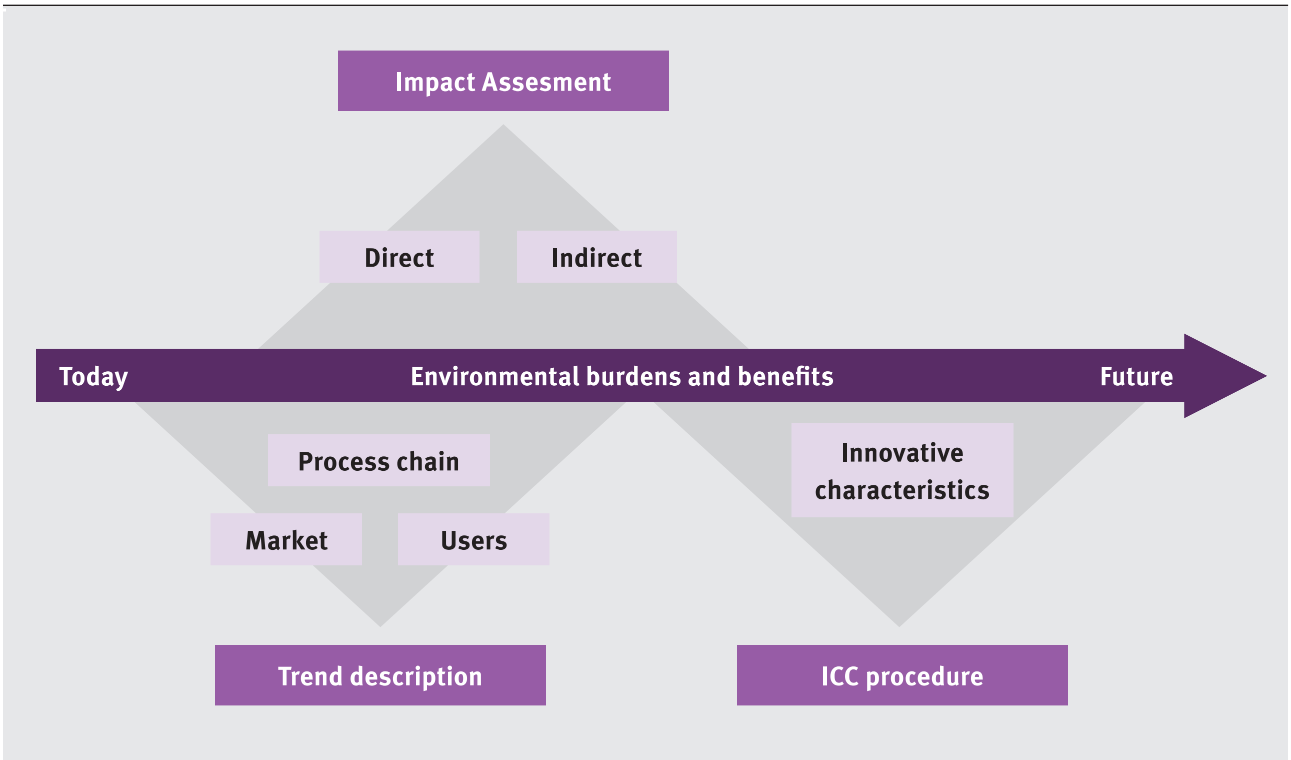
[5] Details of the overall methodology are described in a special method paper on trend description and trend analysis, which is part of the entire project. Based on the method paper, more trend reports will be published in the future. Another trend report (on the issue of consumption 4.0) will be prepared as another part of the current entire project.
[6] The software program used was Atlas.ti.

For the evaluation of the direct burden and benefit profiles, the methodology for a streamlined environmental assessment (German: Vereinfachte Umweltbewertung – VERUM) by the German Environment Agency (UBA) was used. It defines five general types of impact and 15 specific categories of impact. These include: chemical, physical, biological impacts, use of resources, and incidents / accidents (for a more detailed description, see Annex, Table 4). Each of the different processes, materials and behaviours were analysed as to whether any potential effects are to be expected in the 15 categories.

The identification of indirect environmental impacts was based on a newly formulated assessment pattern. The categories under study for this approach come from a number of different sources, namely the Millennium Ecosystem Assessment by UNEP 2012, central categories of environmental sociology and social psychology (Huber 2011; Kollmuss and Agyeman 2002; Oskamp and Schultz 2005), and categories of political science regarding the political system and its central areas (Hague and Harrop 2010). The dimensions examined include demography, society and culture, economy, politics, science and technology as well as space (for a synoptic view of dimensions and categories, see Annex, Table 5). The processes, materials used and the behaviour of actors involved in 3D printing were assessed as to potential changes in these fields which in turn, could appear relevant or irrelevant for environmental burdens or benefits. Such assessment included the results of the trend description (see above), the evaluations elaborated internally in the team and in an expert workshop[7], and also findings from scientific literature.

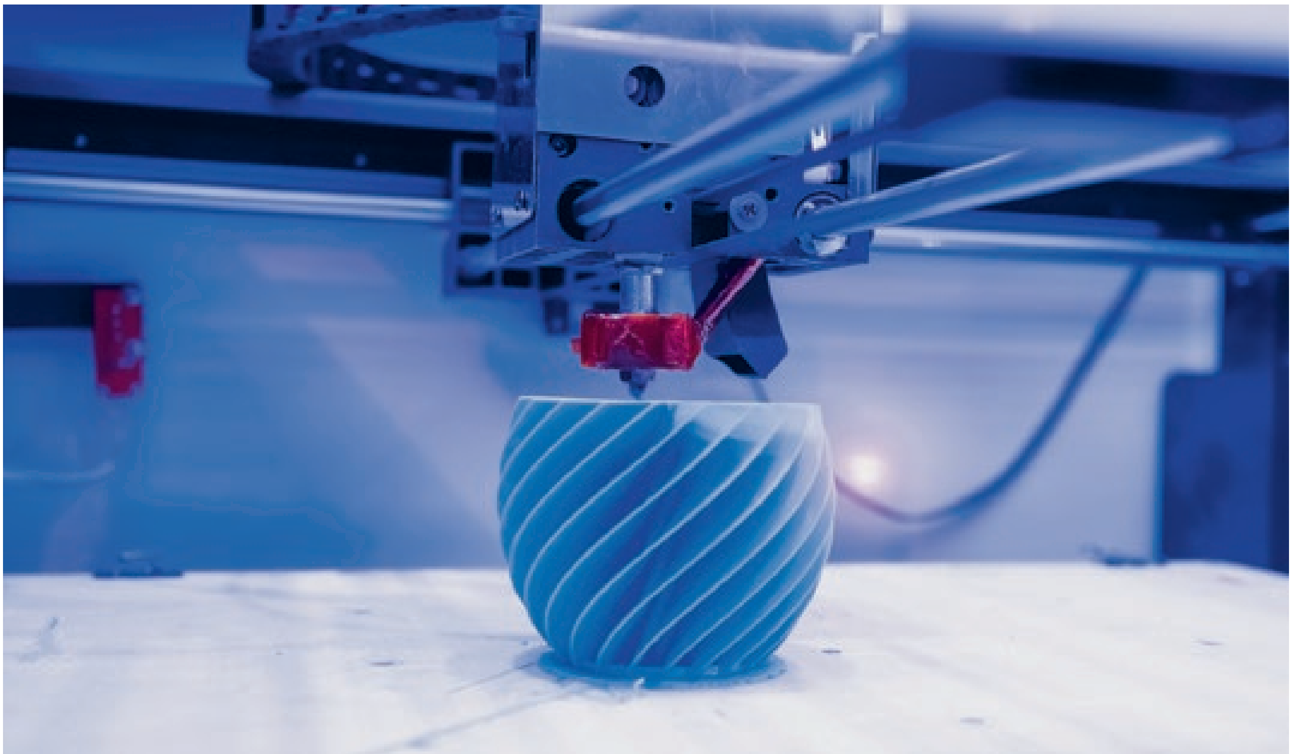
Figure 2:

Methods for trend description and trend analysis



Source: Chart generated by the authors

[7] The expert workshop was held on 29th September 2016 at the Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Berlin.



3) The innovative properties of 3D printing and the challenges resulting from such properties for environmental policy were identified by means of the IIC procedure (identification of innovative characteristics). The IIC procedure differs from the assessment procedure insofar as it has a much more open design: Instead of looking at specific impact categories (like those used in VERUM), this procedure reflects on potential challenges based on the innovative characteristics identified. There is a much greater degree of abstraction from the 3D printing characteristics that can already be observed. The focus is farther forward into an unknown future.

Figure 2 illustrates the interaction between the three methods and their different perspectives.

1.4 Structure

The trend report consists of three parts: **Chapter 2** provides a comprehensive description of the trend of 3D printing, presenting the process chain, the processes and materials, the history and current market development as well as the fields of application and actors involved. **Chapter 3** explains the results of the three different methods to identify environmentally relevant developments and impacts of 3D printing. Finally, **Chapter 4** identifies specific needs for research and action and draws a conclusion with regard to the environmental impacts of 3D printing and their implications for environmental policy.

The results of the first and second method, namely parts of the trend description – the trend hypotheses – and the criteria-based identification of environmental impacts (assessment), are jointly explained in Chapter 3 in order to provide an optimal presentation of the environmental burdens and benefits arising from 3D printing. Another reason to do so consists in the objectives of the individual approaches: Both the first and second method tend to focus on a (near) future which is still clearly discernible. They attempt to look into tomorrow based on current knowledge, with the help of assessments and qualitative prognoses. In contrast, the third method is much more detached from the here-and-now, thus venturing into areas inaccessible to the two other perspectives.

2 Trend description

2.1 Development of 3D printing

The great attention that 3D printing currently receives has often ignored that additive procedures have a 30 year history. Additive processes were first used in the automotive industry for efficient manufacture of prototypes (rapid prototyping) from the mid1980s. Innovations in computer and laser technology as well as commercialisation of CAD (computer aided design) software formed the basis for developing the first 3D printing processes.

1986 is referred to as the "year of birth" of 3D printing: it was the year when Charles Hull, a US American engineer, deposited a first patent for stereolithography (SLA) and founded the 3D Systems Corporation, still one of the most important 3D printing companies today. From 1988, the first 3D printer (SLA-1) was available on the market. In the 1990s, further processes were patented such as selective laser sintering (SLS), fused deposition modelling (FDM), ballistic particle manufacturing (BPM), laminated object manufacturing (LOM) and solid ground curing (SGC). In addition, new enterprises were founded with the intention of establishing 3D printing on the market. Companies which are still performing very successfully today include the EOS GmbH (Germany) and Stratasys Inc. (USA), who have been manufacturing printing systems used by industry, among other products.

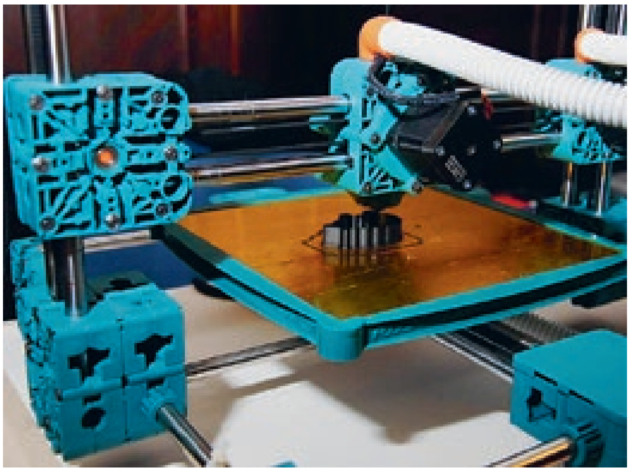
From the beginning of 2000, technological advances allowed production of improved quality. As a result, not only prototypes, but special tools and casts as well as small batches or customised objects could also be produced. The new terminology referred to such processes as "rapid tooling" (RT), "rapid casting" or "rapid manufacturing" (RM) (3dprintingindustry 2017). Today, the term of additive manufacturing (AM) is used as a generic term for the various applications of 3D printing in science and industry.

From 2007, private users could buy the first 3D printers at prices of less than USD 10,000. However, a real commercial success was only achieved with devices costing half that price, such as the B9Creator (see picture), which was placed on the market in 2012 (all picture credits are listed in Chapter 7). In 2005, Adrian Bowyer, a British engineer, invented the RepRap (short for replicating rapid prototyper), thus initiating the new Maker Movement. The RepRap is a 3D printer able to reproduce the majority of its own parts. It is operated by means of a software available free of charge. The added value for users of the RepRap, among other advantages, is its open source character: the designs on which the device is based are freely available on the internet. In Germany, FabLabs exist already in many cities, including Berlin, Munich and Erlangen (for a comprehensive list, see: 3D-Druck Magazin 2017). In the future, 3D printers will also be used by children. For example, Mattel has planned to introduce the ThingMaker 3D printer in autumn 2017 (3D-Druck Magazin 2016). High growth rates on the 3D printing technology market and technological progress, above all in the fields of bioprinting[8], the development of new materials and enhanced precision and printing speed have resulted in 3D printing becoming one of the most influential technological innovations, which can also be expected to bring about far-reaching social changes.

[8] The term of bioprinting refers to 3D printing processes forming the basis to print individual cells or tissues. In particular, the techniques of tissue engineering are applied in such processes. This technology is at the stage of basic research.

2.2 Process chain, processes and materials used in 3D printing

The term '3D printing' can be used generically to refer to a variety of processes which all have one thing in common: they serve to directly produce a three-dimensional model previously designed virtually as 3D computer model by means of a computer-aided design (CAD) software. Below, the nature of 3D printing and its environment is described with its typical process chain, established processes and the materials used.



The various 3D printing technologies differ considerably with regard to their technological processes and usable materials. In the process chain, eight steps can be identified, on principle, which are performed during the majority of 3D printing processes.(Gibson et al. 2015):

1. A virtual three-dimensional model of an object is designed by means of a CAD system. Such three-dimensional model can also be obtained by means of a 3D scan.

2. The CAD data are then converted into an STL (Surface Tessellation Language) file, a format serving to describe geometrical information of three-dimensional data models. This is the interface used most frequently for 3D printers available on the market.

3. The STL data are transferred into a 3D printer.

4. The printer is configured, and the print parameters are specified. This is done either manually by the user or in a semi-automatic manner (material and parameter set). Such parameters include, among others, the print position in the printer, the atmosphere and temperature of the print chamber, the properties of the energy source and the material used, the layer thickness and the print time.

5. The 3D printer will usually manufacture the object in an automated way.

6. Once finished, the object can usually be directly removed from the 3D printer.

7. Depending on the type of printing process used, the printed object has to undergo several post-processing steps: For example, excess print material (e.g. powder residues) is removed, or the object is infiltrated with binders to increase strength.

8. Once finished, the additively produced objects are ready for use. The objects may then subjected to further treatment, such as priming or coating, depending on the application.

Technologies used most frequently in additive manufacturing include the powder-based processes (in particular, powder-bed fusion (PBF), and the extrusion-based (EB) process.(Marquardt 2014). Also photopolymerisation (PP) processes are increasingly applied. For powder-based processes, a thin layer of powder (plastic, metal, ceramic etc.) is spread over a working surface, and a defined contour is melted by means of a laser, which will solidify afterwards. Then, a new layer of powder is spread across the previous one, and the process is repeated (PBF process) until the entire object has been created. Instead of melting by laser, thermosetting plastics (e.g. resins) can be used to bind the powder (e.g. starch) in a geometrically defined manner (a process referred to as binder jetting). In contrast, in the extrusion-based process, thermoplastic materials are made malleable via a heated nozzle and deposited in a geometrically defined manner. During the photopolymerisation process, liquid polymers are cured, by means of ultraviolet light, in a point-by-point or layer-by-layer manner on a build platform.

Below, the additive manufacturing production processes and their typical materials are described in detail, based on Gibson et al. (2015).[9] Table 1 (see below) provides a comprehensive synoptic view of the established processes, the usable materials, their advantages and disadvantages as well as the current acquisition costs of printing devices.

Powder bed fusion (PBF) processes

In PBF processes, thin powder layers, which are deposited in a defined building space, are sintered or fused, respectively, by means of one or more thermal sources (as a rule, laser or electron beam sources). After 3D printing is completed, loose powder has to be cleaned off the parts. In a simplified view, three PBF processes can be distinguished, namely polymer laser sintering (PLS), metal laser sintering (MLS) and electron beam melting (EBM) (Gibson et al. 2015).

Typically, PLS systems use polymers (e.g. polyamide), which have melting temperatures of about 200° C. For 3D printing, the build chamber is usually filled with an inert gas (nitrogen). During the process, the powder bed temperature is maintained slightly below the melting temperature of the polymers.

In industrial manufacturing, MLS systems are known under different synonymous names, e.g. as selective laser powder remelting (SLPR), selective laser melting (SLM), laser cusing and direct metal laser sintering (DMLS). MLS systems differ from PLS systems in the laser type used and in the fact that in MLS systems, the component is firmly attached to the build platform to prevent deformation. Typically, nitrogen or argon are used as inert gases.

EBM systems differ from MLS systems in the use of an electron beam instead of a laser. In addition, no inert gas is required for EBM systems because they work under vacuum. The energy costs of EBM systems are lower than those of new MLS systems. Since the powder bed is quickly pre-heated by the electron beam source, no additional heating systems are needed.

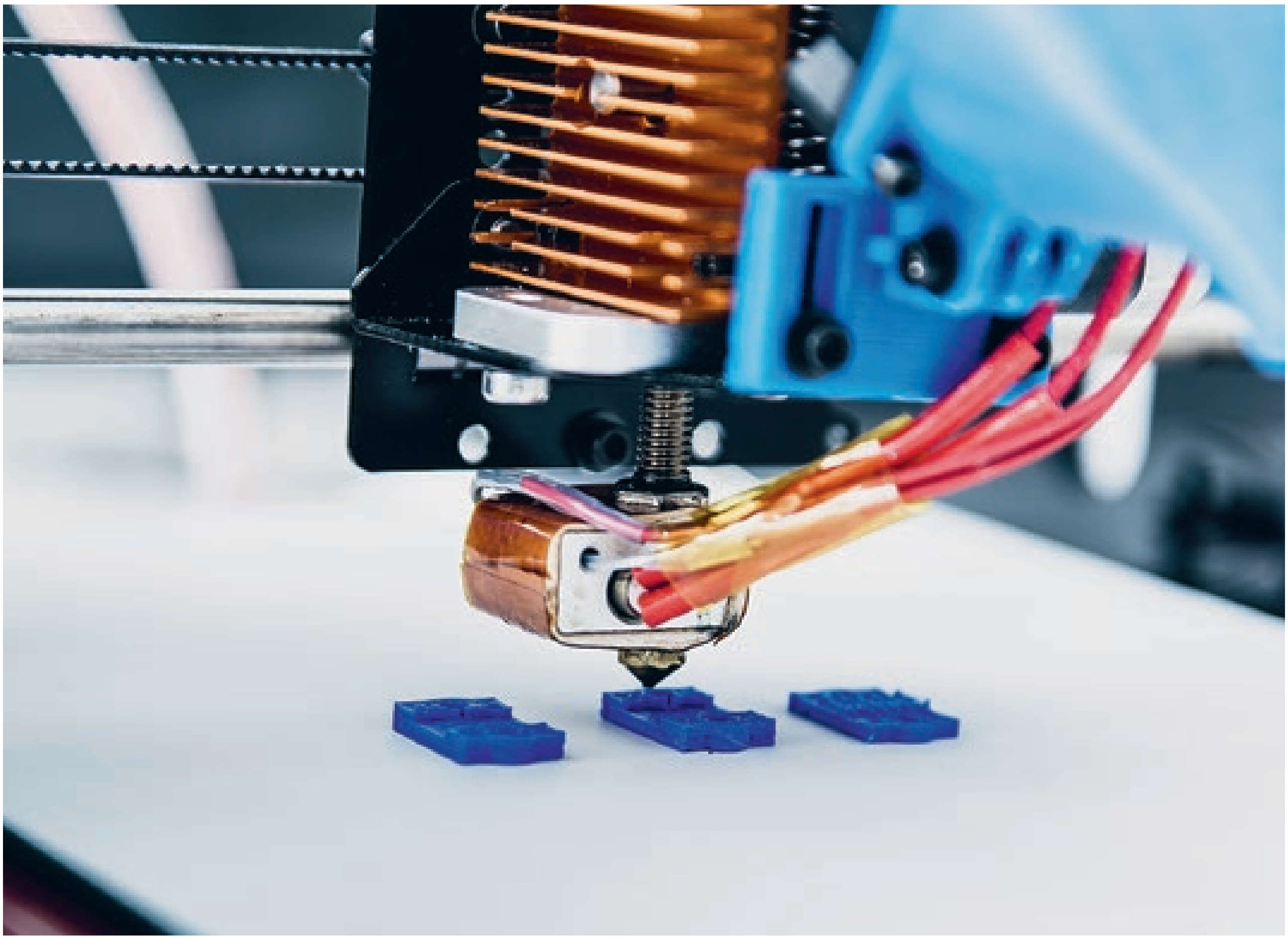
Extrusion-based (EB) processes

In EB processes, a distinction is made between physical and chemical processes. In chemical EB processes, a liquid medium is deposited through a nozzle. Subsequently, the liquid changes into the solid state by way of a chemical reaction. In physical EB processes, filaments[10] of thermoplastics (e. g. polylactate) are melted via a heated nozzle at about 200° C, then extruded and deposited onto a usually heated build platform (30-60° C). No chemical post-treatment of the components or removal of residual powder, respectively, is required. This process is often referred to as fused deposition modelling (FDM).

Photopolymerisation (PP) processes or stereolithography (SLA)

In PP processes, liquid photopolymers are cured by means of UV radiation in a point-by-point or layer-by-layer manner on a build platform so that the polymer becomes solidified. During the process, the build platform is immersed into the photopolymer. UV radiation sources used most frequently are lasers. In a simplified view, three PP processes can be distinguished: vector scan (point-wise approach), mask projection (layer-wise approach) and two-photon approach (high resolution point-by-point approach) (Gibson et al. 2015). Differences consist mainly in the resolution/speed, but these are irrelevant in terms of environmental impact.

[9] The English technical terms are also used in German technical literature.
[10] In the physical EB process, filament is the feedstock which is continuously fed into the print nozzle of the 3D printer and heated to achieve its plastic deformation and thus, enable deposition onto a platform. Typical filament materials for 3D printing include plastics such as ABS or PLA.



Material jetting (MJ)

In MJ processes, a liquid photopolymer is deposited onto a build platform via a print head in a drop-by-drop approach and polymerised by UV light. For the drop-by-drop deposition, the following technologies have become established: continuous stream (CS), DOD method and polyJet.

Binder jetting (BJ)

In BJ processes, a binder is deposited onto a powder, so that the powder is infiltrated layer by layer and consolidated to form a three-dimensional object. This process is also known under the synonym of 3D printing (3DP).[11] After printing, the objects are infiltrated with additional binders or subjected to thermal treatment (sintered) to achieve higher rigidity. Such subsequent infiltration or thermal treatment, respectively, is not applied in the other printing processes.

Sheet lamination (SL) process

In SL processes, thin two-dimensional sheets are cut from a material and bonded together in a layer-by-layer approach to form a three-dimensional object. Joining technologies used include gluing, thermal bonding, clamping and ultrasonic welding. The SL process is also referred to as laminated object manufacturing (LOM), and it is a special case among the additive manufacturing technologies.

Directed energy deposition (DED) processes

DED processes are characterised by simultaneous melting (by means of a laser or an electron beam source) of both the substrate and the material which is to be deposited upon the substrate and continuously fed to the print position. In contrast to PBF, the material is melted during deposition.

[11] Not to be confused with "3D printing" as a generic term for such additive manufacturing processes.

Table 1:

Established procedures, materials, advantages and disadvantages, and current acquisition costs

Frequently used materials are marked bold.

Established procedures	Materials	Advantages	Disadvantages	Acquisition costs
Powder Bed Fusion Processes (PBF)	**PLS:** thermoplastic and elastomer; polyamide or nylon (PA); polystyrene based material (PS); polyether ether ketone (PEEK); biodegradable material like polycaprolactone (PCL), polylactide (PLA), poly-L-lactide (PLLA); composite material like PCL + ceramic particles (e.g. hydroxyapatite (HA) **MLS:** stainless steel and tool steel; titanium and alloys; nickel alloy; alluminum alloy; cobalt-chromium alloy; silver and gold; ceramics **EBM:** conductive metals	Precision Build quality Large selection of material	Large investment costs Surface quality Speed Limited object size in need of specific infrastructure (shielding gas, three-phase electric power, material feed)	> 100,000 €
Extrusion Based Processes (EB)	Thermoplastic; polylactide (PLA); Acrylonitrile butadiene styrene (ABS) and ABSBlends; polyamide or nylon (PA), polycarbonate (PC) and PC-Blends; Acrylonitrile styrene acrylate (ASA); polyphenylsulfone (PPSF / PPSU); composite material like PLA with wood or natural fiber	Low investment costs Large selection of plastics Use in office space possible	Speed Precision Acceptable build quality Objects may bulge out after printing (wrapping effect)	< 10,000 €
Photopoly-merization Processes (PP) or Stereo-lithography (SLA)	Photopolymer (e.g. acrylic resin, epoxy or vinyl ester)	Printing large objects possible Precision Build quality	Speed High investment costs in individual cases	> 50,000 € (for industry use) < 10,000 € (for non-professional use)
Material Jetting	Photopolymer Polyester-based plastics	Precision Build quality Use in office space possible	Speed Limited selection of materials Limited object size	> 30,000 €
Binder Jetting (BJ)	Starch + water-borne binder; PMMA + wax based binder; metals; (stainless steel, bronze, inconel) + bronze or plastic; sand + plastic; ceramics + plastic or metals	Speed Investment costs Multicolor objects	Limited selection of materials Precision Build quality Structural robustness (fragile objects)	> 10,000 €
Sheet Lamination Processes (SL)	Paper; metals; plastics; ceramics	Multicolor objects (paper)	Surface quality Build quality Post-processing	> 10,000 €
Directed Energy Deposition Processes (DED)	Metal; plastics; ceramics	Possible to repair components, see PBF	see PBF	see PBF

Source: Gibson et al. 2015; Hagl 2015; and expert meeting at Inside 3D Printing conference in 2015

2.3 The 3D printing market

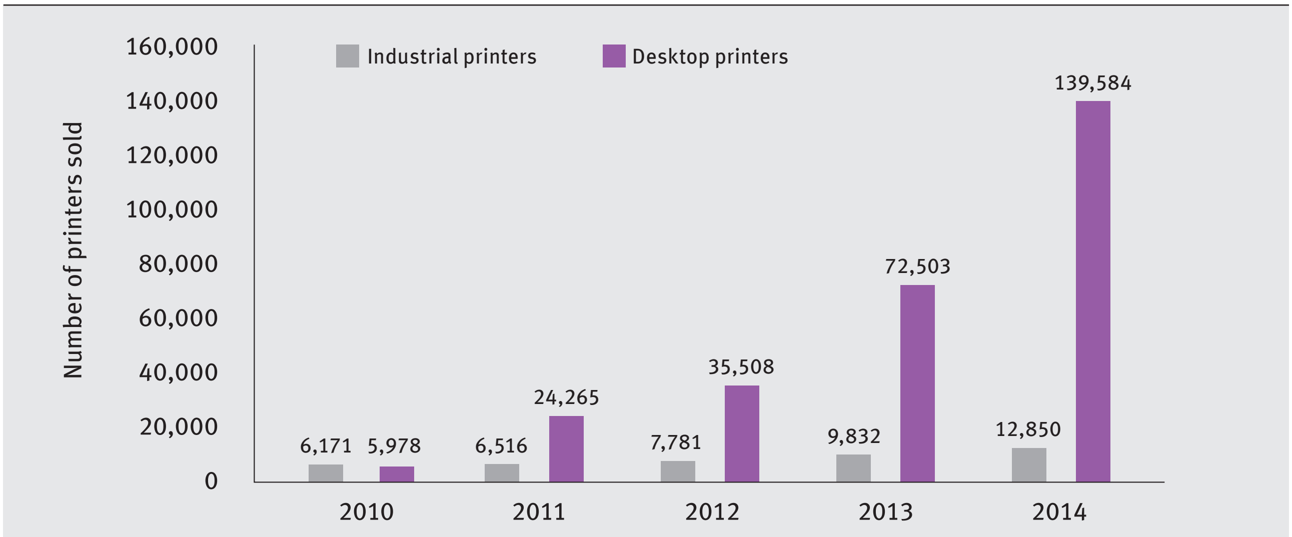
Between 2003 and 2013, the worldwide turnover of products for manufacturing by means of 3D printing, including 3D printers, material, accessories, software and services, increased from USD 529 million to 3.07 billion (Harhoff and Schnitzer 2015). Statements regarding developments on the 3D printing market can be made on the basis of several studies(Krämer 2014a; Krämer 2014b; Krämer 2015; Condemarin 2015). On principle, market development studies are subject to a relatively high uncertainty due to the method used (such as trend extrapolation). Nevertheless, all studies quoted in this context expect the 3D product market to grow, and at least, they do not contradict each other.

Referring to the entire market volume (i.e. including devices, materials, accessories and services), and based on the year 2013, an average annual growth of 45.7 per cent was estimated for the following five years, which would result in a volume of about USD 16 billion in 2018 (Krämer 2014b).[12] Of the total USD 16 billion estimated for 2018, devices account for about USD 5.4 billion, while services and materials account for about USD 10.8 billion (Krämer 2014b). According to another study, the market volume is expected to grow to about USD 17.2 billion by 2020 (Condemarin 2015).

Figure 3 shows the increase in the sale of 3D printers observed so far. For 2016, the number of 3D printers sold on a global level was assumed to grow to about 500,000. It is estimated that by 2019, about 5.6 billion devices will be in operation all over the world (Krämer 2015). Figure 3 also shows that the systems currently used are predominantly desktop systems. Desktop systems are defined as systems costing less than USD 5000. They are mainly used in small companies (e.g. by designers, architects, and service providers), in research and education. Industrial systems account for a minor share only.

Figure 3:

Desktop AM systems (USD < 5,000) vs. industrial AM systems sold globally



Source: Wohlers (2015)

[12] In this case, the authors' assumption was based on an initial value different from the figures mentioned above: They had estimated the total market volume for 2013 to amount to USD 2.5 billion.

Another interesting fact shown in Figure 3 is that the increase in the number of industrial printers is considerably lower than that recorded for desktop systems. Only in the field of desktop systems can one speak of a truly rapid growth in 3D printing. The growth rates observed in the industrial sector are high but not utterly extraordinary. It should be taken into account, however, that the growth rates for 3D printing will be quite different in individual sectors, as shown in Figure 4 below. Thus, the use in the energy sector is estimated to grow by 30-35 per cent in total in the 2014 to 2020 period (in the energy sector, 3D printing is used to produce, for example, components and conductors).

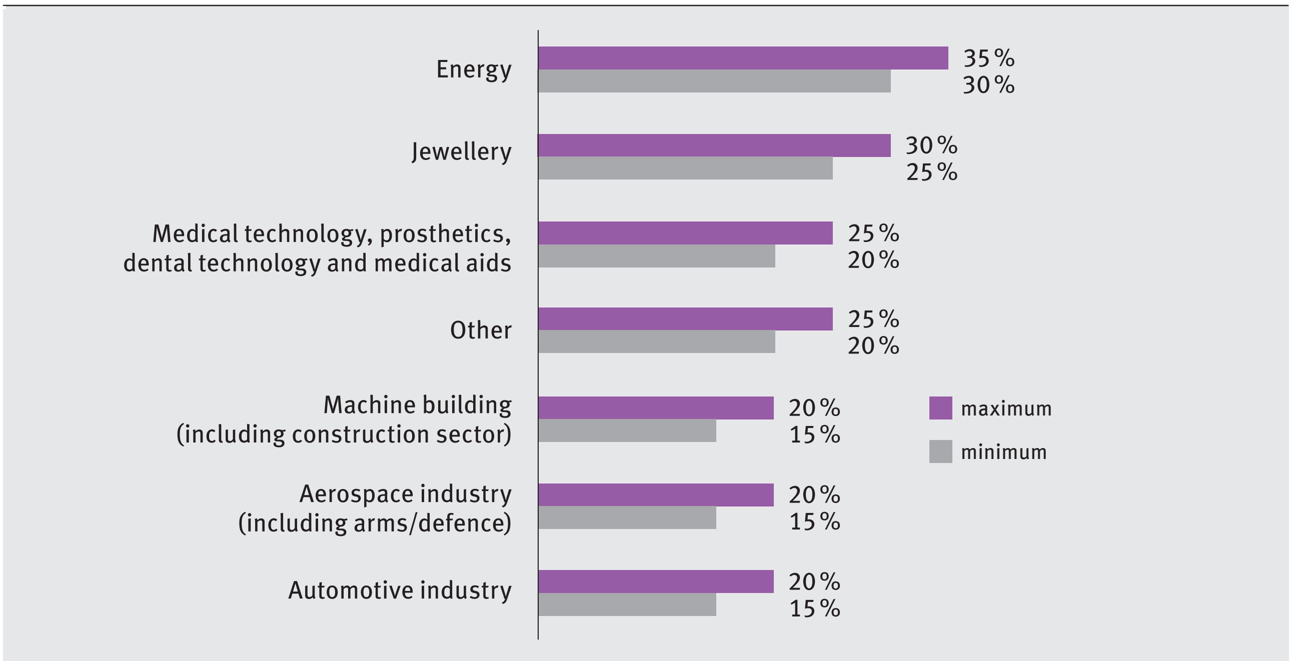
The above figures for 3D printing are intended to provide an adequate understanding of this market compared to other similar ones. These figures are still rather low when measured in terms of the trade volumes e.g. for paper printers, copiers and multifunction peripherals (MFPs): In 2014, for example, about 105 million units of the latter were sold, i.e. about 750 times the number of desktop 3D printing devices sold in the same year (Mitani and Lam 2015).

In terms of industrial use, the comparison with industrial injection moulding machines is the most interesting one because this production method is partly similar to 3D printing (e.g. regarding the printing materials used, namely plastics). In 2010, for example, the number of industrial injection moulding machines sold worldwide amounted to an estimated almost 100,000 units (ICC 2010), i.e. much more than the number of industrial 3D printers sold. At the same time, there is no indication for injection moulding being forced out of the market by 3D printing. For the 2014-2020 period, the growth rates for plastic injection moulding alone are estimated to reach about 5 per cent (Khuje 2016).

The position of 3D printing can be seen even more clearly in the context of industrial manufacturing processes, when compared to the world market for mechanical engineering: In 2014, worldwide machinery sales alone amounted to about EUR 942 billion (VDMA 2016). This shows that 3D printing is still a niche market.

Figure 4:

Estimated total growth rates for selected sectors (2014-2020)



Source: Condemarin (2015)

A situation similar to that outlined above (i.e. a low starting position with a very strong growth in certain sectors) is also found for the materials used. Projections for the market volume of thermoplastics, the most popular printing material so far, amount to one billion USD in 2025, while the price per kg is expected to decrease. For the seven materials used most frequently at present, a total market volume of about USD 8 billion has been estimated for 2025 (Gordon and Harrop 2015). Such materials include photopolymers, thermoplastics, thermoplastic powders, metal powders, gypsum, sand and binders. Materials that will be used increasingly in the future in addition include silicon, biomaterials, carbon fibre, regolith, ceramics, graphenes and electroconductive metals. Furthermore, composite materials will gain importance in the future (Gordon and Harrop 2015). Again, these figures are put into perspective when compared to the market volume for plastic materials which are used for injection moulding: The latter is expected to reach almost USD 300 billion in 2022 (Newswire 2016).

2.4 Central actors and fields of application

Essentially, the fields of application of 3D printing can be divided into industrial, private and experimental applications. While for industrial manufacturing, the technological maturity is already in an advanced state in many applications, manufacturing for consumers and bioprinting are still at an early technological stage (Harhoff and Schnitzer 2015).

Currently, industrial applications still include mainly small batches, spare parts and prototype construction, but also an integration of 3D printing into large-scale production is already being discussed. However, integration of 3D printing into such process chains will probably entail heavy investment costs since large-scale production is based on highly complex process chains and is optimised for conventional production processes. In addition, such integration would require a redesign of established and tested process chains.

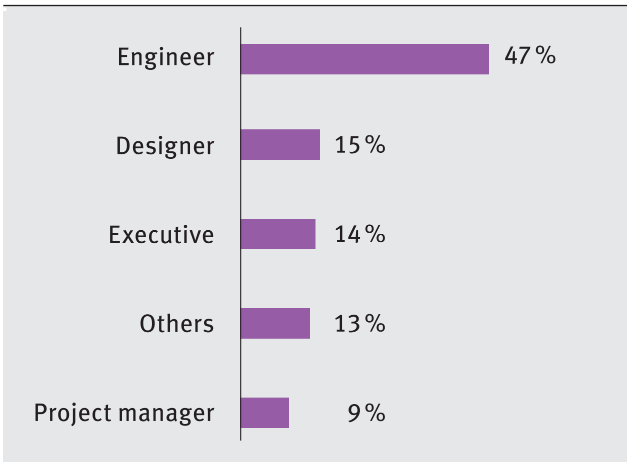
A majority of products manufactured by means of 3D printing can be assigned to the following sectors (after Marquardt 2014):

- Automotive industry
- Architecture, furniture industry, design and art
- Electrical engineering and electronics industry
- Film and entertainment industry
- Aerospace industry
- Medical technology, prosthetics, dental technology, medical aids
- Food industry
- Arms/defence industry
- Sports equipment industry
- Toys and game industry
- Textile and clothing industry

In the context of an online survey conducted by SMS Research Advisors among 700 users of 3D printing in North America (Stratasys Direct Manufacturing 2015), the central professional profiles, sectors and fields of application for the economy were presented. The majority of participants consisted of engineers, with 60 per cent of all participants being employees of companies with an annual turnover of less than USD 50 million (see Figure 5).

Figure 5:

Professional profiles of 3D printing users (N=700) in companies

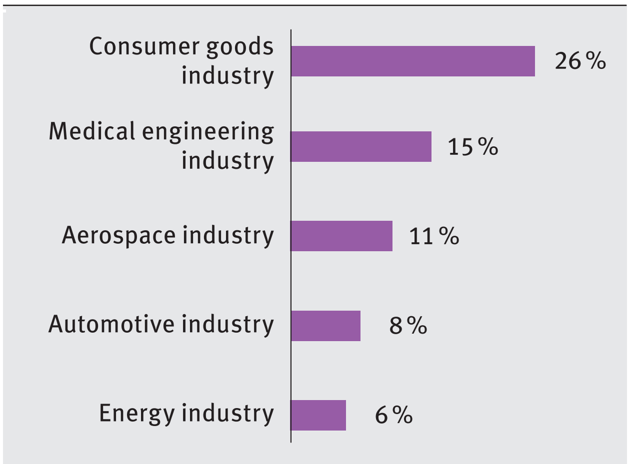


Source: Adapted from Stratasys Direct Manufacturing 2015

Central sectors mentioned included the consumer products industry, medical technology industry, aerospace industry, automotive industry and energy industry (see Figure 6).

Figure 6:

Use of 3D printing, by industries (currently or over the next three years)

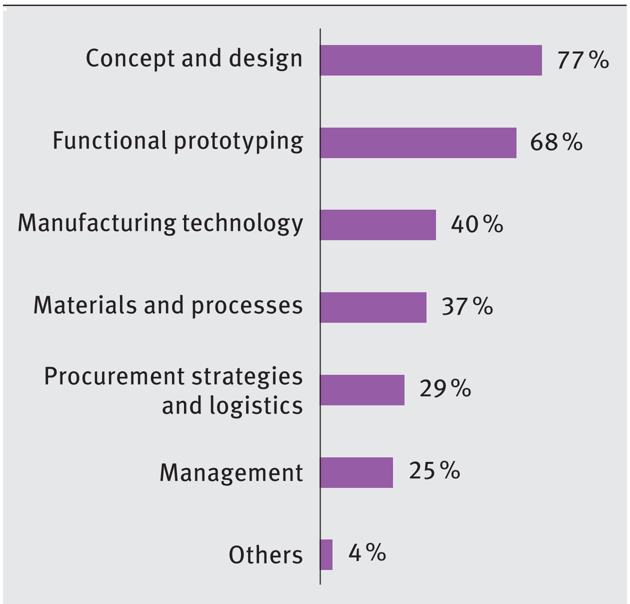


Source: Adapted from Stratasys Direct Manufacturing 2015

The most important fields of application found include concepts and design, functional prototyping, manufacturing engineering, materials and processes, sourcing/procurement strategies and logistics (see Figure 7).

Figure 7:

Use of 3D printing, by application fields (currently or over the next three years)



Source: Adapted from Stratasys Direct Manufacturing 2015

In the future, 3D printing will allow a better compliance with individual consumption and product needs, such as in the field of medical technology. For the latter, a great potential for tailor-made implants and prostheses is seen. A number of products such as hearing aids and dental prostheses are already today mostly manufactured by means of 3D printing (Harhoff and Schnitzer 2015). Such personalised products, where particular emphasis can be placed on individual fit and comfort, can provide an answer to the limited usability of standardised mass products.

In addition, 3D printers become increasingly affordable for private users. In particular, printers working on the basis of fused deposition modelling (FDM) are already being offered at prices below EUR 1,000. This fact enables products to be designed, produced and, if applicable, sold by private users themselves.

So far, 3D printing has been used in particular by private individuals participating in the Maker Movement. The Maker Movement is a subculture committed to DIY (Do It Yourself). Individuals acting in this group are mainly early technology users who apply digital tools and software to design products or create prototypes. They mainly collaborate in (online) communities, sharing their results and designs on the basis of an open source culture (Harhoff and Schnitzer 2015). There are no precise figures available at present as to the dimensions of the German and international Maker Movement. However, what is referred to as FabLabs (fabrication laboratories) and similar workshops for shared DIYs by means of 3D printers and similar devices can meanwhile be found even in smaller towns. In view of this fact, even if still perceived as a niche phenomenon, the movement can be assumed to be on the increase.

The role of public policies as an actor in 3D printing is mainly that of a funder.[13] In Germany, funding of 3D printing is provided, in particular, in the context of special fields of application. 3D printing is supported in the framework of institutional funding and project funding by the federal government, in the first place by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung – BMBF). Objectives of the two current funding measures of BMBF, namely (i) "Additive generative manufacturing – The 3D revolution for product manufacturing in the digital age" (term: 2013-2020; total budget: EUR 45 Million) and (ii) "Additive manufacturing – Individualised products, complex mass products, innovative materials" (ProMat_3D) (announced in 2015), include:

- Development of 3D printing to become a key technology;
- Building of sustainable network structures;
- Measurable enhancement of export demand;
- Positioning of Germany as a lead supplier; and
- Promotion of production and materials research.

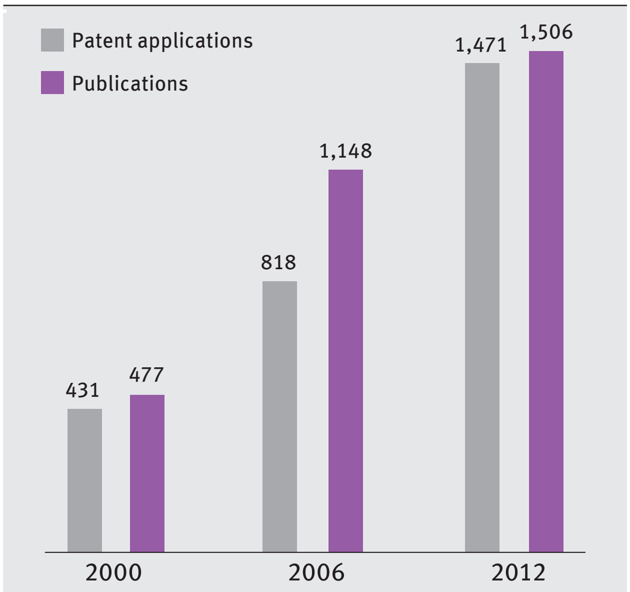
Often, the impacts of research and innovation policies become apparent with a delay. In order to anticipate the long-term directions and implications of current funding projects, an evaluation of important databases (German Environment Agency, German Research Foundation as well as the funding catalogues of BMBF, Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety, Federal Ministry for Economic Affairs and Energy, Federal Ministry of Food and Agriculture and Federal Ministry of Transport and Digital Infrastructure) on the subject of 3D printing was carried out. Among the 30 projects funded (completed or in progress) in the field of 3D printing, the engineering sciences are particularly well represented. Nevertheless, the social, environmental and economic sciences are also found to play an important role. Although the issues of sustainability and resource efficiency are less represented than for example those of substances and materials, they are already being worked on in the field of engineering sciences (Richter and Wischmann 2016).

In order to assess the existing research activities on 3D printing, the scientific research at universities as well as research and development activities of non-university institutions and companies were examined. Parameters selected for such assessment included the number of articles on 3D printing published in specialist journals, and that of PTC patent families filed. On the global level, both the number of published specialist articles with a focus in the field of 3D printing, and the number of PCT patent families filed per year has more than tripled between 2000 and 2012 (see Fig. 8).

Between 2000 and 2014, the majority of papers on 3D printing were published by scientists from the USA, China and Germany (Harhoff and Schnitzer 2015). Three technical universities in Germany are among the top 30 research institutions in the field of 3D printing, namely the Technical University of Munich, the Friedrich-Alexander University of Erlangen-Nuremberg, and the RWTH Aachen University (Harhoff and Schnitzer 2015). Based on the research projects analysed, and in view of the current objectives of funding policy in Germany, it can be assumed that the scientific debate about 3D printing has been mainly focused on engineering aspects.

Figure 8:

Number of patent applications and scientific publications on 3D printing



Source: Harhoff and Schnitzer 2015

[13] Funding of 3D printing in Germany is also provided by EU funds (an example is the EU-funded project "Performance", which was also joined by German companies and universities). An evaluation of all European projects referring to 3D printing could not be provided in the context of this trend report.

3 Assessment of burdens and benefits from 3D printing

“By its very nature 3D printing is a sustainable technology empowering 3D Systems’ printers to produce affordable products one layer at a time using only the necessary amount of material required for each part with near zero waste in an energy efficient process.” (3D Systems 2015)

There is a commonly held view that 3D printing can conserve resources, save energy and enhance sustainability of production and consumption (cf. e.g. Campbell 2011; Chen et al. 2015; Mani et al. 2014). In the following, this perception is subjected to a critical and systematic review. Included in the review are both the direct and indirect effects on the environment, as well as environmental implications of the innovation potential of 3D printing. Only the relevant results of the three methods are presented (for a detailed description of the methods used, see Chapter 1). As a result, a comprehensive picture of the environmental impacts of 3D printing is offered.

3.1 Direct environmental impacts

Production processes have a direct impact on the environment. They expend energy, use materials and thus, resources, and release pollutants. The same applies to 3D printing. As explained in Chapter 2, environmental burdens are generated depending on the type of printing method, the materials used and the type of application of 3D printing, among other factors. All three fields are examined in detail below.

3.1.1 Printing processes

“You have to look at the 3D printer, take a step back and realize it’s a little factory in a box.” (University of California, Riverside 2015)

The different 3D printing processes have a noteworthy impact only on certain environmental impact categories. The assessment procedure has found the following fields

Figure 9:

Facets of 3D printing

Direct environmental impacts | **Indirect environmental impacts** | **Environmental impacts of the innovative potential**

Source: see Picture credits, Chapter 7

to be affected: greenhouse gas emissions resulting from the energy demand of the processes; indoor air pollution from particulate matter; volatile organic compounds (VOC); nanoparticles; solvents; accidents resulting from use by unskilled persons; benefits in terms of resource utilisation owing to resource-efficient processes; and benefits with regard to wastewater generation because no cutting fluid is required (also see Fig. 10 below). Other fields examined are also affected by 3D printing but were found to be insignificant: physical factors such as exposure to noise and radiation as well as that to biological pressures such as pathogens or invasive substances (e.g. fungal spores), which may constitute a considerable risk in the context of "conventional" manufacturing processes, were not found to be significant for 3D printing.

Energy demand

"Energy use dominates the environmental impacts of 3D printers." (Faludi 2013)

Environmental burdens result from the high energy demand of all 3D printing devices. The energy demand differs between the individual printing technologies (Olson 2013; Baumers et al. 2011). Nevertheless, energy use dominates the direct environmental impacts of 3D printing in all manufacturing processes (Faludi et al. 2015a; Faludi et al. 2015b). If the energy demand is covered by fossil fuels, greenhouse gases are generated that contribute to climate change.

Energy consumption depends on a number of factors. These include, firstly, the time required to 3D print an object (Mognol et al. 2006). Secondly, the frequency of printing and the utilisation intervals play an important role. A printer used only rarely or with long idle times between the print orders has a high energy consumption due to the new warm-up times required for each order. Thus, the energy use per product increases tenfold if the printer is not operated at maximum utilisation (Faludi et al. 2015b). However, this difference varies considerably for the different 3D printing technologies. For fused deposition modeling, an extrusion-based process, there is almost no difference energy-wise whether only a single part is built or the printer is fully utilised, while during laser sintering (a powder-based process), 98 per cent less energy is used per printed part under conditions of full utilisation (Baumers et al. 2011). Such large deviation found for the laser sintering process is due to high energy demands during warm-up and cool-down (Baumers et. al 2011).

Under certain conditions, 3D printers may use less energy than other substituted manufacturing processes. However, it is impossible to make a general statement regarding the energy expenditure of different processes because their sustainability depends on the type and number of parts produced, among other factors. Also, 3D will presumably not replace other manufacturing processes (cf. Chapter 2.4 on the 3D printing market).

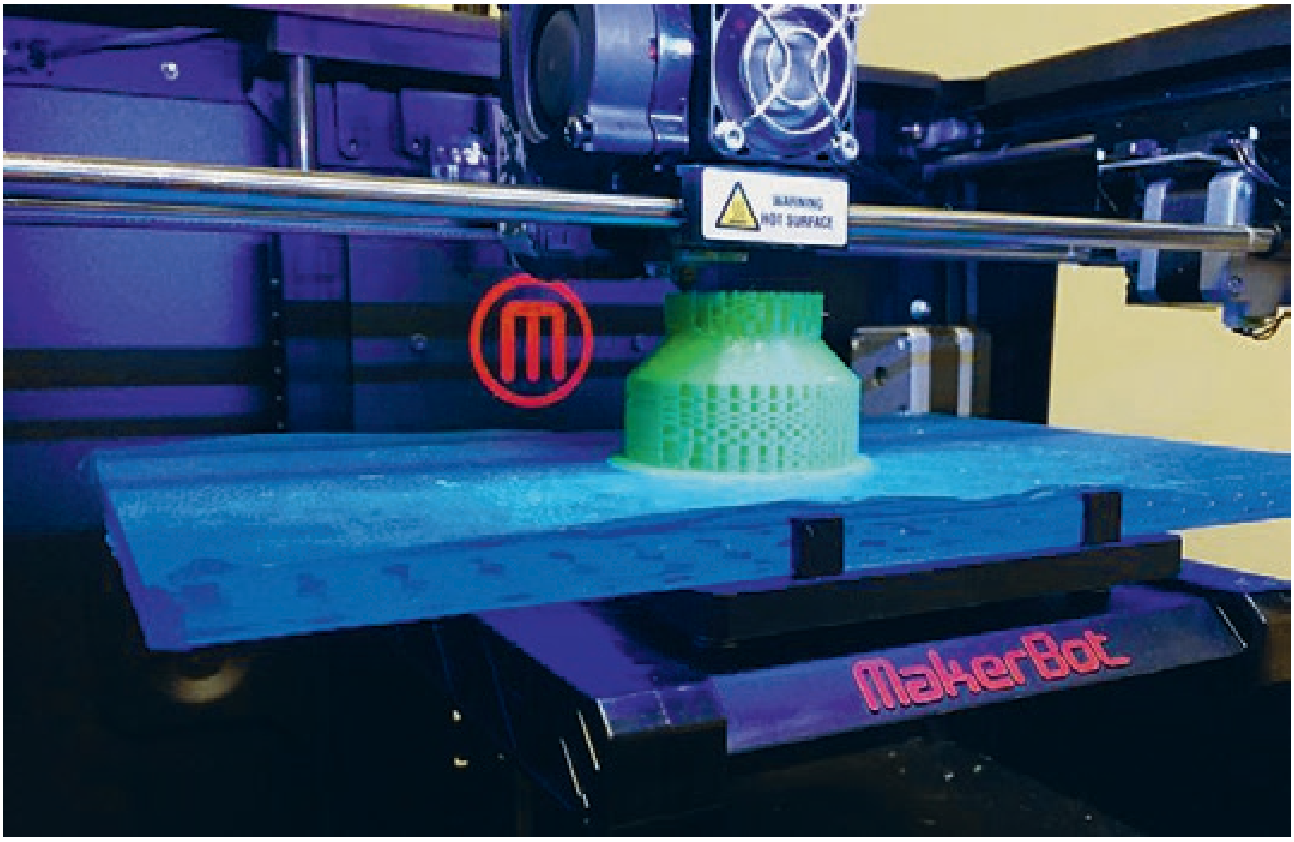
Figure 10:

Assessment of direct environmental impacts, 3D printing processes

Process	Greenhouse gases	Consumption of mineral resources	Indoor pollutants	Wastewater	Incidents / Accidents
Powder-based – PLS	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
Powder-based – MLS	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
Extrusion-based – phys.	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
Extrusion-based – chem.	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
VAT; stereolithography	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
Material Jetting	Potentially relevant (negative)	Potentially relevant (positive)	Irrelevant	Potentially relevant (positive)	Potentially relevant (negative)
Binder Jetting	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)
Sheet Lamination	Potentially relevant (negative)	Potentially relevant (positive)	Irrelevant	Potentially relevant (positive)	Potentially relevant (negative)
Directed Energy Deposition	Potentially relevant (negative)	Potentially relevant (positive)	Irrelevant	Potentially relevant (positive)	Potentially relevant (negative)

Potentially relevant (negative) Potentially relevant (positive) Irrelevant

Source: Chart generated by the authors



However, life-cycle assessments have been made for single printed objects, as compared to substituted manufacturing processes. Thus, for small production volumes, selective laser sintering (SLS) is more suitable than injection moulding in terms of energy consumption (Telenko and Seepersad 2011). The reason is that energy is consumed during the production of the tools required for injection moulding. At the same time, however, the energy consumption of SLS is substantially higher. Accordingly, injection moulding should be preferred for larger production volumes. Under conditions of full utilisation, extrusion-based processes use less energy for the production of one part than computer numerical control (CNC) milling. The same applies to stereolithography processes (Faludi et al. 2015a). In the future, the option to individually select sets of printing parameters will constitute an important basis to enhance energy efficiency of 3D printing processes (Mognol et al. 2006). Networked 3D printers may enable a more efficient utilisation of the devices and improve the utilisation profiles of the printers involved.

On an overall basis, the energy demands of 3D printing processes should be set into perspective against the current and the expected future market volume. As stated in Chapter 2, the industrial use is on the increase, but nevertheless, as compared to other manufacturing procedures, the number of devices and the market volume will still remain relatively small in the foreseeable future. This is why both the benefits and the burdens assumed for different applications will probably neither develop into a major problem for environmental policy nor are they expected to provide a major opportunity. Nevertheless, energy consumption should be kept in view by environmental policy because also in the future, it will constitute an important parameter for the sustainability of this technology. Currently, energy consumption is of key importance mainly for industry (because some processes are energy intensive in this sector). Should desktop 3D printers become more and more established in home use, the aspect of energy use could also gain importance in this field.

Raw material efficiency

“In a nutshell, 3D printers are not necessarily less wasteful; their waste is not necessarily recyclable; their waste isn't even that important compared to their electricity use.” (Faludi 2013)

One of the most debated advantages of 3D printing compared to conventional manufacturing, in particular subtractive processes, is the possibility of a practically waste-free manufacturing of products and components. Unique shapes in particular, such as personalised prostheses, can save considerable amounts of material (and production costs) if they are built by 3D printing. In dental technology, a clear development towards CAD-planned and additively manufactured implants can be observed (van Noort 2012). Compared to conventional manufacturing processes, printed solar cells with a thickness of several hundred nanometres show a great potential for saving materials and positively affecting life-cycle assessments (Krebs 2009). In metal processing, raw materials can be saved if the component is built additively by 3D printing because not only is less waste is generated, less material is required for the components in the first place (Petrovic et al. 2011).

Nevertheless, the argument of waste-free manufacturing has to be put into perspective to some extent because 3D printing also generates waste e.g. from support structures, misprints and the degradation of materials (Ahn 2013). However, support structures are not produced for all printing technologies, only for extrusion-based and powder-based processes and for binder jetting (Almeida and Correia 2016a). In extrusion-based processes, the support structure is deposited by secondary materials; in powder-based processes and binder jetting, the powder bed acts as a support structure. In extrusion-based processes, the support structure must be washed or broken away afterwards.

So far, standards are absent for design and best practice principles so that the objects created on the basis of the CAD model may differ as to their surface and positional tolerance (Gao et al. 2015). Reasons for this include the different printing processes and materials used and the positioning of the model (Gao et al. 2015). As a consequence, several trials may become necessary until the object complies with the requirements, a fact leading to misprints. In the future, implementation of electronics and circuits during the printing process could complicate the process and result in additional misprints.

Particulate matter, nanoparticles, volatile organic compounds, solvents and waste water

“During printing with ABS, a single printer emitted about 200 billion ultrafine particles per minute.” (Meier 2013)

During 3D printing, emissions may originate from several sources and during several process steps (Prof. Dr. Hans-Joachim Schmid 2016 personal comment).[14] Emissions are generated during the preparation of printing materials, during the actual printing process, during removal of the parts, during post-processing and the utilisation phase. In Table 2, plausible assumptions on several emissions generated during 3D printing are listed. Most of these will require further studies. (The Table does not contain all possible emissions). Technologies used in private and desktop environments have been marked in the table (these include photopolymerisation, stereolithography and extrusion-based processes).

Depending on the technology used, dusts, flue gases and vapours are released that are harmful to health. Emissions occurring for example during powder-based processes include: airborne and inhalable dusts released during the preparation of printing materials. Dust also forms due to additives in the printing materials, which may be harmful to health. Pollution from nanoparticles may be caused by additives. Dusts are also generated in the actual process, for example metal dust (potentially including particulate matter) in processes involving metals. Machines for industrial use have filters but nevertheless, due to the melting processes, nanoparticles may be generated, which later may be released and inhaled during removal, cleaning, polishing and surface treatment of the component. In addition, the components may contain residual particles and solvents which are emitted during the use phase.

For desktop use and industrial application of 3D printing, such emissions have already been examined more closely to some extent. Negative effects have to be expected e.g. for powder-based and extrusion-based processes (Stephens 2013) as well as for VAT/stereolithography (Short et al. 2015) and binder jetting (Afshar-Mohajer 2015). In these processes, particulate matter (PM) and volatile organic compounds (VOCs) are released. In

[14] The personal comments stated below originate from an expert workshop held on 29th September 2016 at the Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Berlin.

binder jetting, for example, the emission of particles measuring 2.5 µm (PM2.5) is ten times higher than the limit value of 35 µg/m³ fixed by the US Environmental Protection Agency (EPA). The emission rate found during printing with extrusion-based processes using PLA (polylactides) and ABS (acrylnitrile butadiene styrene) materials was between ca. 2.0 × 1,010 per minute for PLA-printed objects and ca. 1.9 × 1,011 per minute for ABS-printed objects (Stephens 2013). High levels of pollution from particulate matter and VOCs were also measured during printing with five commercially available extrusion-based printers and nine different printing materials (ABS, PLA, nylon, laybrick and laywood, among others) (Azimi et al. 2016), with higher emissions found for ABS than for PLA. VOC emissions vary considerably, with the highest levels resulting from nylon, PCTPE (plasticized copolyamide thermoplastic elastomer) and ABS (Azimi et al. 2016). It was found that styrene, which is classified as a possible human carcinogen, was emitted during printing with ABS materials and high impact polystyrene; and caprolactam, which is also harmful to human health, was emitted in considerable amounts during printing with nylon, PCTPE, laybrick and laywood (Azimi et al. 2016).

The measured maximum values of total volatile organic compounds (TVOC) were 1,725 µg/m³ and thus, clearly exceeded the value of 300 µg/m³ recommended by the Institute for Environment and Sustainability, Joint Research Centre of the European Commission (Afshar-Mohajer 2015). Particulate matter pollution caused by metal jetting, sheet lamination and direct energy deposition has not yet been sufficiently studied. However, during these processes plastic materials may be used and therefore particulate matter and VOCs are likely to be emitted owing to polymerisation.

In industry, environmental benefits result from the fact that neither water nor cutting fluid are needed for cooling and milling (Huang et al. 2013). Chemicals used in the cutting fluid have an adverse effect on the environment and pose health risks for the workers (Alves et al. 2006). Such chemicals include biocides, anticorrosives and antifoaming agents, which may contaminate the wastewater.

As mentioned in Chapter 2, a strong increase in the number of desktop printers is observed. As a result, the use of 3D printers by unskilled/lay persons in particular may constitute a problem in the future. Private users (including children), users in schools and public institutions, but also architects and designers will experience increasing risks from exposure to VOCs and particulate matter. Less serious risks have to be assumed for users in industrial environments owing to occupational health and safety provisions, as long as sufficient training is provided and processes are automated as much as possible.

Table 2:

Plausible assumptions on emissions from 3D printing (making no claim to be exhaustive)

Technology	Feedstock preparation	Building process	Parts release	Post processing	Use until end of life
Binder jetting (BJ)	Dust formation (during powder filling)	Flue gases	Dust (formed during parts release and depowdering)	Flue gases (sintering); infiltration; dust formation (polishing); surface treatment	Depending on the post-processing (e.g. infiltration), residual monomers; residual particles
Powder bed fusion processes	Dust formation (during powder filling)	Release of vapours and dusts (pyrolysis)	Dust (formed during parts release and depowdering)	Dust formation (polishing); surface treatment	Residual particles, residual solvent
Photopolymerization processes or stereolithography*	Gaseous emissions (from highly reactive monomers, curing/cross-linking agents and activators)	Gaseous emissions (from monomers) –› possible formation of aerosols and particles, UV radiation (UV soaking)	Gaseous emissions (from monomers)	Dust formation due to surface treatment, pyrolysis of polymeric materials due to thermal treatment	Residual monomers
Extrusion-based processes*	–	Release of vapours and dusts (from heated polymers)	–	Surface treatment (rarely), e.g. evaporation from immersion in acetone	–
Directed energy deposition processes	Dust formation (during powder filling)	Release of vapours and dusts (pyrolysis)	–	–	–
Material jetting	Gaseous emissions (from highly reactive monomers, curing/cross-linking agents and activators)	Gaseous emissions (from monomers) –› possible formation of aerosols and particles	Gaseous emissions (from monomers)	Removal of support material (wax)	Residual monomers

Processes marked with an asterisk (*) are also used as desktop applications by lay users.

Source: Adapted and supplemented after Seeger and Günster (2016; unpublished)

3.1.2 Materials: Extraction, processing, production and material properties

"Choosing good materials can also be important. Not only do better materials reduce resource use and waste, they reduce toxicity and even reduce energy use." (Faludi 2013)

Most plastic materials are based on petroleum (the picture shows printing filament based on plastic materials). During the extraction and processing of petroleum, greenhouse gases are generated, which have negative impacts on the environment (Hornbogen et al. 2013). Greenhouse gas emissions are also caused by biodegradable plastics such as polycaprolactone (PCL) and polylactides (PLA), e.g. during the cultivation of crops and processing. It needs to be considered that from an environmental perspective that biodegradability under laboratory conditions does not always correspond to that in practice, and that no real ecological benefit (e.g. humus formation) is produced by composting. Environmental impacts may also arise from the introduction of microplastics if plastics are increasingly disposed of in the environment as a consequence of a misleading communication of biodegradability.

Thermal utilisation of photoreactive plastics leads to ambient air pollution from nitrogen oxides, carbon monoxide and carbon dioxide. Depending on the additives employed, toxic gases such as hydrogen cyanide or sulphur compounds may form in addition. Currently, an increasing number of PLA composites and filler materials from renewable resources (e.g. coffee or coconut fibres) are placed on the market (Doris 2015a, 2014). Composite materials are used in 3D printing e.g. to build more rigid and firmer objects.

The use of metals will lead to other patterns of environmental burdens and benefits. Almost all types of metal processing are energy-intensive. If the energy demand is covered by fossil fuels, greenhouse gases are emitted. The extraction as well as the processing and disposal of metals is mostly associated with a considerable wastewater load and high input of pollutants. In addition, land and natural space are taken up by extraction activities. Metal resources are limited by nature, leading to a potential supply shortage unless these materials are recycled to a sufficient extent.

Replacement of metals and plastics by novel materials from renewable resources will lead to environmental impacts, such as fertilisers and pesticides used to cultivate crops for natural source materials, e.g. for starch and paper. Nutrients and pollutants may be introduced into the surface water and ground water. In general, all plastics,

Figure 11:

Direct environmental impacts, extraction, processing, production

Materials	Greenhouse gases	Ambient air pollutants	Wastewater	Diffuse inputs of nutrients and pollutants	Consumption of mineral resources	Water consumption	Use of natural space
Plastics	Potentially relevant (negative)	Potentially relevant (negative)	Irrelevant	Potentially relevant (negative)	Potentially relevant (negative)	Irrelevant	Potentially relevant (negative)
Metals	Potentially relevant (negative)	Potentially relevant (negative)	Potentially relevant (negative)	Potentially relevant (negative)	Potentially relevant (negative)	Irrelevant	Potentially relevant (negative)
Renewables	Potentially relevant (negative)	Irrelevant	Irrelevant	Potentially relevant (negative)	Potentially relevant (positive)	Potentially relevant (negative)	Potentially relevant (negative)

Legend: Potentially relevant (negative) · Potentially relevant (positive) · Irrelevant

Source: Chart generated by the authors

metals and materials from renewable natural resources imply a high share of grey energy (embodied energy) because highly refined materials are required for 3D printing (Olson 2013). In addition, natural space and water resources are consumed by agricultural production. Non-sustainable wood production for paper manufacture in particular poses a major hazard to regions with vulnerable ecosystems. In recent times, more plastic filaments from natural materials such as Green-TEC filament, BioFila, Buzzed and Willowflex have been placed on the market. However, it has to be taken into account that these materials are so far sold predominantly to private customers because the filament is still relatively new to the market and more expensive than other materials currently used. Altogether, these materials still constitute a niche market.

In addition to the negative environmental impacts caused by the extraction and processing of raw materials needed for the production of printing materials, environmental burdens may also originate from the properties of these materials. Objects produced by means of fused deposition modeling (FDM) and stereolithography (SLA) may be toxic, as suggested by first research results for these two widely used and commercially available 3D printing processes.[15] In these studies, the toxicity of parts produced from polymer filament by means of FDM and SLA was assessed in zebrafish (a method commonly used in toxicology) (Oskui et al. 2016; Macdonald et al. 2016). The parameters analysed included the rates of survival and developmental abnormalities, as compared to a control group. These first studies have shown SLA-printed parts to be significantly more toxic than FDM-printed parts: more than 50 per cent of the fish exposed to SLA-printed parts died after three days. After seven days, all zebrafish had died (in contrast, somewhat less than 60 per cent of the zebrafish exposed to FDM-printed parts were still alive after seven days). The cause of the toxicity of the SLA printed parts assumed by the authors is that the monomers and short-chain polymers contained in the filament become washed out from the printed part (the precise chemical composition of the materials is unknown for the materials examined; however, according to the authors, the safety data sheet indicates the printing materials used to contain acrylates and/or methacrylate monomers that may be toxic) (Oskui et al. 2016: 4). The toxicity of SLA-printed objects can be reduced by subsequent treatment with ultraviolet light. However, on principle, this fact illustrates the requirement to ensure a safe use and disposal of 3D printed objects.

Figure 12:

Direct environmental impacts, material properties

	Indoor pollutants	Consumption of natural resources
Toxicity, FDM / SLA-printed objects	Potentially relevant (negative)	Irrelevant
Recyclability / polymerisation	Irrelevant	Potentially relevant (negative)
Simultaneous printing of different materials	Irrelevant	Potentially relevant (negative)
Degradation of powders and photopolymers	Irrelevant	Potentially relevant (negative)

Legend: Potentially relevant (negative) — Irrelevant

Source: Chart generated by the authors

[15] The toxicity of printed objects may, in addition, result from the process itself.

Another problem consists in the recyclability of the materials and the 3D-printed objects, respectively. During photopolymerization (e.g. stereolithography), materials are transformed in a chemical process. The final products are not recyclable (cf. OECD 2016: 29f.). In addition, future 3D printers will allow for simultaneous printing of different materials, which are combined in one part. As a result, recycling becomes more difficult or even impossible because the separation of pure materials is not easily practicable. The recovery of primary plastics from 3D-printed composites constitutes a special challenge since the fill materials (powder, fibres etc.) are difficult to separate from the plastic matrix. During printing of metals and alloys, components can be produced that have different properties as compared to parts produced by means of classical processes (e.g. milling). Thus, steels can be printed which have new mechanical properties owing to a precise determination of the print parameters. As a result, among other consequences, the input of raw materials into the closed loop recycling economy may change.

The degradation of powders and photopolymers causes another special problem: When polymers are used in the powder bed process, 30 per cent of the material may lose quality due to the printing process and therefore, cannot be re-used (Silva and Rezende 2013). Degradation of the materials is also possible if metal powders are used. However, impure powders cannot be used for the printing processes (OECD 2017).

Overall, any possible future benefit from material savings is put into perspective by the poor recyclability, the degradation of some materials, and the use of supporting structures in some 3D printing processes. In the future, however, process enhancements will improve raw material efficiency, especially with regard to material degradation.

3.1.3 Application fields of 3D printing

"Meanwhile, 3D printing is so easy to handle and component parts can be produced so quickly that application possibilities have become enormously versatile."
(translated from FIZ Karlsruhe 2016)

3D printing is being used by industry, service providers, craftsmen and private individuals. Printed parts include, for example prototypes, spare parts and tools. These different patterns of use and types of service provision were examined for their potential environmental impacts by means of the assessment procedure. The relevant results are presented in this Chapter and illustrated in Figure 12. Burdens and benefits were found above all in the fields of chemical impacts and the consumption of natural resources. Categories found to be irrelevant include physical impacts (noise, radiation, killing of animals), biological impacts (pathogens, invasive substances) and incidents/accidents.

Printing for personal use

"Excess production of more or less value-free items justifies the question we are asked again and again: Why do you actually need a 3D printer in the household?"
(translated from FAZ 2014)

The private use of 3D printers is expected to rapidly increase in the future, above all because these devices are becoming more and more affordable and are increasingly attracting social attention (also see above, the market development discussed in Chapter 2, and Introduction). 3D printing will provide benefits when it comes to repairs at home because it allows a rapid and easy production of spare parts that are only rarely, or not at all, commercially available (see below, section on the printing of spare parts). Burdens will occur if defective objects ("crappy objects") are printed due to a lack of technical knowledge, or if objects are constantly adapted and improved and thus, unnecessary waste is generated. It has to be assumed that as a result of an increasing use of 3D technology, markedly more nonsense objects will be printed in the next years which have no added value for users/consumers (such as disposable sunglasses or disposable crockery). Printing for personal use may also be associated with changes in lifestyle and consumption patterns (see Chapter 3.2).

Printing of prototypes

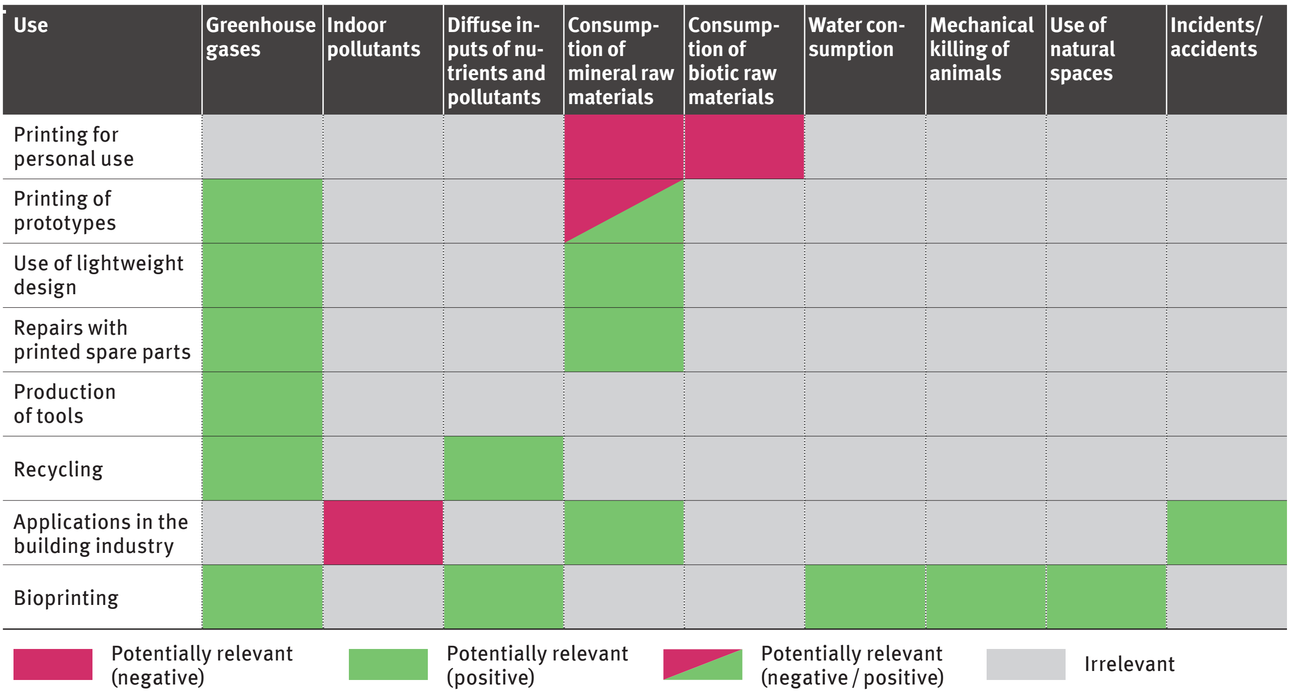
"In the manufacturing industry, the practical applications of 3D printing and rapid prototyping are simply limitless. This translates to better and more efficient research, design, and development of newer products without necessarily wasting a lot of resources on trial and error methods." (Anubis 3D 2016)

The special strengths of rapid and flexible manufacturing are used above all in "rapid prototyping", the original application of 3D printing. In almost all industrial sectors, 3D printing has become an important means to efficiently produce prototypes and thus accelerate the innovation process. Presently, the automotive industry is the largest user. For example, at the Ford factory, the average time needed to develop prototypes could be reduced from formerly 3-4 months to a few weeks (Loy and Tatham 2016). Depending on the printing process used, the production of prototypes requires considerably less resources and energy than production by means of conventional processes. Further expansion could provide even more significant environmental benefits. In addition, rapid prototyping allows for multiple repetition of the development process so that adjustments can be made, if required (Loy and Tatham 2016). Early and rapid prototyping may reduce the number of errors occurring in the further development process (Gao et al. 2015) However, a possible negative effect could consist in unnecessary testing and evaluating since these are faster and easier to accomplish through rapid prototyping (Gao et al. 2015).

Thanks to further quality improvement and decreasing purchase costs of 3D printing devices, this technology will probably become available more easily for applications in open workshops for private users (FabLabs or makerspaces) in the future, enabling individuals to test their ideas. Also in the fields of design and architecture, 3D printing will be used more frequently in the future. Architects and designers are thus enabled to test and adjust their products more quickly. In this way, innovation processes can be accelerated considerably.

Figure 13:

Direct environmental impacts, use and provision of services



Source: Chart generated by the authors

Application of lightweight design

"3D printing provides industry with unimagined opportunities for weight reduction by means of design options that had been unrealistic before." (translated from Leichtbau BW GmbH 2016)

The potential benefits result from the possibility of constructing especially complex lightweight structures by means of 3D printing (Petschow 2014). The lower weight of vehicle and aircraft components produced in lightweight construction leads to a reduction of fuel consumption and consequently, of greenhouse gas emissions (Burkhart and Aurich 2015). A study aiming to assess the greenhouse gas savings potential of aircraft with lightweight components, as compared to conventional aircraft, estimated the potential reduction to amount to 92-215 million metric tons of greenhouse gas equivalents per year. In addition, the use of metals harmful to the environment and human health, such as aluminium, titanium and nickel, can be reduced.

Lightweight production by means of 3D printing is applied by users in the automotive as well as in the aerospace industry. In the future composite materials will play an important role, making the lightweight technology offered by 3D printing attractive for more applications and actors, e.g. in the field of renewable energies as a material for wind turbine blades.

Manufacturing of spare parts and tools

"Thanks to 3D printing, companies may no longer need to store spare parts physically in a warehouse. Instead, they can print these parts on demand, where required, and rapidly deliver these items to the customer" (DHL 2016: 18)

Also in the industrial sector, the production of special spare parts by means of 3D printing provides benefits with regard to environmental resources and energy consumption by enabling or accelerating repairs that can expand the service life of tools and products. For example, aircraft manufacturers are increasingly relying on 3D-printed spare parts particularly for complex lightweight constructions in order to make the aircraft ready for operation again within a short period of time (cf. Khajavi et al. 2014). 3D printing of spare parts is also used by companies like Siemens, e.g. by directly printing spare parts (gas turbine blades) onto gas turbines (Andreas Graichen and Christoph Kiener 2016, Siemens, personal comment). The parts to be replaced are first removed. As a result, the turbines last longer.

Companies are appearing that specialise in the printing of spare parts (such as ExOne, a spare part provider based in the USA). Such companies are mainly commissioned by enterprises not using 3D printers themselves. Thus, e.g. Germany's Deutsche Bahn has planned to have spare parts for their trains that are no longer available manufactured by service providers (Stefanie Brickwede and Cagdas Girgin 2016, Deutsche Bahn, personal comment).

Additional advantages of customising the production include the prevention of overproduction and elimination of storage costs. However, the case study on the use of 3D printing in the spare parts supply chain for a fighter jet (cf. Siavash et al. 2013) has shown that presently, a centralised production of spare parts should still be preferred to a decentralised production. Nevertheless, 3D printing could become attractive in the future as soon as prices of printers will drop and their technical capabilities increase.

In many production sectors, the construction of special forming tools is an elaborate process. Complex tools with cooling channels, such as those needed for injection moulding of plastic parts, are easier and faster to produce with 3D-printed constructions. It has to be expected that with an increasing use of 3D printing in companies, also the production of the companies' own tools and spare parts will gain in importance in the future. Adverse health effects from the use of 3D printing for spare parts and tools are less likely to occur in industrial environments because standards of occupational safety and health have to be complied with in industry irrespective of the technology applied. However, effects may occur due to externalisation if tools are produced abroad in countries with lower social and environmental standards.

Private individuals have the opportunity to produce spare parts by way of 3D printing. For example, the RepRap can print spare parts that can considerably extend the service life of the RepRap. Private individuals may produce spare parts based on designs freely available on the internet or (in the future), 3D scanning technology. For example, more than 400 templates for spare parts (e.g. board games, dishwashers or wash basins) are offered on thingiverse.com (thingiverse 2016). Openly accessible platforms for CAD models that provide well-created files will be important for the future of private spare part printing. In addition, it should be ensured that private users (i.e. third parties) are given easy access to spare part templates offered by companies (either free of charge or for a fee). In this respect, copyright issues have to be clarified so that for example, 3D printing service providers are able to print spare parts for private users.

Decentral recycling

"By combining new technologies in collecting plastic waste with developments in recycling plastic into 3D Printer filament, we can convert quite literally 'one man's trash into another man's treasure.'" (3DPrinterOS 2016)

Above all, 3D printing technology has created opportunities to implement new recycling concepts for plastics.[16] For example, plastic waste from the ocean can be used to produce new printing materials, thus mitigating the pollution of soils and water bodies (Finger 2014; Lomas 2014). However, it has to be taken into account that due to salt, friction and UV exposure, materials from the ocean may degrade, and therefore, recycling and processing will constitute a challenge. Private persons may also directly establish a closed-loop recycling system where printed objects are transformed to become filament again (using energy) (cf. OECD 2017).

Current research on the recycling of plastic waste from private households has demonstrated that less grey energy (embodied energy) is needed than in conventional recycling systems (cf. Kreiger et al. 2014). In such procedures, household plastic waste is crushed on site and processed into new filament, which is used to produce new products. For less densely populated regions, this could result in energy savings of up to 80 per cent of the energy demand for transport and the collection of plastic waste. For the USA, about 100 million MJ of energy could be conserved per annum (Kreiger et al. 2014).

There are already early examples of this: an opportunity to raise awareness of the plastic waste problem using 3D printers is provided by Plastic Bank, a Canadian start-up company. In this project, plastic waste is collected at special exchange centres. The waste is then processed into filament, which is used to produce household items such as bowls, plates and buckets (3ders 2013). These items are made available to the people involved in collecting the plastic waste, in exchange for the waste they collected. So far, plastic waste can only be recycled to a limited extent. However, there are already simple devices for plastic recycling such as the RecycleBot (cf. Appropedia 2016). Similar to the RepRap, a self-replicating low-budget 3D printer, the RecycleBot was developed in an open-source project. By means of the RecycleBot, finely crushed plastic scraps can be melted and processed into filament. Old milk bottles can turn into new printing material, for example. Other examples include Precious Plastic (Precious Plastic 2016), Filabot (Filabot 2016) and Filafab (Filafab 2016). Precious Plastic develops recycling machines, sharing the blueprints free of charge as open-source files through an online community. Filabot is a commercially available recycling machine, and Filafab can be used to transform plastics (e.g. plastics from domestic waste) into 3D printing filament. In addition, 3D printers can be produced from recycled material. WoeLab, a makerspace based in Togo, has used electronic waste for this purpose (Sher 2014).

A major problem faced by decentralised recycling consists in sorting the materials so that they are as clean and pure as possible. The technology used for sorting and quality control in the closed-loop recycling economy is complex and expensive. It is unlikely that this technology can be scaled down (OECD 2017).

[16] The plastic materials are not recycled by the 3D printer itself. However, the recycling process is supported by the innovative properties of the technology such as flexible production sites and the possibility of being used by a wider range of producers. An example is on-site printing of new products using filament produced from plastic waste, as described in this section (also see Chapter 3.3).

In order to reduce the great number of potentially recyclable plastics, a possible strategy could be to focus on certain types of plastics. If the materials are sorted correctly, the quality of the printing material produced can be rated as good to very good.

Another problem comes from the fact that decentralised recycling requires the willingness of users to pay attention to recycling methods and sorting; transaction costs are generated. All things considered, the use of decentralised recycling is above all an opportunity for developing countries where closed-loop recycling structures are still underdeveloped.

Applications in the building industry

"Concrete 3D printer breaks down walls of traditional construction" (3dprintingindustry 2015)

The application of 3D printing in the building industry is currently expanding from a simple tool for construction and model making to the creation of full scale building parts. The materials used include, among others, concrete and polymers. Currently, first pilot projects are under way, such as the printing of large infrastructural parts, e.g. a bridge, building parts and entire houses (see MX3D 2016). There are three 3D printing processes that are suitable for large-scale objects: Contour Crafting, D-Shape (Monolite) and Concrete Printing. In the future, there could be several advantages to the application of 3D printing in the building industry. Under certain conditions, in situ printing of building parts may be more eco-friendly in terms of resource consumption than conventional construction processes because no craning of components is required and complex geometries are easier to implement. The aluminium structure used for the D-Shape process is very light and can be easily transported, assembled and dismantled (Oberti and Plantamura 2015). In addition, such printers can also be used in dangerous places under difficult working conditions, thus reducing the risk of accidents. By means of these printers, construction components could possibly be produced more rapidly, more accurately and with less waste. In addition, material and labour costs are reduced.

If in the future, significant quantities of materials can be saved from using 3D printing in the building industry. Major positive environmental impacts can be expected because the amount of materials used in the building industry is generally very large However, it has to be taken into account that in the foreseeable future the advantages of 3D printing will become most relevant for complex objects where only one material is used. Yet, the reality of the building industry is the opposite: relatively simple objects are produced using several materials. Also in the foreseeable future, buildings e.g. houses built by conventional means will still incur lower costs than houses or parts of buildings manufactured by 3D printing. Nevertheless, 3D printing could have advantages in the future when it comes to more complex forms of construction, e.g. in buildings and building complexes characterised by a higher adaptability to climate change based on their structure (different types of formwork) (Reutter 2015).

Disadvantages lie with the construction material and weather-dependency of on-site manufacturing, for example due to the longer curing times required for the concrete mixtures suitable for 3D printing (Lim et al. 2012). Furthermore, 3D printing of building parts requires the addition of concrete admixtures to accelerate concrete curing. The reason is that during 3D printing, cement is deposited in a layer-by-layer manner, and each layer must be sufficiently cured before a new one is added (Oberti and Plantamura 2015). The properties of additives used in the existing processes are not sufficiently understood. On principle, burdens from indoor air pollution could occur (Oberti and Plantamura 2015). A potential health risk for workers could also be posed by emissions of particulate matter.

Bioprinting and food production

"Biofabricating meat and leather is a civilized way to move past killing animals for hamburgers and handbags." (Forgacs 2013)

Some groups are expected to further develop and progress bioprinting in the future (cf. e.g. Murpy and Atala 2014). The term 'bioprinting' refers to 3D printing technologies serving as a basis for defined deposition of single organic cells and organic tissue, and multiplication of such cells in a bioreactor. In such processes, the techniques of tissue engineering are applied. Because the current level of technological maturity is low, bioprinting is still an issue for research only (Harhoff and Schnitzer 2015). Nevertheless, a constant stream of success stories are being published about it.

A central application field for bioprinting is the health sector. In contrast to many other fields such as the building industry, 3D printing is already used in many ways (see Chapter 2). Further innovations in the medical field can be expected to follow in the future, such as new medical instruments, implants and prostheses. Basic research already exists in the field of bioprinting. Two-dimensional tissue has already been tested and produced. Three-dimensional objects such as blood vessels and hollow organs are subjects of developmental research, and research is underway on the printing of entire organs (Murphy and Atala 2014; also see Chapter 2 and Chapter 3.1.3, on bioprinting). Altogether, a multitude of applications are imaginable, that exceed the current state of development, once these technologies reach the medical market.

However, it has to be taken into account that, especially with regard to bioprinting of complex objects, considerable time will still be required until organs can indeed be printed and implanted. In addition, it should be noted that in the future, the production of organs will be possible also without using 3D printing technology. Research in this field is already exploring, for example, how to extract cell components of organs from pigs and rats by means of a washing solution. Subsequently, the remaining connective tissue matrix can be seeded with cells again (cf. TRM Leipzig 2015). 3D printing is therefore not unique feature in this field.

Another important application for bioprinting is in toxicity analyses. Within the medical field, it is currently possible to print with living cells onto a supporting structure, on which the cells can then grow (Koll 2015). Artificial tissues of this kind (e.g. skin models) are intended for use in toxicity analyses in the near future, possibly serving as alternatives to animal experiments. In Germany alone, more than 2 million animals were used for testing in 2014 (BMEL 2015). As a result, animal suffering and/or the number of animals killed for medical purposes could be reduced. This technology is already being applied,, e.g. L'Oréal USA has entered into a collaboration with Organovo for the creation of 3D-printed and subsequently cultured living tissue, which can be used for the evaluation of new products (L'Oréal 2015).

In addition, artificial biomaterial for food or leather for commercial purposes could be produced from harvesting animal tissue cells. This generates positive implications for the environment, namely a mitigation of the environmental impacts of global meat production (i.e. changes to land use, greenhouse gas emissions, nitrogen pollution, among others). Research findings in this field have shown that the production of artificial meat requires up to 45 per cent less energy, causes up to 96 per cent less greenhouse gas emissions, uses up to 99 per cent less land and up to 96 per cent less water, as compared to conventional meat production (Tuomisto et al. 2011).

The first applications already exist in this field. For example, a piece of cultured meat ready for consumption was printed at Maastricht University in 2013 (Maastricht University 2015). Based on these initial achievements, the Dutch start-up company Mosa Meat was founded, which has envisaged developing cultured meat to a commercial leveland introducing it into the mass market. A similar goal is pursued by Beyond Meat, a U.S. American company (http://beyondmeat.com). Another company dedicated to this subject is Modern Meadow, the parent company of Organovo Holdings. They have been carrying out research for a number of years with the aim to produce artificial biomaterial for human consumption and as a leather substitute (Modern Meadow, 2015). In the USA, the research in cellular agriculture is supported by New Harvest, a non-profit institute (New Harvest, 2015). New Harvest organises research conferences on cellular agriculture and provides funding for projects aimed at producing milk, eggs and meat without exploiting or killing animals. However, it will still take some time until alternatives to meat from animals can be produced in large quantities. According to researchers from the University of Maastricht, this could be accomplished within an estimated period of 10-20 years. The development costs of producing their first piece of meat measuring 2 × 1 × 0.1 cm amounted to EUR 250,000 (DWN, 2013). The collection of the source material should also be considered from an animal ethics persepctive. In this respect, it is particularly important to take account the husbandry of donor animals, as well as the nutrient solution for cell cultures (these are based on foetal calf serum, which is collected from live foetuses of slaughtered cows)if the production of artificial meat is upscaled (to commercial levels).

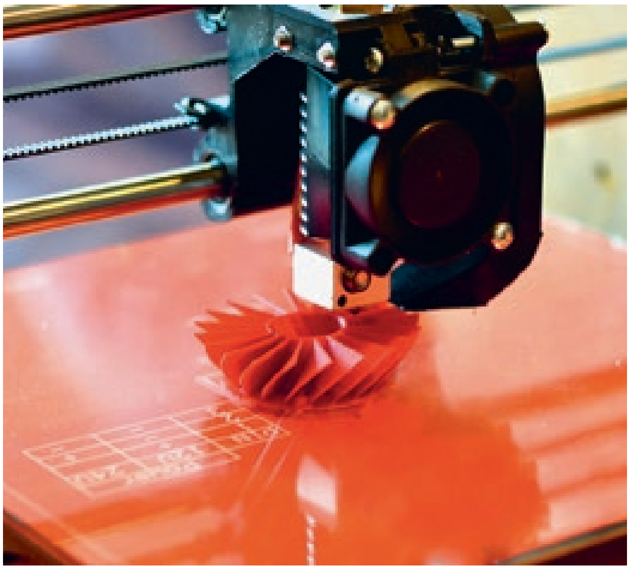
Another option for the use of 3D printing could be in the production of vegan meat, e.g. in the form of vegan burgers. For this purpose, the Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer Institut für Verfahrenstechnik und Verpackung – IVV) uses the technology of wet texturing, where a vegetal protein mash is heated and deposited via a nozzle. Based on these developments, the AMIDORI Food Company (http://www.amidori.com) was founded. The extrusion technology is also used by the company Beyond Meat (http://beyondmeat.com) from the USA. At early market trials at fresh meat counters they offer a meatless burger which is very similar to the original, both in texture and taste. Further investigation is needed to examine whether extrusion-based 3D printing technologies can be used to produce vegan meat, and what would be the possible advantages of their use.

3.1.4 Summary of the direct environmental impacts of 3D printing

The analysis of the three areas of "printing procedures", "materials" and "application fields" shows a number of different environmental impacts of 3D printing. On the one hand, these printing technologies will cause future burdens due to their high energy demand and generation of indoor pollutants (particulate matter, VOC, nanoparticles). On the other, however, benefits can be expected to a certain extent, due to more resource-efficient processes. The production of raw and printing materials will have negative impacts on the environment via the use of natural space and diffuse inputs of nutrients and pollutants. Other burdens arise from the toxicity and poor recyclability of some materials. Future benefits to be expected overall from using 3D printing include:

- benefits for the industry from the use of prototypes, lightweight design, spare parts and tools;
- benefits for private individuals from recycling and possibly from the consumption of foods produced by means of 3D printing. Further future environmental benefits could arise from toxicity testing supported by 3D printing.

For a better assessment of the extent of such environmental impacts, the development of the 3D printing market has to be taken into account as well. In this respect it was generally found that in the foreseeable future, 3D printing will account for an extremely small share of the machinery in operation on the global level. Hence, the burdens arising from energy demand and material consumption are put into perspective. A different assessment has to be made with regard to indoor pollutants and substance toxicity, i.e. the potential exposure of users in desktop environments, such as private individuals, designers and architects. The number of devices sold to such users is steeply rising. This sector should therefore be closely monitored by environmental policy.



3.2 Indirect (environmental) impacts

Trends like 3D printing also have indirect impacts on the environment and society. For example, the advent of 3D printing may be followed by changes in consumption patterns or the emergence of social changes, which, in turn, may lead to environmental effects. Altogether, burdens or benefits for the environment resulting from such changes are generated over long and complex multi-causal effect chains (Kaltschmitt and Schebeck 2015). For an environmental assessment of trends, it is therefore crucial (but also particularly difficult) to also identify the indirect effects.

The fields that have indirect effects on the environment due to 3D printing were identified and subjected to a detailed analysis in the assessment procedure developed for this project. To this end, indirect environmental impacts of 3D printing were sought for in the search fields of population and demography, society and culture, politics, science, and technology and space. The findings are presented in as certain terms as possible. Due to the indirect nature of the effects, a major part of such environmental implications can only be roughly outlined in this context.

3.2.1 Development of new niche markets and business models

3D printing also has an impact on the economy, above all on the competitive position and profitability of companies. 3D printing can open up new business models (Rayna et al. 2016). 3D printing offers companies several advantages: A number of niche markets can be served more easily that had not been brought into focus so far due to a lack of commercial viability, e.g. in cases of uncertain demand for a product where large-scale production would be unprofitable.

This is illustrated by several application examples. Hasbro, a Japanese toy manufacturer, collaborates with Shapeways, a 3D service provider. On the website SuperFanArt, customers may use and modify registered trademarks by Hasbro and create their own models of the brands such as My Little Pony (all3dp 2015). Designs accepted by Hasbro are published on the website and may be purchased by customers. Shapeways produces and distributes these toys. In this way, a new business model has emerged for Hasbro: Already developed products only need to be approved, thus rendering the company's own development redundant. At the same time, a long-term relationship can be established with customers and possibly, with an entire online community. In this case, environmental impacts arise from the modified production technique of the toys, from a possible increase in sales and from changes to the logistics (also cf. next section).

Local Motors, an American company, provides open source access to the design process of 3D printed cars (Local Motors 2016). Users may cooperate in several tasks such as designing individual car components. The ideas submitted are discussed online, and eventually, the most compelling of these ideas are selected by Local Motors. These are then improved and subsequently implemented. Based on such approach, Local Motors can benefit from the users' expertise and simultaneously, establish a long-term relationship with them. This may result in different environmental impacts: Benefits may be expected if, for example, more expertise on eco-friendly car design is introduced, owing to the transparent and public development process. At the same time, production may become increasingly customised, leading to higher production costs if such customised cars are produced in small quantities.

The above (small-scale) examples make 3D printing appear as a driver of economic development, based on opening up niche markets. These effects have not yet been quantified on a macroeconomic level, or for individual companies (and the examples mentioned above). Also the environmental impacts have not yet been analysed. Previous research has found (on a higher aggregate level) changes in income levels are closely related to the connection between economic growth and environmental impacts (Bagliania et al. 2008; Bringezu et al. 2004; Atıl Aşıcı and Acar 2016). Growth of enterprises, industries or even entire economies can create new jobs and lead to increasing incomes. However, changes in income levels are closely correlated with environmental impacts such as the demand for resources because they lead to an increase in consumption. 3D printing may further promote economic development and in this way, lead to indirect environmental impacts (particularly if the growth does not occur in emerging green markets, which would serve the transformation towards a green economy).

3.2.2 Decentralisation of logistics and transport

The use of 3D printing may contribute to a relocation of production and affect established logistics structures, as product transport can be dispensed with due to on-site printing(Campbell 2011). Such decentralisation may result in an ecological benefit from reduced emissions that affect environmental protection objectives such as ambient air, soils and water (Bühner 2013). Additionally, thanks to 3D printing, goods are easier to produce on demand, and decisions on production can be postponed until there is sufficient demand for the product (Tang et al. 2016). However, transport cannot be eliminated completely because it will still be required for the raw materials for printing material and printer parts (Faludi et al. 2015a). The transport routes of the printing filament for domestic 3D printers may even be as long as those of products from mass production (Petschow 2014).

Overall, it becomes evident that a decentralisation of production by means of 3D printing technology does not necessarily contribute to a reduction of the carbon footprint if material, processing and disposal are taken into account, in addition to the distances travelled (Petschow 2014). Essential factors include the type of transport (especially air transport) and the individual behaviour of users that may have an impact on the carbon footprint (product service life) (Petschow 2014). Case studies have also demonstrated that 3D printing does not necessarily contribute to relocation. On the contrary, a detrimental development could even arise since CAD templates are easily sent abroad (Sandström 2016). From an industrial and entrepreneurial perspective, a regionalisation of spare part production in individual centres is imaginable, while a scenario where printers are directly delivered to the customer (e.g. by service providers) is improbable (since such a process would be too costly/difficult to implement).

An advantage of home production is that return shipments of products are eliminated because they are printed directly on site. In addition, a decentralised production of spare parts has economic advantages because it could save on storage costs, reduce waiting times and contribute to a sparing use of resources owing to material savings (Petschow 2014). It has to be taken into account, however, that resource consumption would increase due to the growing number of printers in operation.

3.2.3 Changes in consumption patterns and lifestyles

3D printing may have cultural implications. These will mainly relate to the use of 3D printers in the private sphere. Multifaceted interrelationships start to appear. As described in Chapter 2.3, the number of desktop printers sold is steeply rising. Simultaneously, 3D printing is increasingly used in FabLabs and makerspaces. In this context, 3D printing can be seen as a social practice associated with certain values, lifestyles and motivations. These values, lifestyles and motivations may in turn have environmental relevance. Presently, there is only initial qualitative research examining this practice in more detail (see e.g. Kohtala and Sampsa 2015; Fordyce 2015; Prendeville et al. 2016).

The social practice in makerspaces and FabLabs can, on principle, be associated with a number of values relating to the environment in a positive way. These include, for instance, “participation”, “collaboration”, “sharing”, “self-actualisation”, “experimenting” and “openness” (see Bonvoisin 2016). A number of authors have also pointed out that FabLabs and makerspaces are part of the counterculture, i.e. a movement generally characterised by a sceptical attitude towards the throwaway

society and increasing consumption (see Bonvoisin 2016). At the same time, the motivations of FabLab and makerspace users vary considerably. Often, the fun in tinkering and interacting with others are of paramount importance. Not all users of 3D printing take an interest in aspects of sustainability and environmental protection. For example, a case study conducted among 3D printing hobbyists in a workshop has revealed only about 25 per cent of the users to reflect environmental issues (Kothala 2015).

In addition to the FabLabs and makerspaces, the social practice of 3D printing at home is relevant. However there is hardly any research available so far with regard to values and lifestyles of environmental relevance. The use of 3D printers could (depending on the amount of goods produced) lead to changes in the relationship between consumption and production because 3D printing technology eliminates the strict separation between them. As a consequence, the side effects of mass production (such as material consumption) could become more apparent to individual consumers. An important factor is that consumers may develop a stronger bond to objects they have made themselves. This factor is often presented as an advantage of 3D printing. For example, research has pointed out that self-made objects are associated with memories, which could possibly extend the useful lifetime of such products (see for example Chen et al. 2015; Gao et al. 2015). It is worth considering, however, that in the private sphere, 3D printing is so far used for special applications only (e.g. decoration). This is exemplified by Thingiverse, a sharing platform for print designs. Its users share designs of spare parts (see above, Chapter 3.1.3), but the majority of designs offered are for art, fashion, gadgets and hobby items (also see Olson 2013, and Chapter 3.1.3, on 3D printing at home). In addition, a mass-produced article may be associated with certain memories (depending on the item concerned). Without further studies, it is not yet possible to predict precisely which behavioural patterns will eventually assert themselves and whether, in light of a diversity of social values, any generalizable developments or consumption trends, respectively, can be derived at all.

Nevertheless, from an overall perspective, 3D printing provides the opportunity to strengthen sustainability values via the maker movement and FabLabs. In terms of environmental policy, the use of printers at home will be most important because, as described in Chapter 2, the number of desktop printers will increase considerably in the near future. In this respect, 3D printing presents an ambivalent picture: similar to consumption in general, ecology-minded use can be expected in individual cases (e.g. for spare parts; also see Chapter 3.1). Also, a bond to printed objects for a few individual users, initiated by the cultural processes described above, is foreseeable. Altogether, however, 3D printing is not likely to result in comprehensive changes in the behaviour of wide groups of users that would be relevant for sustainability. Existing motivations and behaviour of consumers will tend to have retroactive effects on 3D printing. It appears that the potential positive effects on lifestyles, motivations and values described above are not powerful enough to mitigate such a development.

3.2.4 Summary of indirect environmental impacts of 3D printing

The analysis of indirect impacts found several of the indirect dimensions could be affected. Correlations with the dimensions of economy as well as society and culture appear to be particularly relevant. In commercial environments, 3D printing has been used for some time already, increasingly beyond rapid prototyping (see Chapter 2). As compared to the global mechanical engineering sector, 3D printing will still remain a niche market in the foreseeable future. Nevertheless, 3D printing can provide competitive advantages within this niche market and allow for new business models. The field of society and culture is also relevant because, as explained in Chapter 2, the number of desktop printers used will continue to grow considerably. Consequently, especially the lifestyles and values associated with 3D printing will gain in importance.

The environmental impacts (and the VERUM impact categories) are difficult to assess due to the diffuse relationships over a chain of effects. Altogether, there is a great number of interv ening variables that influence the environmental impacts. These include rebound effects from increased resource efficiency. From an overall perspective, however, the demand for natural resources is particularly affected because the quantities of resources used will depend on demographic development, changes in incomes and consumer behaviour.

3.3 Identification of innovative characteristics

Future environmental impacts can also be identified via the innovative potential of trends. Such approach is based on the ICC procedure briefly described in Chapter 1. The method abstracts from the specific 3D printing technologies and printing materials as well as current and foreseeable use. The innovative characteristics of 3D printing are chosen as a starting point. Based on these characteristics, conceivable future impacts on the environment are examined.

Such an approach is characterised by significantly greater openness and the look ahead into a more distant future. Such perspective complements the two previous analyses (Chapters 3.1 and 3.2), which are more focussed on impacts that are already foreseeable.

The IIC procedure for 3D printing has found a number of specific innovative characteristics, namely:

1. Freedom of design and production
2. New producers
3. Flexible production sites

Some of the characteristics and their consequences are already implicitly included in the sections above. And several implications of the innovative characteristics of 3D printing are becoming obvious already today. Below, however, the focus is overall on implications not yet discussed in detail so far.

“Freedom of design and production” describes the innovative characteristic of 3D printing to build, in a layer-by-layer manner, complex geometries from formless raw materials. In contrast to milling or cutting, 3D printing does not have to concern itself with the practicability of production from semi-finished products. As a result, some of the previous specifications for items such as their thickness are eliminated.

The innovative characteristic of “New producers” means that anyone can become a producer, owing to affordable prices and a relatively simple handling of desktop 3D printers. Presently, the price of printing devices for private use is between EUR 800 and 2,500 (also see overview in Chapter 2). In addition, it can be expected that former barriers with regard to accessibility of technologies, e.g. handling of the CAD software, will probably be reduced in the future. For example, the toy company Mattel has envisaged to make 3D printing available to children from 3 years of age already with the market launch of the ThingMaker 3D printer (Mattel 2016).

The innovative characteristic of “Flexible production sites” results from 3D printing devices being relatively site-independent and easily installed and thus, they can produce itemsin-situ, based on a digital CAD model. Transportation is only required for the printing filament and the finished product.

These three innovative characteristics create an area of tension for environmental policy. 3D printing is associated with certain new freedoms that make this trend innovative. As described above, “Freedom of design and production” can be interpreted as the freedom to design and produce items. “Flexible production sites” means the freedom to produce something in many different places. “New producers” implies the freedom for many different actors to produce objects. This is why a number of authors have referred to this production technology as being “democratic” (see, for example, Gao et al. 2015). These new freedoms can be “democratic” because they offer access to production for an ever increasing number of people.

However, the freedom to create something conflicts with the requirement to control the (negative) impacts of such freedoms (in this case, of production processes) and make them humane and eco-friendly. Environmental policy faces the fundamental challenge that on the one hand, the positive aspects associated with 3D printing should not be restricted, and should even be promoted, if required. On the other hand, there is the need to minimise potential future burdens resulting from such new freedoms. This tense relation should be taken into account, particularly because environmental policy has to deal with the basic problem of time lag, i.e. the problem of there being a delay in reacting to new environmental issues. Specific challenges and implications for environmental policy are derived from the innovative characteristics identified above. The tense relationship is present in all these environmental impacts, although the resulting burdens and benefits are unique in each case.

3.1.1 Freedom of design and production

New buildings

For a long time architects have been fascinated with designing energy-efficient buildings that are modelled on natural termite mounds. In the hottest regions of Africa and Australia, with outside temperatures fluctuating by up to 40° C within one day and night cycle, termites manage to maintain a constant climate of about 30° C in their nest mound, which consists of dead wood, clay and saliva. This results, firstly, from the naturally circulating air in the chimney-like structure. Owing to its low density, warm air rises and can escape at the top, while cool air is drawn in from the bottom. Secondly, because the mound is narrow and tall, a small surface area is exposed to the sun at noon, while in the morning and evening, with the sun shining in a flat angle, a maximum surface is exposed, thus heating the building before or after a cold night. This system could be successfully transferred to the construction of buildings when 3D printing was introduced as a standard in the building industry. By means of printers mounted onto cranes, the material for facades is build up in a manner allowing an optimal reflection of solar radiation. Also the tubular shape can be adjusted for optimum height. Buildings constructed in this way use only 10 per cent of the energy needed by other buildings, and they create a comfortable indoor climate both in summer and in winter. Furniture can be printed directly into the new room geometry so the buildings are ready for occupancy immediately. Softer shapes of rooms can be designed in this way.

The ability for designing and producing complex objects more freely than in other manufacturing processes will potentially result in a broader range of future environmental impacts. The issue of lightweight construction has already been discussed above. However, freedom of design has many more implications:

Evasion of environmental standards

Evasion of environmental and social standards, as well as other production standards, is facilitated by the freedom of design. This is illustrated by occasional attempts to print weapons. In this respect, environmental policy may face a number of problems. For example, private users may print products without being aware that these have to comply with certain environmental standards. Likewise, environmental standards may be intentionally evaded. It is relatively easy, for example, to 3D print inadequate filter units that only have the formal appearance of effective filters. Or a car tyre is printed out which meets neither environmental nor safety standards, but can be produced quite inexpensively by means of a private printer. In the future, incorrect dimensioning, selection of inappropriate materials or production faults may lead to many kinds of (environmentally relevant) accidents or long-lasting (gradual) environmental impacts.

Acceleration of fashions

In the wake of freedom of design, private printing also becomes more dependent on social fashions. People could print anything that they desire – always depending on the social structures and changes. Such social fashions already exist and have an influence on consumption. With 3D printing, however, they attain a new quality, because due to developments in the IT sector, fashions can spread even faster. Products can be created by private individuals in numerous places: as soon as my friend shows me her new handbag I can print out a similar one myself. Overall, the gap between social changes and production is getting considerably shorter, and policy options for influencing this process are shrinking (for example, because major producers become no longer necessary). In addition, the private use of 3D printers will result in the production of goods which were not in demand before. Like many other innovations, 3D printing can thus create new needs, which have to be met.

Environmental benefits from freedom of design and bionics

Thanks to freedom of design, new sustainable objects can be conceived, tested and produced. Certainly, freedom of design and production will not automatically result in eco-friendly products. However, particularly in combination with bionics[17], 3D printing can promote the development of products that are more resource-efficient. Thus, natural structures have the ability of self-healing and self-cleaning. Based on the freedom of design inherent to 3D printing, such natural structures can be emulated more easily.[18]

Reduced consumption of natural products in the food sector

Freedom of design calls for specific conditions for production. For example, materials must be available in powder or filament form. Hence, the material form required is often far removed from that of their natural source products. This is particularly conspicuous in the food sector: foods are mainly produced by means of extrusion-based processes, but also by means of powder bed fusion (see Chapter 2.2, and Lipton et al. 2015), where the print material must be either a liquid or a powder. Hence, natural products need to be processed before. Presently, foods produced by printing include, among others, chocolate, pizza, purees and pasta. In addition, much more applications can be expected to be implemented in the future. Consequently, the more 3D printing is applied in the food sector, the fewer foods will remain unprocessed. As a result, 3D printing can promote an alienation of consumers from natural products.[19]

Extension of the useful lifetime

Thanks to the new freedom of production, spare parts can be produced beyond the former deadline for guaranteed availability. The life of products can therefore be extended almost infinitely. Each individual component that breaks or fails to operate can be replaced. However, it remains unclear whether this would eventually create any added value for the environment. For example, extending the lifetime of energy-intensive consumer products (refrigerators, cars etc.) could also hamper the transformation towards a low-carbon economy and society.

Customised products – without information

A high prevalence of customised products would, in the long term, reduce the possibilities for systematic consumer information. This problem would apply now to simple issues such as user instructions. Labelling, which is particularly relevant in the environmental context, would also be increasingly affected. Eco-labelling of products that are put on the market in a customised way will become almost impossible. Hence, it will be very difficult to provide uniform information on the environmental properties of a product.

3.3.2 New producers

Shoe designers

The production and purchase of many products may change considerably in the future. One example is shoes. Currently shoes are produced for a mass market. To buy shoes, you go to a shoe shop and try on different models. In rare cases, one would visit a shoemaker. Nowadays, footwear is scarcely produced for individual orders, also due to the high costs. This could completely change in the future. If you need new shoes, you might visit a new kind of shop, that of the shoe designers. This is beneficial for customers for a number of reasons: shoe designers are familiar with both the features of good footwear (biomechanical properties etc.) and foot anatomy, the needs and preferences of their customers and the latest footwear fashions. Customers can have their new shoes printed out as needed, possibly at

[17] The term of bionics refers to a field of research concerned with innovations that are based on the emulation of natural functions, mechanisms and structures (Almeida and Oliveira 2016b).
[18] Not only thanks to bionics but also thanks to freedom of design in general, sustainable ideas can be put into practice more easily. However, especially bionics can offer a particularly great potential to fully exploit the opportunities provided by freedom of design.
[19] Even if natural products may serve as source materials for printed foods, they have to be modified into a printable form (a fact also applying to print materials from renewable resources in non-food sectors).

monthly intervals (e.g. with customer cards offering special discounts). For new customers, a laser scanner captures every detail of their individual foot and creates a CAD model on this basis. Thanks to customisation, the sole printed from this model will fit perfectly. The customer can freely choose between forms, colours and materials because the shoe is not designed for mass production. Old footwear can be shredded immediately on site and processed into printing material.

3D printing broadens the range of users towards private individuals (as described in Chapter 2). Again, this may create new challenges for environmental policy.

Self-producing designers

Between the classical trade and classical crafts, a new type of business could establish itself in the future which will benefit from the possibilities of 3D printing: the self-producing designers. They create customised products on site, including furniture, clothes, jewellery etc. Self-producing designers are able to develop their potential much more freely and can fully express their strengths such as creativity and inventiveness. In terms of environmental policy, such development becomes relevant because completely new groups will be involved. For instance, it must be ensured that the staff of the new enterprises are able to appropriately operate the 3D printing technology, otherwise risks to human health could increasingly arise from inexperienced producers. Training and environmental management will be required in order to counteract potential negative impacts.

3D printing crafts

In addition to the above-mentioned option of further personal development and of establishing oneself as a self-producing designer of customised goods as it was already centuries ago (see above), even more opportunities could open up for crafts businesses. In the future, any kind of component or spare part can be self-produced at any time. This could be beneficial for a gas fitter or plumber as well as for a watchmaker. As a result, they can considerably increase opportunities to develop repair shop businesses. Clear changes may occur in the future from current cases where devices are not worth repairing due to waiting times and cost of spare parts, for example. At the same time, craftsmanship will be able to optimise existing products. For example, if a table needs to be extended for an additional family member, 20 cm are added by printing, and the table legs moved manually. In these situations environmental policy will face some challenges: companies would need to train to operate new manufacturing equipment and managing their environmental impacts, and compliance with environmental standards has to be ensured. New challenges will also arise for environmental regulators, because many more production facilities have to be inspected, in parallel to a simultaneously increasing range of production options.

Prosumers

The number of prosumers will increase due to 3D printing. Private individuals will increasingly produce certain goods for themselves, thus blurring the roles of producers and consumers. This could result in in a challenge in that more individuals, including complete novices, need to be informed (at least in part) about the environmental impacts of production processes. On the other hand, this development also poses some opportunities: people will be more willing to assume responsibility for their own products. Private users will tend to avoid using toxic, carcinogenic or mutagenic materials merely for reasons of self-protection (provided they have been appropriately informed about the ingredients and their health effects). To a certain degree, this should therefore help products to become more eco-friendly.

Decline of the classical trading business

In the wake of 3D printing, trade could shrink if printing by private persons increases. This will reduce the possibilities of trade to exert influence on customers – advertising and related consumer incentives will decline. At the same time, an important source of advice and a central contact in case of complaints about goods purchased will disappear. For environmental policy, this would mean the loss or weakening of the role of a key actor who, on principle, could provide information about the environmental properties of products.

Challenges for producer responsibility

The emergence of new producers (self-producing designers, craftspeople, but also private individuals) means that almost anybody is able to produce something. Therefore, it may become much more difficult in the future to locate producers and, for example, hold them accountable for product defects or non-compliance with environmental standards. As a consequence, the concept of producer responsibility will no longer work in many cases. An example of related problems is the field of waste management: if there are no central producers who, as a matter of principle, take responsibility for waste management, then it will become much more difficult to establish disposal systems. Appropriate disposal will become even more complex because customised products will require individual recycling solutions. There will be no labelling to provide details on the substances used, and hypothetically any product may contain many types of ingredients. This will finally lead to a wide discrepancy between a de facto decreasing producer responsibility, on the one hand, and an increasing need for it, on the other.

3.3.3 Flexible production sites

Africa as a production centre

Jointly with other trends, 3D printing may, in the long term, also have consequences of an entirely different nature. New production sites can establish themselves much more easily and will face far fewer requirements. This will, in turn, offer completely new opportunities to individual countries and regions.

Take, for example, the Nigerian city of Yelwa: Due to a steep population growth in the country and migration from surrounding villages, the population of the city has grown, over a 50-year period, from approximately 90,000 inhabitants to almost one million in 2010. In parallel to the population growth, the local economy has increased, driven by the new possibilities provided by 3D printing. The majority of consumer goods needed are produced by the city itself. Based on the new means of production, the inventiveness of the population can be immediately put into practice. There has been an increase both in the general level of prosperity and the standard of living. In this respect, Yelwa is not an isolated case. Not least thanks to 3D printing, numerous urban centres in West Africa have experienced a rapid economic development. At the same time, however, the new production technology has caused new environmental problems. Deforestation has increased because increasing amounts of wood are used as a raw material for printing materials. And although the pollutant emissions due to printing devices have decreased noticeably, human exposure to air pollution has considerably increased. This is also due to production currently taking place in residential areas.

3D printing can be used flexibly and quite independently of the location in a range of places. This causes specific challenges for environmental policy.

Workplaces becoming more flexible

Thanks to 3D-printing technologies, living and working could move closer to each other in the future. Many activities will increasingly be carried out in neighbourhoods, i.e. in local service centres rather than in a remote factory. In this way, commuting distances become shorter, and traffic is reduced considerably – a key concern of environmental policy. However, the shift of production to localised neighbourhoods will also cause new problems. Inhabitants will be potentially exposed to pollutants from 3D printing. Hence, environmental policy will have to ensure compliance with much stricter limit values.

Anonymous supply chains

The flexible production site will also have impacts on supply chains. A fundamental challenge of sustainable supply chain management is to ensure that suppliers also comply with environmental and social standards. To this aim, several initiatives have already been launched which are intended to guarantee such standards on a global level (cf. e.g. the Sustainability Reporting Standards by the Global Reporting Initiative; GRI 2016). These are mostly based on voluntary commitments from industry. Due to an increasing decentralisation of production, it may also become difficult to control compliance with standards throughout the supply chain because production sites and producers of the goods concerned will become less and less traceable.

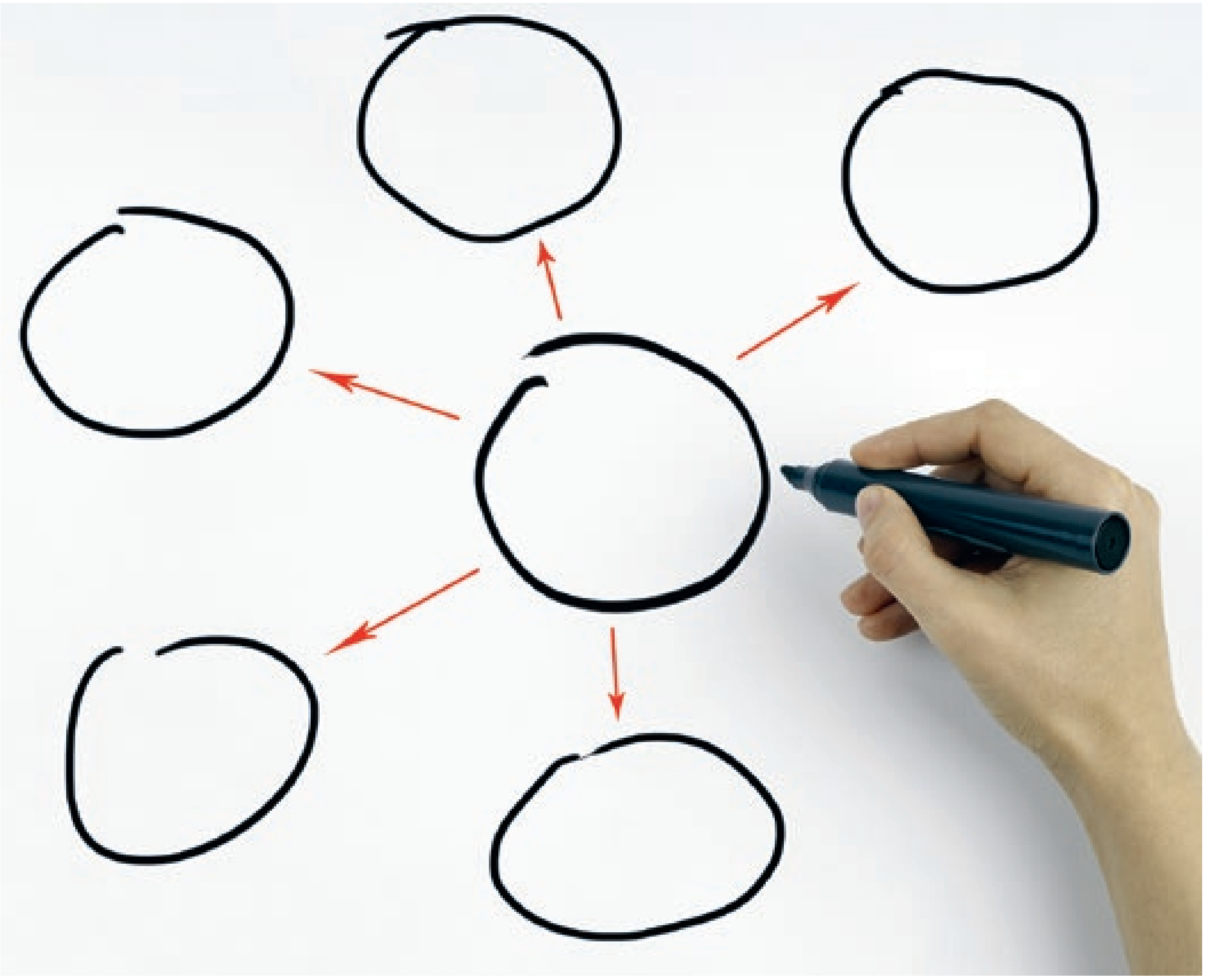
Export of environmental standards for devices and accessories

Through the export of 3D printers, environmental standards could be implicitly set on a global level. This would require high standards to be introduced for 3D printer manufacturing in the producing countries. If appropriately stringent provisions for 3D printing are implemented in the future, these would be introduced into the importing countries via the global machine trade. In this way, the export of printers could contribute to local benefits for the environment.

Adapted (environmental) technology

Today, 3D printing is being used in the context of disaster management in order to rapidly produce goods urgently needed, anytime and anywhere. In the future, the almost ubiquitous application of 3D printers may also result in goods being more suited for local conditions. Manufacturing in locations where the goods are actually needed provides the opportunity to better adapt such products to the local climatic, cultural, social and economic conditions. From the perspective of environmental policy, this should ultimately lead to a more effective utilisation of resources at a global level because the use of technology inappropriate for the local conditions, abilities and needs is avoided.

The opportunities for development of 3D printing discussed above and the resulting environmental implications are both multifaceted and far-reaching. Relatively long periods of time may pass before many of the developments outlined above materialise to the extent of having noticeable consequences in our everyday lives. Thus, considerable time may be available for environmental policy to react, both with regard to resulting opportunities and to potential risks. However, it is also essential to make good use of this time.

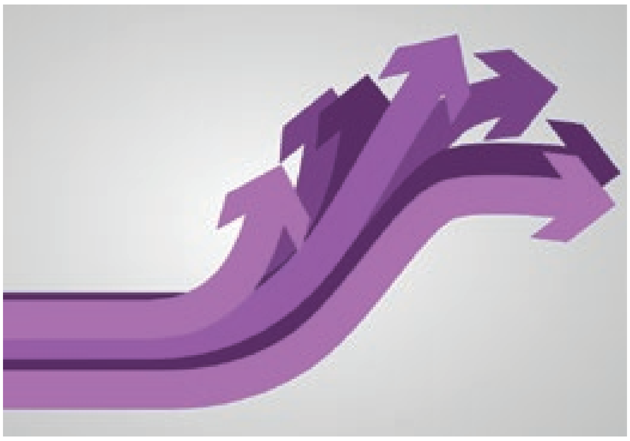


4 Conclusion, need for research and recommendations for action

4.1 Conclusion: Assessment of environmental impacts of 3D printing

As mentioned in Chapter 2, 3D printing has been used in industry since the 1980s. Hence, for major enterprises and industry, the technology is not an innovation per se. The public attention 3D printing currently receives is above all due to the fact that since about 2007, the technology has increasingly been used by private individuals and micro-sized enterprises (such as crafts, self-producing designers, architects etc.) as well as start-up companies and FabLabs. Meanwhile, 3D printing has also entered into the public domain and is used in schools and libraries. In the future, 3D printing will also be used by children (cf. Chapter 2.1). Such expansion of the production technology both within industrial settings and also smaller-scale applications becomes evident from the growth figures for 3D printers and market projections. Overall, the market volume is rapidly growing, and will continue to grow in the foreseeable future. However, a differentiated approach is required when assessing the projected growth rates: as far as devices and printing materials are concerned, the figures for industry are increasing slowly. In contrast, for desktop settings the foreseeable growth rate (and that already observed) is much greater. The number of desktop printers sold in particular will continue to increase sharply (cf. Chapter 2.3). This phenomenon can certainly be regarded as a "3D printing revolution". Consequently, 3D printing becomes relevant for strategic foresight in environmental policy because the environmental impacts of the printing technology are expected to increase in number.

Simultaneously, the market volume of 3D printing can be put into perspective, and the environmental impacts of this technology can be assessed in a better way, by taking a closer look at the global machine trade. In spite of a strong growth, the 3D printing market will remain comparatively small in the foreseeable future. The same applies to the materials used for printing and the number of printers sold. From this angle, the assertion of a "3D printing revolution" must be viewed in a critical light: rather than completely revolutionising industrial production, this technology will become integrated into existing production processes. This should also be taken



into account when assessing 3D printing from the perspective of environmental policy: Ultimately, there is no sufficient reason to expect any dramatic shifts to occur (in society as a whole).

In light of market development, various fields of application, different printing processes and the materials used, 3D printing has been examined in Chapter 3 by means of three approaches. The environmental impacts discussed in this Chapter have drawn a complex picture of the manufacturing process. Both the potential burdens and benefits of the technology have been found to depend, among other factors, on the printing process and the materials used, the field of application and the printed object itself, when compared with other production processes in each case respectively. A life-cycle analysis of this kind has already been made for individual components and printed objects, respectively (cf. Faludi et al. 2015a and 2015b). However, scientific environmental studies are still lagging behind the expansion of the technology overall.

Despite the complexity of the environmental impacts of 3D printing, pathways can be indicated that illustrate the significance of 3D printing with regard to environmental policy. The impacts identified in this report are presented in the Table below (for a more detailed presentation, see Chapter 3). Some of the effects are ambivalent and have been marked accordingly in the Table.

Table 3:

Identified positive and negative environmental impacts of 3D printing

Category	Positive and negative environmental impacts
Printing process (Chapter 3.1.1)	Burden from high energy demand Benefit from raw material efficiency Burdens from particulate matter pollution, volatile organic compounds, solvents, nanoparticles Benefits from elimination of cutting fluid (as compared to milling)
Printing materials (Chapter 3.1.2)	Burdens from the production of raw materials, processing and production of printing materials (plastics, metals, green materials) Burdens from toxicity of materials (also a matter of process) and emissions from the materials themselves Burdens from poor recyclability of some materials Benefits from green materials (cascading use of raw materials)
Applications (Chapter 3.1.3)	Burdens from printing of nonsense objects for personal use Benefits from prototype construction (e.g. reduced production times) Benefits from lightweight construction (e.g. reduced CO_2 emissions from aircraft) Benefits from spare parts and tools (extended lifetime of products) Benefits from decentralised recycling (less transportation) Potential benefits in the building industry (possibly more resource-efficient than other technologies, potential of better adaptation of buildings and building complexes to climate change) Benefits in the fields of bioprinting and foods (e.g. toxicity testing, leather)
Indirect effects (Chapter 3.2)	Development of new niche markets and business models (potential effects on resource consumption; but also opportunities for implementing green ideas) Benefits from decentral logistics Changes in consumption habits and lifestyles (ambivalent effects)
Freedom of design and production (Chapter 3.3.1)	Benefits from freedom of design and bionics (e.g. lightweight construction) Potential benefits from an extension of product lifetime Burdens from a decrease in the use of natural products Burdens from less consumer information on environment-related product characteristics Potential burdens from possible evasion of environmental standards Potential burdens from acceleration of production cycles (fashions)
New producers (Chapter 3.3.2)	Potential burdens from new economic actors such as self-producing designers and 3D printing crafts (e.g. health risks, non-compliance with environmental standards) Ambivalent effects due to shrinking trade (benefits from reduced purchase incentives for consumers by trade; burdens from reduced product information) Potential burdens from splitting production sites (e.g. effects on product responsibility)
Flexible production sites (Chapter 3.3.3)	Potential burdens from a shift of production to residential environments Potential burdens from anonymous supply chains (effects on sustainable supply chain management) Potential benefits from export of environmental standards (equipment technology) Potential benefits from adapted (environmental protection) technology

Source: Chart generated by the authors

The above list of identified positive and negative environmental impacts provides information on key opportunities and risks posed by 3D printing. These call for particular attention from environmental policy makers and can be regarded as important findings for the strategic foresight for 3D printing. Some of the environmental impacts described can already be observed quite clearly, others may be regarded more as future issues. Some of these impacts can be assigned to specific groups of actors (e.g. lightweight construction in industry), others are considered as horizontal issues (recyclability of printed parts both in desktop environments and major enterprises).

Medium-term risks to human health and the environment posed by 3D printing

3D printers and materials can lead to **health burdens.** Health risks arise both in industrial settings, especially for employees in large enterprises, but also in small-scale applications using desktop printers (private use, non-profit and small enterprises). Factors influencing such health risks include: the technical know-how of the users, the awareness of the environmental burdens caused by 3D printing, the surveillance and control of arising health burdens, the price of printers and materials, and, partially related to these, the technical characteristics of the devices and materials used. For the industrial environment, the extent of potential burdens is less severe because of established mechanisms for occupational safety and experienced and trained staff being more familiar with potential risks. Nevertheless, burdens may arise, above all in installations not yet automated, e.g. during post-treatment, if workers are exposed to particulate matter and nanoparticles. More severe burdens have to be expected in the field of desktop applications because these users are considerably less familiar with the risks involved and often lack the specialist knowledge required. In addition, appropriate protective devices are used less frequently due to the associated costs. Burdens may be caused by emissions from the materials themselves or from the process (particulate matter, nanoparticles, volatile organic compounds), particularly if no filters are used. Lay persons may also become exposed to risks during post-treatment (handling of parts after printing) and disposal. Specific risks are also associated with toxicity of the printing materials and the printed objects.

3D printing also poses problems from the perspective of the closed-loop recycling economy. This refers to both the **waste** generated and the **recyclability** of printing materials. Thus, powders used in powder bed processes in industry will degrade and, as a rule, can undergo downcycling only, e.g. for further use in injection moulding.[20]

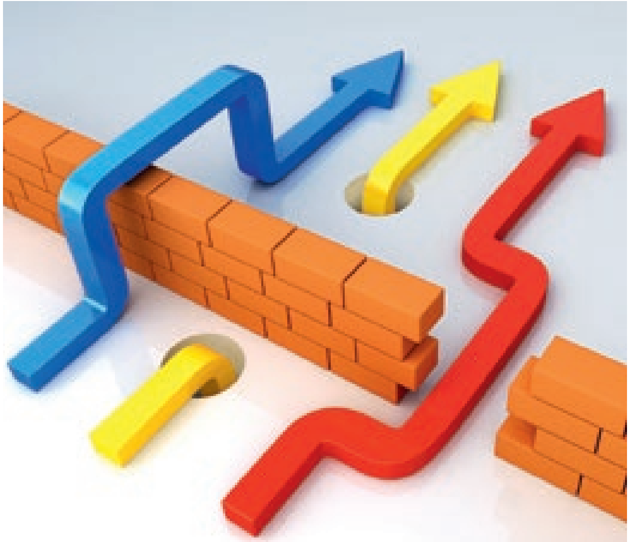
The same applies to liquid photopolymers that are used for example in stereolithography in desktop settings. When exposed to solar irradiation (UV light), the materials may cure and change to a gel-like consistency. As a result, they are no longer suitable for 3D printing and practically non-recyclable. This happens, for example, during extended idle times of printers or when the printed parts are released from the build platform. During 3D printing, classical materials (e.g. steel) may gain new properties that will affect established material cycles. The increasing use of desktop printers by self-employed persons, micro-sized enterprises and at home also raises the question how printed objects can be integrated in the closed-loop recycling economy in a meaningful way.

3D printers cause burdens for the environment due to their high **energy demand.** The energy demand varies from one technology to another (see Chapter 3.1.1), and also depending on the field of application. When compared to conventional production methods, the energy demand is even lower in some cases. However, energy demand dominates the total environmental impacts of 3D printing, according to life-cycle assessments for several component parts. Several negative environmental impacts may arise from the energy demand of 3D printers. These include CO_2 emission and the corresponding impacts on climate change, as well as resource consumption of fossil energy sources with implications for intergenerational equity (availability of such resources for future generations). Energy efficiency of 3D printing constitutes an important parameter for making this technology more sustainable.

[20] In this context, downcycling refers to the fact that due to a deterioration of material properties, the degraded powder can no longer be used for the same application but only for applications with less strict material requirements (e.g. for plastic foam).

Medium-term opportunities from 3D printing regarding human health and the environment

Along with the risks, 3D printing also offers great opportunities. For some of processes, 3D printing may contribute to **resource efficiency** in production, thus supporting the transformation towards a green economy. As described in Chapter 3.1, resource efficiency gains are generated by the processes themselves (with certain reservations, cf. Chapter 3.1), printing of prototypes, use in lightweight construction, and improvements of the process flow and functional integration. Similar to other resource efficiency gains, possible rebound effects have to be taken into account, which may lead to a partial compensation of such efficiency gains.



Benefits could potentially result from **green materials.** 3D printing will promote the use of green materials both for technological and economic reasons (also see OECD 2017: 27ff.). PLA (an agricultural plastic material) is already widely used in desktop 3D printing, in contrast to other manufacturing processes, where the use of green materials is much less dominant. This is also due to the FDM process since the material properties of PLA are more favourable for this process than other materials. In addition, 3D printing may contribute to a reduction of labour costs. As a result, companies can reduce their costs even if they use green materials, which are more expensive. Eventually, benefits may be generated from an increasing use of raw materials such as residues of wood, carrots and sugar cane, as well as from using recycled filaments. However, the environmental impacts of using sustainable materials have to be taken into account in this context (see Chapter 3.1.2).

Thanks to the possibility to produce **spare parts** and repair existing products, the lifetime of goods can be extended. Spare parts can be produced either in single centralised 3D printing centres in cities or regions or by means of decentralised 3D printers available e.g. in urban districts or several locations in a single region.

In a more distant future, special attention is also paid to opportunities provided by the use of **tissue engineering** (artificial production of biological tissues) for the production of artificial meat and meat substitute for toxicity analyses, as well as opportunities from 3D printing of tissues (or entire organs) for medical purposes. Artificial meat production supported by bioprinting could generate considerable benefits (reduction of energy demand and greenhouse gas emissions, less use of natural space, and decrease in water consumption). Similar benefits can be expected from the production of vegan meat substitutes by means of extrusion-based processes. In this respect, however, issues of animal ethics have to be taken into account as well (see Chapter 3.1.3).

Long-term challenges

Beyond the opportunities and risks described above, central importance is attributed to potential changes that are associated with the **innovative characteristics** of 3D printing that are expected to occur in the more distant future. Such changes will concern the production sites, the producers, the products and their consumers and thus, key aspects of sustainable production and consumption. Some potential impacts of such changes have been outlined in this report. These include less consumer and product information, new buying incentives due to accelerating fashions, undermining of environmental and social standards due to unclear supply chains creating more difficult conditions for product responsibility, impediments for product-oriented environmental protection, and risks for new producers due to work being shifted to residential environments. Environmental policy should be aware of such changes, observe them, and take counteraction, if required.

4.2 Recommendations for action by environmental policy and need for research

There is a need for environmental policy to take action. The reasons for this include both the risks identified in this report, which have to be minimised, but also to the (environmental) opportunities, which would need political support because they are not implemented all by themselves. The need for action refers primarily (but not exclusively) to the priorities mentioned above (i.e. to the opportunities and risks of 3D printing). The sustainability of the technology must be given considerably more emphasis on the environmental agenda because central responsibilities of environmental policy are affected (including e.g. health protection, transformation towards closed-loop recycling and green economy).

In order to minimise potential **health burdens** from 3D printers and 3D printing materials, a number of steps are recommended for the different application contexts. In industrial environments, where possible, all of the process steps should be automated in order to minimise exposure, especially during the preparation of printing and the post-processing of the printed objects. To this aim, companies should ensure a systematic monitoring of exposure of their staff to 3D printing and take countermeasures, if required. In addition, appropriate training for staff and clear communication of potential risks are important. In this respect, environmental policy can, offer support by providing information on health risks posed by 3D printing, but can also exert special pressure if the voluntary measures of industry fail to produce the desired effect. To this aim, supervision should ensure that companies implement internal measures of compliance.

For small-scale applications using desktop printers, a stronger commitment by environmental policy is needed because these settings are more likely to produce severe health risks, as explained in the present report. The industry must provide health harmless printing filaments (and printing materials, in general), which do not pose any risks for desktop users. In this respect, it is not enough just to provide information by means of safety data sheets. It also has to be ensured that the materials used are non-toxic and can be stored in a way that avoids harmful emissions, and finally, that the printed objects are safe for users in desktop environments. During the printing process, it is necessary to ensure that emissions of particulate matter, nanoparticles and volatile organic compounds are minimised. Devices and materials must comply with standards, e.g. by compulsory introduction of filter systems. If need be, regulatory measures should be applied in this respect, for example by adapting the relevant regulations of the Ecodesign Directive.

Environmental policy should inform desktop users both about the health risks posed by exposure to emissions from 3D printing and the possibilities to minimise such exposure. Such information should be tailored to the target groups involved. It could be communicated, for example, via universities, 3D printing fairs (Maker Fairs) and crafts, architectural and trade associations. Also the introduction or transfer, respectively, of label or certification schemes indicating environmentally less harmful production processes would be worth considering. High-tech equipment and materials should be promoted.

The toxicity of materials and printed objects as well as the health risks posed by 3D printing processes should be further investigated. There is a need for research e.g. with regard to the spatial/temporal distribution of emissions of particulate matter and VOC, and the deposition on surfaces (Afshar-Mohajer et al. 2015). In addition, strategies for preventing exposure to toxic substances should be developed. In this respect, research could focus on improving both the printing processes and the materials used, or on the use of completely new substances and compositions. Innovations such as the use of other printing materials such as salt, gypsum or wood shavings should be investigated further, and likewise, the use of green materials and recycled filaments (Faludi et al.2015b).

To reduce the **energy demand** of devices, a number of steps are of key importance. Again, such steps refer to the different groups of users of 3D printing (small-scale use of desktop printers vs. application in industry and major enterprises). From the perspective of environmental policy, it should be ensured that the design of 3D printers is as energy efficient as possible, i.e. a low-power standby mode should be included (cf. OECD 2016), and that the devices are used in an energy-efficient way, i.e. as fully utilised as possible, with short idle times and short times required for setting up and cleaning (also cf. OECD 2016). In addition, energy-saving 3D printing technologies should be used. The further development of 3D printers is, in part, a project for research (e.g. further development of laser technologies). However, environmental policy should also set standards (standby function, among other requirements) that have to be complied with. If necessary, compliance with such standards should be enforced by regulatory measures. Industry could focus more efforts on minimising the energy demand. Such efforts should include integrating 3D printers into production lines, e.g. in order to use industrial cooling concepts (water cooling etc.) for lasers, and fully utilising the printers' capacity. From the perspective of environmental policy, providing targeted information for enterprises and desktop users on the possibilities to decrease energy demand (energy labelling) is of key importance for energy-efficiency measures.

In order to reduce the high energy demand of printers, research should focus especially on further technical means to accelerate processes or decrease heating-up times. Finally, the energy efficiency of 3D printing should be further improved, e.g. by research on how to achieve a better thermal insulation of the print chamber and the heated components, and on reducing the production time (Baumers et al 2011).

To some extent, 3D printing also has energy saving potentials. Such potentials largely depend on the technology used (cf. Chapter 3.1.1), as compared to the substituted manufacturing processes, and on the object produced. The ability of 3D printing to manufacture with greater energy efficiency, to a certain extent, has been demonstrated by several life-cycle assessments (cf. Chapter 3.1.1). Rebound effects may occur for such energy efficiency potentials if, for example, the demand increases as a result of reduced production costs of goods. On principle, such rebound effects can be counteracted by several strategies, for example by extracting profits from efficiency gains by means of a tax, or informing consumers. However, considering such strategies must be preceded by further research to clarify if and to what extent rebound effects occur in 3D printing.

In industrial settings, the issues of **recycling** and **disposal** of used powders are already being considered and, as a rule, such powders are subjected to adequate procedures. The increasing use of printers in desktop environments also calls for a more circular approach to materials use. As a first step Environmental policy could start to focus on this as a research project. It should be examined how printed objects could be included in the closed-loop recycling economy, for example by means of imprinted labels informing about the material properties of the printed object. Altogether, a systematic analysis should be performed of the new materials used, the types of waste generated, the ways such materials change during the printing process, and options to integrate them in existing cycles.

In order to realise **gains in resource efficiency** in the industrial sector, the use of lightweight construction in the aviation industry should be promoted as a way to contribute to climate protection because, as explained above in Chapter 3.1, this technology can help in meeting emission reduction targets (Huang et al.2013; Nickels 2015). Altogether, as explained in Chapter 3.1, 3D printing offers certain potential for sustainable production provided that further research is undertaken to improve speed, accuracy and applicability of 3D printing and promote its integration into major production processes (cf. Frazier 2014). Further research should also focus on materials that can be processed with little energy input, such as plastics that do not require the print bed to be heated (cf. Faludi et al.2015b). To support life-cycle assessments by businesses, it is of key importance that data on the energy efficiency of printers and on the use of secondary raw materials are made available at lowest possible cost.

The potential of 3D printers for **spare part production** should be encouraged by reducing barriers and creating appropriate incentives. This also includes issues of liability and copyright that could become relevant if spare parts are produced on desktop printers. Third parties should be entitled to produce spare parts themselves also beyond former deadlines for guaranteed availability. Possible solutions could include payment of a licence fee, or central spare part production by 3D printing service providers. In order to ensure long-term reparability of objects, CAD drawings of different spare parts/components should be made available by industry on a long-term basis. This could be implemented, on the one hand, by creating appropriate incentive structures, and on the other, by obliging industry to make such templates available.

In the fields of **toxicity analyses, production of artificial meat and meat substitutes** and **artificial leather,** environmental policy can take supportive action. This includes making available and communicating existing approaches on the use of tissue engineering for toxicity analyses. For example, networking between actors in the field of cosmetics could be encouraged, and possibilities for further promotion of tissue engineering could be discussed together with scientists and policy makers. A major step forward is still needed in the production of artificial meat and leather because the costs are still extremely high at present. Hence, it is important for environmental policy to act above all as an agenda setter for innovation and research policy. The use of artificial meat can be expected to meet with considerable reservations among the population. Further research is needed so that the potential environmental benefits can be implemented. These include, above all, the cost-effective production of tissues and the research into artificial products that are also consumer-friendly, i.e. their texture and taste should be similar to conventional products so that consumers are not put off. Perspectives on animal ethics should also be taken into account.

For the changes expected to arise from the **innovative characteristics** in the more distant future, a step-wise approach would appear to be appropriate. Firstly, it seems important to establish early contact with industrial associations and first-time users in order to jointly explore options for ensuring integrated environmental protection in new micro-enterprises and provide consumer and product information. In a joint effort, strategies should be developed to minimise environmental burdens and to ensure that both the enterprises and the manufactured products remain committed to sustainability after its importance possibly increases resulting from 3D printing. Furthermore, the proportions of both existing and future new target groups for production-oriented environmental protection should be analysed. In this context, a more detailed analysis should be conducted regarding the types of micro-enterprises involved in 3D printing and the fields of business they belong to. Such analyses could also include existing operational environmental protection measures and future issues for environmental protection measures related to 3D printing. Secondly, in view of the effects of supply chains, it appears important to promote existing approaches to sustainable supply chain management (such as sustainability reporting standards, e.g. by the Global Reporting Initiative, GRI). It also has to be ensured that environmental standards are complied with throughout the entire supply chain.

As a concluding point, after analysing environmental impacts and discussing recommendations for action by environmental policy, reference is made again to the relationship with ongoing strategic processes pursued by environmental policy. National environmental policy is increasingly considered as a transformative force for society (see BMUB, Integriertes Umweltprogramm [Intergrated Environmental Programme] 2030). Based on the increasing social and economic use of 3D printing, the research project analysing environmentally relevant trends has examined the environmental impacts likely to result from this technology. With a view to a transformative environmental policy, attention should now be directed to society again, and initiatives should be launched into society in order to make 3D printing a sustainable technology. This applies in particular also to medium and long-term transformation potentially resulting from 3D printing. To this end, the present report has worked out approaches and problem areas, which should now be taken up and tackled by environmental policy and other policy areas (e.g. the Federal Ministry of Education and Research [Bundesministerium für Bildung und Forschung - BMBF] for research funding) in the sense of a transformative environmental policy. In this context, also a social debate should be stimulated on the environmental impacts of 3D printing, beyond the measures of “classical environmental policy” mentioned above.

5 Annex: Assessment procedure

Table 4:

Impact types and categories of the streamlined environmental assessment (Vereinfachte Umweltbewertung – VERUM)

Types of impact	Categories of impact
Chemical impacts	Greenhouse gases Nutrients and other pollutants in ambient air Indoor pollutants Wastewater Diffuse inputs of nutrients and pollutants, pesticides
Physical impacts	Noise Radiation Mechanical killing of animals
Biological impacts	Pathogens Invasive substances
Resource consumption	Consumption of mineral resources including fossil energy sources Consumption of biotic resources Water consumption Use of natural space
Incidents/accidents	

Source: UBA 2014

Table 5:

Dimensions and categories of indirect environmental impacts

Dimensions	Categories
Demography	Fertility Mortality Migration Age distribution
Space	Urbanisation and rural exodus Urban sprawl and suburbanisation Population density
Economy	Economic growth Competitiveness Productivity Energy and material intensity Structural transformation Consumption behaviour Mobility and transport Income distribution Unemployment Poverty Prosperity and high standard of living Social security
Science and technology	Innovation Technological change
Politics	Political participation and political freedoms Interest groups Form of state/form of rule/system of government Media system and media Party system and political parties Legal system Administrative system
Society and culture	Environmental awareness Discourses/narratives/frames Formation of values, attitudes, opinions and lifestyles Knowledge creation

Source: Chart generated by the authors

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Chapter 3.2.1 Development of new niche markets and business models

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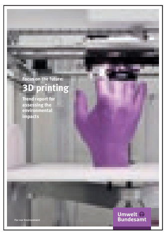

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