Energy Policy 74 (2014) 158–167

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A global sustainability perspective on 3D printing technologies

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HIGHLIGHTS

- Global sustainability aspects of 3DP in manufacturing are assessed in two ways.
- 3DP will strongly influence manufacturing in aerospace, medical components, tooling.
- 3DP re-shifts production to consumer countries due to decreased labour costs.
- Regulatory frameworks have to be adjusted to new technological environments.
- 3DP leads to cost reductions, energy saving and reduced CO_2 emissions.

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form
15 July 2014
Accepted 25 August 2014
Available online 23 September 2014

Keywords:
3D printing
Costs
TPES
CO_2 emissions
Life cycle
Industrial manufacturing

ABSTRACT

Three-dimensional printing (3DP) represents a relative novel technology in manufacturing which is associated with potentially strong stimuli for sustainable development. Until now, research has merely assessed case study-related potentials of 3DP and described specific aspects of 3DP. This study represents the first comprehensive assessment of 3DP from a global sustainability perspective. It contains a qualitative assessment of 3DP-induced sustainability implications and quantifies changes in life cycle costs, energy and CO_2 emissions globally by 2025.

3DP is identified to cost-effectively lower manufacturing inputs and outputs in markets with low volume, customized and high-value production chains as aerospace and medical component manufacturing. This lowers energy use, resource demands and related CO_2 emissions over the entire product life cycle, induces changes in labour structures and generates shifts towards more digital and localized supply chains.

The model calculations show that 3DP contains the potential to reduce costs by 170–593 billion US $, the total primary energy supply by 2.54–9.30 EJ and CO_2 emissions by 130.5–525.5 Mt by 2025. The great range within the saving potentials can be explained with the immature state of the technology and the associated uncertainties of predicting market and technology developments. The energy and CO_2 emission intensities of industrial manufacturing are reducible by maximally 5% through 3DP by 2025, as 3DP remains a niche technology. If 3DP was applicable to larger production volumes in consumer products or automotive manufacturing, it contains the (theoretical) potential to absolutely decouple energy and CO_2 emission from economic activity.

1. Introduction

1.1. Industrial metabolism

Since the start of the industrial era manufacturing processes have shown a rapid development. Existing processes and practices were improved, new technologies were introduced and the size and scale of industrial production expanded enormously. And above all the relative share of raw materials, energy and labour in manufacturing products kept evolving. Industrial metabolism – the transformation of matter, energy and labour into goods, services, waste and ambient emissions – has generated high levels of wealth but at the same time accounts for increasing human interference with the biosphere (Ayres and Simones, 1994; Solomon et al., 2007; UNEP, 2012). Industrial activity accounts for 22% in total final energy consumption (IEA, 2012) and for about 20% in global CO_2 emissions (Barker et al., 2007). The industrial sector should therefore be considered as one of the major sectors where transformative changes are needed towards sustainability, as defined by the World Commission on Environment and Development (WCED, 1987). This implies a shift to more resource-efficient means of production, which will lead to a decreasing

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http://dx.doi.org/10.1016/j.enpol.2014.08.033
0301-4215/

input and output intensity per unit of gross domestic product (GDP) to prevent climate change impacts, exhaustion of natural resources and disruptions of ecological systems (Ayres and Simones, 1994; Parry et al., 2007). A recent addition to industrial practices is three dimensional printing (3DP). This paper aims to assess the current state of the art of 3DP in the context of sustainability. To the best of our knowledge this is the first sustainability-based study of this kind.

1.2. Three dimensional printing

3DP is an industrial manufacturing process with the potential to significantly reduce resource and energy demands as well as process-related CO_2 emissions per unit of GDP (Baumers et al., 2011; Baumers, 2012; Campbell et al., 2011; Petrovic et al., 2011; Kreiger and Pearce, 2013). Contrary to conventional manufacturing subtractive processes, 3DP encompasses additive means of production. Three-dimensional physical objects are produced through layer-by-layer formation of matter based on a digital blueprint (usually a CAD file). The technology evolved during the mid-1980s when computing and control systems progressed (Hopkinson et al., 2006). 3DP has recently gained much attention as the process has proven to be compatible with industrial manufacturing beyond prototyping (Berman, 2012; Gershenfeld, 2012; Reeves, 2008).

Hopkinson et al. (2006) describe 18 different 3DP processes. These can be divided by the physical state of the printed matter (liquid-, solid- and powder-based processes) and by the applied method to fuse matter on a molecular level (thermal, ultra violet (UV)-light, laser or electron beam; Hopkinson et al., 2006). The most commonly applied processes are stereolithography (SLA), selective laser sintering (SLS), digital light processing (DLP), fused deposition modelling (FDM), selective laser melting (SLM) and electron beam melting (EBM; Petrovic et al., 2011). Polymers, alloys of aluminium, steel and titanium, as well as ceramic composites are currently printable at a minimum layer thicknesses of 20–100 μm—depending on the process and the physical state of the material (Hopkinson et al., 2006). Therefore, 3DP can be applied to various manufacturing markets. It enables a potential substitution of conventional processes. 3DP has the great advantage of enabling the realization of complex freeform geometries, as the process is not constrained by the technological limitations of conventional manufacturing processes (Reeves, 2008).

1.3. Socio-economic outlooks of 3D printing

At present, due to limited production speeds and other technological bottlenecks 3DP is mainly applicable to small production volumes, customized products and/or high-value products (Berman, 2012; Hopkinson et al., 2006). Future outlooks describe 3DP as a new technology projected to generate shifts in product designs towards more complex geometries (Berman, 2012; Hopkinson et al., 2006), incentives for the customer involvement in production processes through online platforms (“Maker movement”, see Anderson, 2012), as well as restructuration of supply chains towards more digital and localized processes (Campbell et al., 2011; Reeves, 2008).

Rifkin (2011) considers the digitalization and democratization of manufacturing steered through 3DP an important aspect of the “Third Industrial Revolution” (TIR). He describes the TIR as an age of a renewable energy-powered economy, which shares its information online. 3DP enables a change in material, energy and GHG-intensities with the same significance as labour productivity increases during the First Industrial Revolution (FIR) or the growth in information distribution speed during the Second Industrial Revolution (Rifkin, 2011). Anderson (2012) considers 3DP as a “new industrial revolution” as he emphasizes the potential of democratizing manufacturing processes through online-distributed blueprints and localized production. Gershenfeld (2012) describes 3DP as part of a social transition, which “turns data into things and things into data” and therefore contributes to a knowledge-based economy. He envisions a world where decentralized physical production and globally-shared information redefine the boundaries of socio-economic activity (Gershenfeld, 2012).

Despite the current issues with 3DP, markets for 3DP are expected to grow rapidly (Wohlers, 2013). The mid-term global market potential of 3DP by 2025 is estimated at 230–550 billion US $ (McKinsey Global Institute, 2013). The main identified markets for 3DP are consumer products (100–300 billion US $), direct product manufacturing of medical components and transportation (100–200 billion US $), and tool and mould manufacturing (30–50 billion US $; McKinsey Global Institute, 2013).

If 3DP applications grow rapidly in the next 10 years questions may arise about the sustainability of 3DP manufacturing processes. Therefore, research into the sustainability of 3DP needs to be performed before the markets explode, so adjustments can be made at an early stage. Thus, this research aims to identify sustainability aspects of 3DP in manufacturing on a global scale by 2025 and to understand their influence on the industrial manufacturing. It represents a novel approach as the impacts of 3DP on sustainability have only been assessed in specific case studies or described from a specific perspective. The study contains a qualitative description of various 3DP-induced sustainability implications and a quantification of 3DP-induced changes in costs, energy and CO_2 emissions to identify sustainability potentials. The study also presents risks for a sustainably sound decision-making.

2. Methodology

2.1. Qualitative assessment

A descriptive sustainability evaluation is performed to qualitatively identify implications of 3DP on the three sustainability dimensions economy, environment and society as defined by the WCED (1987). The evaluation is based on a defined set of criteria for which identified implications are described. The criteria are obtained from studying relevant literature in the field of 3DP and sustainability as a comprehensive sustainability evaluation of 3DP has not yet been performed. An aspect has been chosen valid to become a criterion if a 3DP-related sustainability implication has been associated with the aspect (see Table 1).

2.2. Quantitative assessment: Modelling of sustainability implications

Sustainability aspects that can be determined quantitatively will be treated as such. The social dimension will necessarily only be dealt with in a qualitative manner since 3DP is still being developed. The other two sustainability dimensions economy and environment will be quantified through costs, energy and CO_2 emissions. A top-down model will be applied. In this study the top-down approach was chosen as the values for costs, energy and CO_2 emissions for the separate processes in the 3DP chain are not available in literature yet, so the bottom-up approach would yield a lot of uncertainties. The model relates economic information (3DP market potential; see McKinsey Global Institute, 2013) to expected changes in process-related energy and CO_2 emission intensities. Global average energy and CO_2-intensities and their trends until 2025 are based on the IEA (2012) and Barker et al. (2007). The relative changes in costs, energy and CO_2 emissions through 3DP in manufacturing are obtained from case studies. The following

Table 1
Set of criteria for sustainability evaluation of 3D printing-induced sustainability implications.

Criterion	Description	*Source*
Economy		
Market outlook	Estimated market potential in the time frame of assessment	McKinsey Global Institute (2013)
Applications	Suitable applications for 3DP process	Berman (2012)
	Changes in production processes through additive printing	Hopkinson et al. (2006)
Supply chain management	Changes in supply chain structures	Berman (2012)
Production costs	Changes in costs per piece and process (comparison of different process)	Hopkinson et al. (2006)
Material costs	Changes in purchase costs of raw materials	Castle Islands (2013)
Machinery costs	Purchasing prices of different additive manufacturing machinery	Hopkinson et al. (2006)
Production time	Changes in production time per piece	Berman (2012)
Environment		
Resource demands	Changes of material inputs in comparison to subtractive processes	Hopkinson et al. (2006)
Process energy	Changes in energy requirements per piece	Hopkinson et al. (2006)
Process emissions	Changes in ambient process emissions	Reeves (2013)
Life cycle energy	Changes in life cycle energy demands of a product	Reeves (2013)
Life cycle emissions	Changes in life cycle ambient emissions of a product	Reeves (2013)
Recyclable waste	Changes in amount and type of recyclable waste	Berman (2012)
Non-recyclable waste	Changes in amount and type of non-recyclable waste	Berman (2012)
Society		
Development benefits	Suitability for open source appropriate technologies (OSAT)	Gershenfeld (2012)
	Implications for self-directed sustainable development	Pearce et al. (2010)
Labour patterns	Changes in labour intensity, employment schemes, and types of work	Gershenfeld (2012)
Impacts	Social impacts generated through 3DP (positive and negative)	Vanclay (2002)
Acceptance	Socio-economic, community and market acceptance	Wüstenhagen et al. (2007)
Health	Changes in medical treatments or medical components	Petrovic et al. (2011)
Ethics	Ethical questions on morality of stem cell technology	Simon (2013)
Copyright, patent and trade mark	Questions concerning copyrights/shifts in	Weinberg (2013)
	Impacts of OSAT on patents/copyrights	Pearce et al. (2010)
Licensing	Shifts in licensing generated through OSAT applications	Pearce et al. (2010)
Product quality	Changes in product quality	Reeves (2008)

formulae are applied:

$$\text{Changes in costs}: \quad \Delta C = GDP_{3DP} \times \Delta C_{3DP} \tag{2.1}$$

where ΔC is the absolute change in costs; GDP_{3DP} the market potential of 3DP; ΔC_{3DP} the relative change in costs through 3DP compared to conventional processes.

$$\text{Changes in energy}: \quad \Delta E = \frac{GDP_{3DP} \times TPES}{GDP \times \Delta E_{3DP}} \tag{2.2}$$

where ΔE is the absolute change in energy; TPES/GDP the total primary energy supply-intensity per GDP; ΔE_{3DP} the relative change in energy through 3DP compared to conventional processes.

$$\text{Changes in } CO_2 \text{emissions}: \quad \Delta CO_2 = \frac{GDP_{3DP} \times CO_2}{GDP \times \Delta CO_{2,3DP}} \tag{2.3}$$

where ΔCO_2 is the absolute change in CO_2 emissions; CO_2/GDP the CO_2 emission-intensity per GDP; $\Delta CO_{2,3DP}$ the relative change in CO_2 emissions through 3DP compared to conventional processes.

The quantified sustainability implications are first calculated as absolute changes per identified market applicable for 3DP manufacturing. Second, absolute changes are related to the total market size to quantify the relative implication. Third, the total relative influence of 3DP on industry is calculated by weighting the previously calculated relative implications per market. Fourth, relative changes in TPES/GDP and CO_2/GDP-intensities through 3DP are defined by relating the absolute changes in energy and CO_2 emissions to the total market size.

To fully understand the sustainability implications of 3DP the lifecycle phases consist of production (raw materials, manufacturing and distribution), usage and decommissioning. Decommissioning is considered when sustainability implications are quantifiable, which is not always the case. Furthermore, four scenarios are established (Table 2), as both market potential and process-intensities are associated with uncertainties or are based on case studies (see McKinsey Global Institute, 2013; Reeves, 2013). These scenarios represent a sensitivity analysis to show the range of potential sustainability implications on costs, energy and CO_2 emissions. Table 3 contains the quantified parameters per 3DP market in accordance with the established scenarios. The cost saving potentials were directly obtained from McKinsey (McKinsey Global Institute, 2013), whereas the energy and CO_2 emissions were calculated using data from Baumers (2012) and Reeves (2008, 2008a). The values are obtained through a study of relevant literature and divided into a low and a high end of the range to integrate uncertainties into the model.

Table 2
Scenario characteristics.

	Market potential	Process-intensities		
		Change in cost intensity	Change in energy intensity	Change in CO_2 emission intensity
Scenario 1	Low	Low	Low	Low
Scenario 2	Low	High	High	High
Scenario 3	High	Low	Low	Low
Scenario 4	High	High	High	High

3. Results

The results are divided into two parts. First, the qualitative results of the sustainability evaluation are described. Second, the quantified sustainability implications on costs, energy and CO_2 emissions through 3DP are explained.

3.1. Results of the sustainability evaluation

The evaluation has identified various 3DP-related implications among all three sustainability dimensions. The implications

Table 3
Model parameters per 3DP market.

Market	Market potential (in billion US $)		Change in cost intensity (in %)		Change in energy intensity (in %)		Change in CO_2 emission intensity (in %)	
	Low	High	Low	High	Low	High	Low	High
Consumer products	100	300	35	60	19	38	19	38
Aerospace industry	58	116	40	55	38	75	38	75
Automotive industry	5	10	40	55	38	75	38	75
Medical components	38	76	35	60	20	40	20	40
Tooling	30	50	15	30	20	40	20	40
Source	McKinsey Global Institute (2013), Reeves (2013)		Lindemann et al. (2012), McKinsey Global Institute (2013), Reeves (2013)		Baumers et al. (2011), Reeves (2008a, 2012, 2013)		Reeves (2008, 2012, 2013)	

Table 4
Break-even points of 3DP compared to conventional manufacturing processes (3DP represents the more cost-efficient method below the break-even point).

Break-even point (in pieces)	Printed material	Process comparison	*Source*
279–5,800	Polymer	SLA compared to injection moulding	Hopkinson et al. (2006)
7,500	Polymer	FDM compared to injection moulding	Hopkinson et al. (2006)
14,000	Polymer	SLS compared to injection moulding	Hopkinson et al. (2006)
42	Aluminium	SLS compared to high-pressure die casting	Atzeni and Salmi (2012)
190	Steel	SLM compared to milling	Lindemann et al. (2012)

should be considered dynamic, as they might change over time due to changing societal environments. As the assessment is global, the quality and scale of some 3DP-induced implications vary depending on the socio-economic context. It will be explicitly mentioned when the implication shows a contradicting pattern in developed and developing countries.

3.1.1. *Economic implications of 3DP*

As stated earlier, 3DP is considered a 230–550 billion US $ market by 2025, whose main economic impacts are stated for markets with high-value, low volume and customized products (McKinsey Global Institute, 2013) as 3DP enables more costs-effective manufacturing process for these products (Hopkinson et al., 2006). Five key markets for 3DP by 2025 are identified (McKinsey Global Institute, 2013; Reeves, 2013): consumer products, aerospace manufacturing, automotive production, medical components and tooling. A further reduction in production-related capital investment is stated for 3DP due to reduced needs for tooling, shorter production chains and related processes (Atzeni and Salmi, 2012).

When 3DP is compared to conventional processes, the break-even points depicted in Table 4 of different case studies represent a central measure to describe the maximum size of production volumes below which 3DP represents the more costs-effective manufacturing process. The break-even point of a production series is case-specific and depends on technological aspects like part complexity, material and built volume (Hopkinson et al., 2006).

In general, production costs are determined by various aspects as machinery, labour, materials, and pre- and post-processing (Lindemann et al., 2012). 3DP is projected to generate shifts in production cost structures towards high shares (45–75%) of machinery costs in the total production costs, depending on the case (Lindemann et al., 2012). Material costs are case-specific and estimated at (only) 12% of the total 3DP-production costs (Lindemann et al., 2012). Prices for 3DP materials are significantly higher than raw materials for conventional processes, but amortize due to much higher material efficiencies (Reeves, 2008). Product life cycle costs can be lowered, as 3DP enables lightweight designs as well as complex and improved geometries (Petrovic et al., 2011; Reeves, 2012). This generates fuel savings in e.g. aviation, where every kg of saved material lowers the annual kerosene expenses by 3000 US$ (Reeves, 2012).

3DP generates shifts in labour patterns, as the process is highly automated and only requires human workforce in pre- and post-processing (Lindemann et al., 2012; Petrovic et al., 2011). Labour-related implications show different patterns in developed and developing countries. The high degree of automation could be economically beneficial for developed countries with ageing societies, but destabilize developing countries if the production and thereby the production volumes re-shift to consumer countries (Campbell et al., 2011). Open-source-based applications of 3DP could contribute to a sustainable development in rural areas with low-economic profiles, as 3DP bridges the spatial gap to the next market of spare parts, consumer products or tools (Pearce et al., 2010).

Through 3DP supply chains are expected to become shorter, as the need for centralized manufacturing and tooling is reduced (Reeves, 2008). Furthermore, supply chains shift from physical goods to digital ideas/designs (Campbell et al., 2011). This shift increases supply chain dynamics by reducing the “time-to-market” (Petrovic et al., 2011) and by inducing furthermore a relative decline in imports/exports (Campbell et al., 2011). Exports are projected to shift back to consumer countries as 3DP reduces the labour cost-related comparative advantage of countries such as China and the technological advantage of countries like Germany or Japan (Campbell et al., 2011). Global supply chains are furthermore expected to relatively shift from final products to raw materials as goods manufacturing becomes more localized while material raw production is spatially bound to its reserves (Campbell et al., 2011). Lastly, supply chains are expected to become less transport intensive (Birtchnell et al., 2013).

3.1.2. *Environmental implications of 3DP*

3DP has the potential to significantly lower life cycle energy demands of goods and their CO_2 emissions (Reeves, 2012). Manufacturing-related energy demands and CO_2 emissions are lowered through shortened processes and more direct manufacturing.

This reduces the need for tooling (Petrovic et al., 2011), the need for handling (Baumers et al., 2011) and it lowers indirect material-related energy demands through higher resource efficiency (Reeves, 2013). Energy demands and CO_2 emissions of the usage of especially airplanes but also cars can be reduced as 3DP enables the cost-effective manufacturing of complex free form geometries, which enables lightweight designs (Reeves, 2013). Reeves (2012) has demonstrated in a case study of a structural airplane component that manufacturing-related energy demands and CO_2 emissions can be lowered by up to 75%. The 3DP-induced lightweight design further adds usage savings which amount to 63% savings in energy and CO_2 emissions over the entire life cycle of the product. This shows that 3DP has a great environmental potential beyond just the manufacturing of products.

3DP lowers manufacturing-related resource inputs as it solely requires the amount of material which ends up in the printed good without too many losses (Reeves, 2008). Support materials can usually be reused (except for FDM, as the support material is fused; Hopkinson et al., 2006). In aerospace manufacturing high buy-to-fly ratios, which relate raw material requirements to amounts of material in final products, of 20:1 are common (Reeves, 2008). 3DP enables a buy-to-fly ratio of almost 1:1 and thereby induces a significant reduction in resource demands and manufacturing-related waste amounts. Case studies indicate that up to 40% of the raw material-related waste can be avoided through 3DP while 95–98% of the unfused raw material can be reused (Petrovic et al., 2011). Further indirect manufacturing inputs can be avoided as 3DP does not require adjuvants as coolants, lubricants or other partly environmentally harmful substances.

3.1.3. *Social implications of 3DP*

3DP induces changes in social and labour structures due to high degrees of automation and an expected shift towards more localized means of production in consumer countries. In developed countries with ageing societies, high degrees of automation might have beneficial effects while unemployment and social insecurity might be the consequence in developing countries. The changing supply chain structures require an adjustment of labour structures (Campbell et al., 2011). Labour will mostly be required for pre- and post-processing (Lindemann et al., 2012). Therefore, information technology education is needed as companies are projected to shift their product portfolios towards more digital ideas/designs (Campbell et al., 2011).

Pearce et al. (2010) emphasize the potential of sustainable development through 3DP. Online applied 3DP in an open-source manner (considered as open-source appropriate technology (OSAT)) could contribute to socio-economic development in rural areas with rather low economic profiles. 3DP combined with online open-source information bridges the gap to the next market and increases the accessibility of objects needed to improve living conditions (Pearce et al., 2010).

Open-source 3DP applications are expected to offer various opportunities for private users (Anderson, 2012). Spare parts, design objects or lab equipment can be produced on-demand at home. Unfortunately, open-source platforms can also be used to generate security threats. Open-source blueprints of weapon designs offer the private and uncontrolled manufacturing of fire arms without governmental approval or control, which violates the International Traffic in Arms Regulations (ITAR; Simon, 2013). 3DP in combination with open-source based blueprints requires adjustments of current copyright, patent and trademark systems comparable to the evolution of digitalization of music (Korkki, 2013). This is especially the case, if 3D scanners are used to generate the digital blueprint (Simon, 2013; Weinberg, 2013).

The social acceptance (in accordance with its conceptual foundation of Wüstenhagen et al. (2007)) of 3DP varies with the societal entity. Governmental acceptance is considered high as governments have an interest to reduce the resource-intensity of manufacturing and stimulate promising new market developments as potential re-shifts of production capacities to domestic markets (Campbell et al., 2011). High governmental funding in R&D (US DOE, 2012) indicates high governmental interest, but security threats due to open-source available fire arms have raised concerns concerning stricter control of 3D printing technologies (Simon, 2013). Market acceptance is high as new opportunities arise and cost reductions in technology enable further applications of 3DP. Markets for mass customization and new supply chain structures offer opportunities for new business ideas (Gartner, 2013; Reeves, 2012; US DOE, 2013). Community acceptance is considered mixed. A constantly growing community for open-source applications of 3DP indicates increasing public interest,

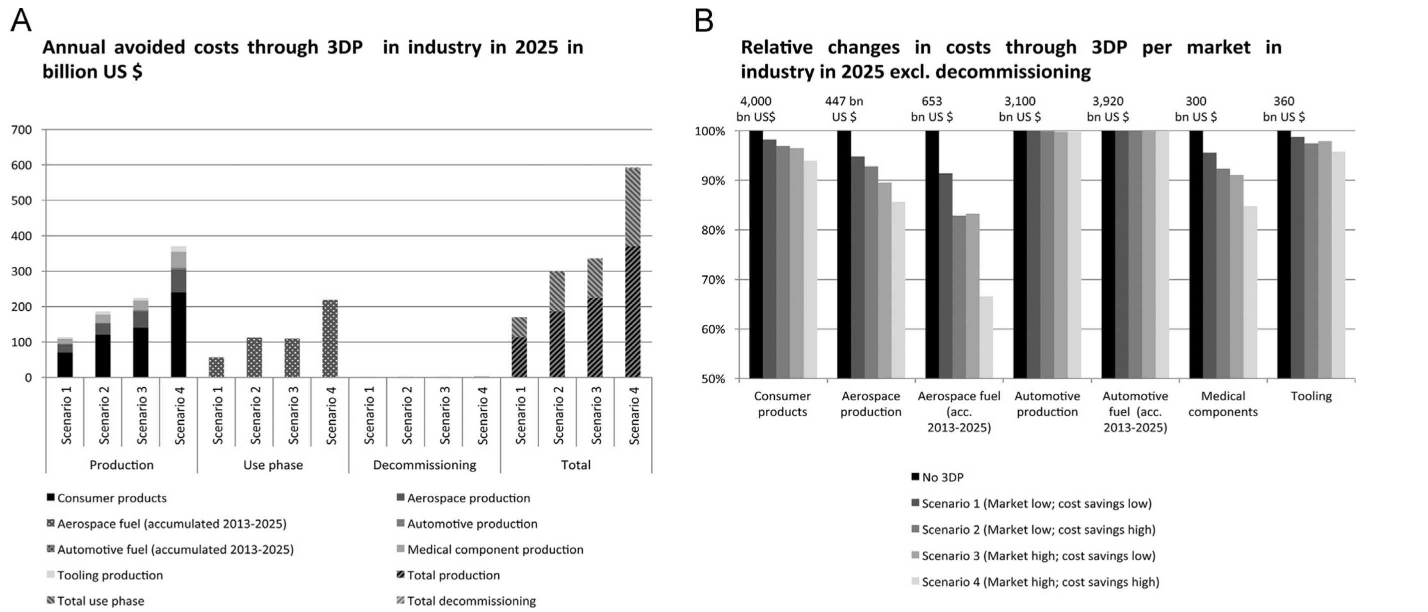

Fig. 1. Modelled implications of 3DP on costs: annual avoided costs through 3DP in industry (A); relative change in costs through 3DP per market (B).

which is reflected as well in the growing sales numbers of consumer 3D printers (Peerproduction, 2013). But security threats have induced reservations against the currently hyped technology (Gartner, 2013; Simon, 2013).

3.2. *Results of the model*

3.2.1. *Sustainability implications of costs*

Quantified sustainability implications of life cycle costs through 3DP show saving potentials mainly during the production and use phase of a product (Fig. 1A). Depending on the scenario, production savings by 2025 are quantified at 113–370 billion US $, use phase savings at 56–219 billion US $ and decommissioning at 1–4 billion US $. This leads to total cost savings of 170–593 billion US $ over the entire life cycle. The cost savings of the production phase (two thirds of the total) are due to reduced handling, shorter supply chains and reduced material demands. 3D printed lightweight designs generate fuel cost savings during usage, which account for one third of the total cost savings. The largest share in production-related cost savings is for consumer products. This is also the largest overall market. The second highest share is for aerospace production. Fuel cost savings almost exclusively apply to aerospace fuel demands due to the high influence of weight on energy demands in aviation compared to cars. Medical components and tooling also play a part in the production savings.

The largest relative influence of 3DP-induced cost savings on markets is identified for aerospace fuel demands (9–33%), followed by aerospace production (5–14%) and medical components (4–15%) depending on the scenario (Fig. 1B). Consumer products and automotive industry (production and usage) would represent the largest markets for a potential influence of 3DP. However, the relative influence through 3DP on costs is small (consumer products) or marginal (automotive industry). This is due to several factors. First, the products in these markets are usually manufactured in large series, which are well above their break-even point (Table 4). Second, the speed of obtaining products using 3DP is a lot lower than for conventional manufacturing. Third, a limited number of materials are suitable for 3DP, making it difficult to replace all products.

3.2.2. *Sustainability implications of energy*

Sustainability implications of energy are expressed as total primary energy supply (TPES). Fig. 2A shows that TPES savings through 3DP are obtainable over the entire life cycle of a product. Production-related TPES savings account to 0.85–2.77 EJ, usage saving to 1.46–5.72 EJ and decommissioning to 0.22–0.81 EJ depending on the scenario in 2025. In total, TPES are reducible through 3DP by 2.54–9.30 EJ over the entire life cycle. Roughly one third of the TPES savings applies to the production phase, 55–60% of the total savings can be harvested during the use phase and 8% are obtainable during decommissioning. The reasons for the TPES savings through 3DP are similar to those associated with costs, but due to the higher energy density per monetary unit, total usage savings are higher compared to total production savings. The largest production-related TPES savings apply to consumer products and aerospace industry followed by medical components and tooling. Usage TPES savings apply exclusively to aerospace energy demands due to the above mentioned reason for costs. Aerospace production contains the largest TPES saving potential in decommissioning as high buy-to-fly ratio reduction potentials decrease the TPES requirements for industrial waste processing or material recycling.

Fig. 2B shows that the largest relative influence of 3DP on the TPES of a market is identified for aerospace fuel demands (9–35%), followed by aerospace production (8–19%), medical components (5–19%) and tooling (3–10%). 3DP does not lead to strong relative influences on consumer products and automotive industry (production and usage) as these markets contain high shares of mass production, for which 3DP is not cost- and energy-effective yet.

3.2.3. *Sustainability implications of CO_2 emissions*

The implications of 3DP of CO_2 emissions are coherent with TPES (Fig. 3). This is because data are obtained from the IEA who relate CO_2 emissions directly to the TPES. 3DP induces CO_2 emission reduction potentials over the entire life cycle of a product. The potentials are quantified at 34.3–151.1 Mt (production), 84.1–328.5 Mt (use phase) and 12.1–44.5 Mt (decommissioning) in 2025 depending on the scenario (Fig. 3A). The total life cycle savings account for 130.5–525.5 Mt in 2025. Production-related CO_2 emissions savings represent about one quarter of the

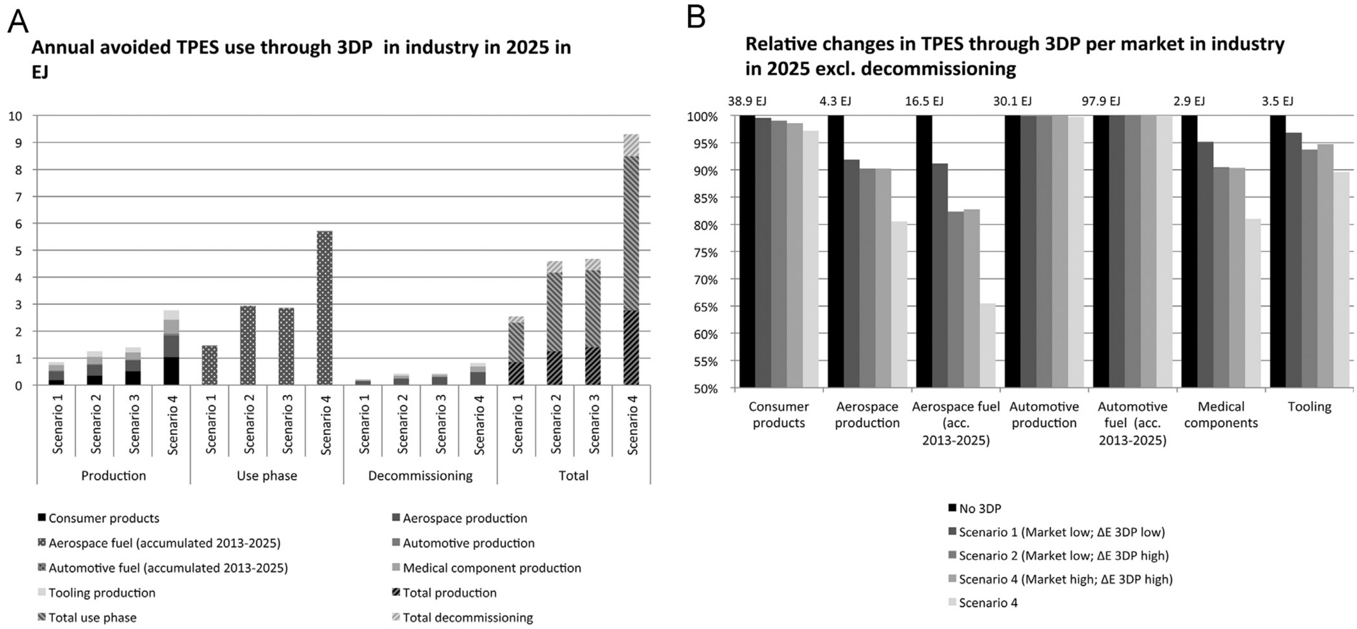

Fig. 2. Modelled implications of 3DP on TPES: annual avoided costs through 3DP in industry (A); relative change in TPES through 3DP per market (B).

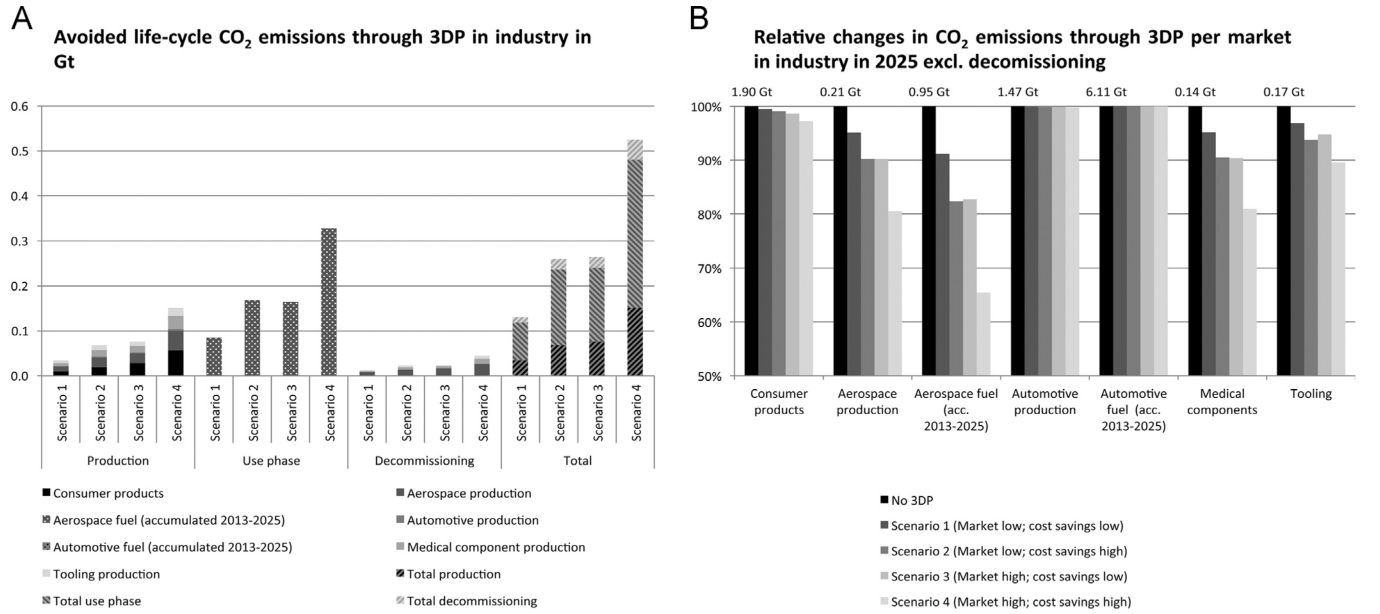

Fig. 3. Modelled implications of 3DP on CO_2 emissions: annual avoided CO_2 emissions through 3DP in industry (A); relative change in CO_2 emissions through 3DP per market (B).

total potential. Roughly two thirds of the total saving potentials are realizable during usage due to the high energy saving potentials in aviation through lightweight designs. Decommissioning accounts for 8%. Comparing CO_2 emission with TPES saving potentials, the slightly lower share of production and slightly higher share of usage in the total life cycle potential can be explained with the relative differences in carbon intensity per TPES.

Relative implications of 3DP in CO_2 emissions on identified markets can be obtained from Fig. 3B. Identical to the TPES, aerospace fuel (9–35%), aerospace production (8–19%), medical components (5–19%) and tooling (3–10%) represent the markets with the largest sustainability implications through 3DP in 2025. Consumer products and automotive industry (production and usage) show little or no influence due to the reasons mentioned earlier.

3.2.4. *Total sustainability implications*

The relative influence of 3DP on sustainability by 2025 on total manufacturing is rather small. This is due to the low share of 3DP in mass production markets as consumer products and automotive industry despite significant reduction potentials over the life cycle in aerospace industry, medical components and tooling. Fig. 4 shows the relative influence of 3DP on the TPES/GDP- and CO_2/GDP-intensity over the product life cycle in 2013–2025. The production and usage are shown, as well as a weighted total which takes into account the size of the phases. The decommissioning phase is excluded as no data are available for the size of global decommissioning markets. Without 3DP, the TPES/GDP-intensity is expected to decrease by 10% in 2013–2025. 3DP could contribute an additional 1.1–3.7% during production and 1.3–5.0% during usage, which accounts for 1.2–4.1% in total terms by 2025 (Fig. 4A). The CO_2/GDP-intensity decreases stronger as it is influenced by both the TPES/GDP-intensity and the CO_2/TPES-intensity. Without 3DP, the CO_2/GDP-intensity is therefore expected to decrease by 13%. 3DP could add 1.2–3.7% during production and 1.3–5.1% during usage, which summarizes as 1.2–4.5% in total (Fig. 4B). The relative difference in saving potential per criterion (costs, energy and CO_2) has a larger influence on sustainability implications than the overall difference in market potentials. In Fig. 4 this can be concluded from the (near) equal TPES/GDP- and CO_2/TPES-intensity reduction potential of Scenario 2 and 3.

4. Discussion

This study aimed to present a comprehensive and global sustainability assessment of 3DP. Until now, publications have mainly focussed on case-specific aspects of sustainability (e.g. Reeves, 2013), using descriptive methods (e.g. Berman, 2012; Petrovic et al., 2011) or describing technology-specific gains in costs, energy and CO_2 emissions (e.g. Baumers, 2012; Lindemann et al., 2012; Kreiger and Pearce, 2013). Our study therefore represents a new approach to understand the sustainability implications of 3DP and is the first sustainability-based study of this kind. A global (top-down) perspective has been chosen as 3DP represents a technology in an early maturation phase (Gartner, 2013) as it is still developing and rapidly growing, implying that existing practical knowledge is still limited making a bottom-up approach difficult, let alone trying to compare a top-down approach to bottom-up. Furthermore, economic assessments on market-related aspects of 3DP have chosen the same global perspective, making it possible for us to use their data (McKinsey Global Institute, 2013; Wohlers, 2013).

The sustainability implications of 3DP have first been assessed qualitatively on the three sustainability dimensions economy, environment and society (according to the WCED, 1987). The applied sustainability evaluation consists of a set of 23 criteria based on literature considered to be 3DP-relevant. The chosen set of criteria represents a first approach for a systematic evaluation of the subject and might therefore be considered too general or incomplete. However, the set of criteria has proven to be useful as it has led to the detection of various 3DP-related sustainability implications on a global scale. These are described related to the quality (positive or negative) and scale (significant or rather insignificant) of the implication. The chosen global perspective partly neglects the dynamic nature of some implications, which may lead to results with too little variability. The mentioned implications might vary in different regional, socio-economic environments and over time. The detected relevant sustainability-related issues are worth assessing in a more distinctive spatial, temporal or economic context. The sustainability implications of 3DP have been assessed quantitatively by top-down modelling of

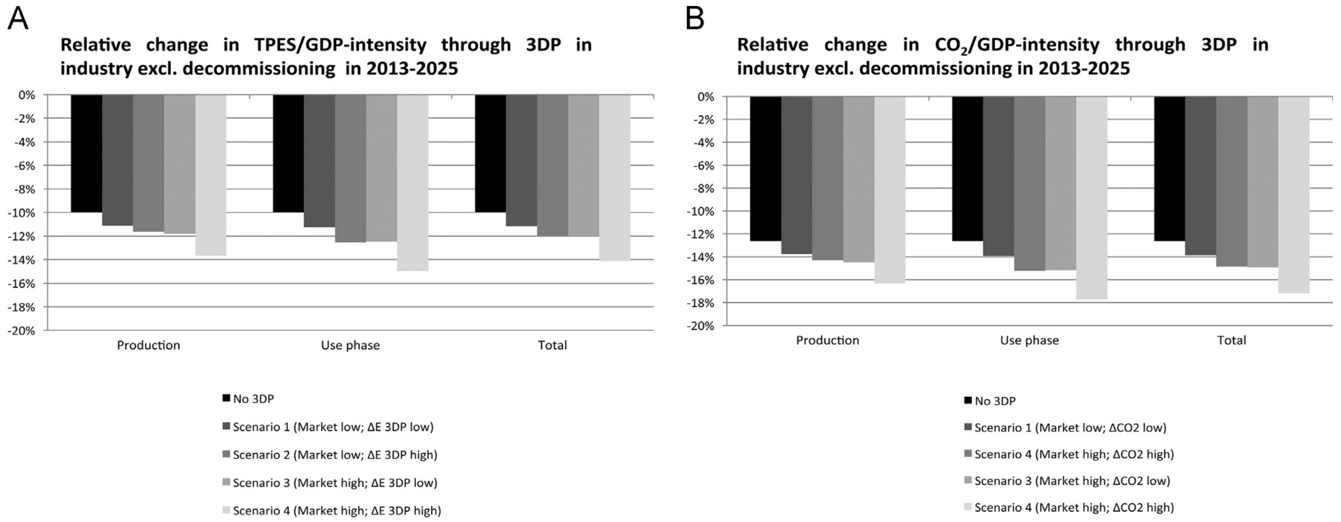

Fig. 4. Modelled implications of 3DP on production process-related intensities in 2013–2025: relative change in TPES/GDP-intensity (A); relative change in CO_2/GDP-intensity.

costs, energy and CO_2 emissions. The model relates economic information on market developments of 3DP to process intensities and 3DP-related changes in process intensities obtained through case studies. Top-down modelling represents a common methodology to quantify developments when available data are limited. Even though the risk is that it yields too general results, it also induces completeness.

The global data on process-related energy and CO_2 emission intensities were obtained from the IEA (2012). However, these are average values. The actual values for OECD countries where 3DP is mainly applied are about half the global average. On the other hand, China represents a non-negligible market for 3DP (Wohlers, 2013), and China's energy and CO_2 emission intensities are more than double the global average. Therefore, the model results on sustainability gains might be too optimistic if 3DP is mainly applied in OECD countries or too pessimistic if China holds a large share in global 3DP. However, if the ratio between 3DP in OECD countries and China reflects current economic activities our model results are valid. Developments in energy and CO_2 emission intensities in 2013–2025 are based on trend extrapolations with relative global annual change factors obtained from Barker et al. (2007). The model also takes into account life cycle considerations as 3DP induces sustainability gains beyond manufacturing. These can be achieved through lightweight designs mainly in aviation, but only, if a consistent "[c]hange in the designers' way of thinking" (Petrovic et al., 2011) is applied. The results on usage savings might be too optimistic as a uniform lightweight design approach is assumed. In practice such a lightweight design might not be practicable or economically feasible, or it might interfere with other design-related requirements. Therefore, future assessments on usage implications of 3DP should focus on the extent to which 3DP-induced lightweight design is applied in aerospace manufacturing.

The internal validity of the model is considered high as every value (absolute or relative) is based on the same mathematical relation. All fields of influence (consumer products, aerospace manufacturing, automotive production, medical components and tooling) were subjected to the same systematic error, so the ratio of their implication per total implication represents a valid value. Therefore, sound conclusions can be drawn from identifying the most promising field of application per specific sustainability implication.

Various uncertainties are associated with the model results due to the presently immature state of the technology. The relative changes in process intensities are based on specific case studies and we are not yet convinced that 3DP-related energy and CO_2 emission savings potentials of 75% during production (Reeves, 2012) are generalizable. The chosen data input for 3DP market outlooks for 2025 (McKinsey Global Institute, 2013) are stated as a range as various uncertainties are associated with the diffusion of 3DP. Therefore, it has been considered necessary to understand the relative change in process intensities as a range, where the literature value represents the higher end and half the value the lower end of the range. This led to the establishment of four scenarios, which should be understood as an integration of sensitivity considerations to the assessment. The model results of absolute changes in costs, energy and CO_2 emissions show that the quantified sustainability implications represent a significant range. The implications of the high end of the range (Scenario 4) are about four to five times greater than the implications of the low end (Scenario 1). This underlines the rather mundane nature of this assessment but as well induces the need for societal decision-makers to identify critical issues to harvest the full potentials of 3DP.

The total impact of 3DP on industrial manufacturing by 2025 is quantified to be rather small (below 5% reduction in overall process intensities) as 3DP at the moment is primarily directed at low volume production series, customized or and high-value products. Its sustainability implications would be higher if the technology was applicable to larger production volumes in mass production markets as consumer products and automotive manufacturing. It should therefore be considered a central issue in 3DP-related sustainability policies to identify possibilities and develop strategies how 3DP could be applied to these markets.

5. Conclusion

This study has assessed the sustainability implications of 3DP concerning industrial manufacturing in a systematic and comprehensive manner both qualitatively and quantitatively from a global perspective by 2025.

3DP in manufacturing is expected to mature within the upcoming decade and to change the input and output intensities of production processes of low volume, customized and high-value products (as in aerospace manufacturing, medical components and tooling). It is associated with a strong lowering of financial and energy resource inputs into production processes, which decreases product costs and mitigates CO_2 emissions. Resource demands and process-related waste amounts can be significantly lowered as the technology applies additive means of production.

Production-related labour demands are reduced and are only required for pre-and post-processing due to the highly automated function principle of the process. Supply chains are vastly affected as 3DP is projected to shorten supply chains through inducing more direct means of production. Furthermore, 3DP is expected to induce shifts towards more localized production and to re-shift production to consumer countries as the share of labour costs in the total production costs decreases. Combined with online platforms, supply chains will become more dynamic and they will be digitalized as pre-chains will shift to digital processing of information while physical pre-chains will be eliminated. Labour implications in developed countries with ageing societies are considered potentially beneficial while reduced labour demands in developing countries are projected to contribute to socio-economic instability. On the other hand, 3DP offers development opportunities for remote areas with low economic profiles as it bridges the gap to the next market and it supplies these areas with objects needed to improve the quality of life. Another important industrial market segment 3DP will influence in the future is that of spare parts. Printing hard-to-obtain spare parts and precious components will stimulate the manufacturing, preservation and restoration of rare and/or antique objects. An example is Cuba where people drive a lot of cars from the 1950s or the international space station (ISS) where a 3D printer is now on board. In the first example spare parts are very hard to come by as these cars are not being produced anymore and in the second case delivering spare parts from Earth to the ISS is very expensive. Designing in a modular fashion may now be quite common, but most old equipment was not designed in a modular way. This means that when one part is broken and its spare part is not produced anymore by the industry, the whole object needs to be thrown away, leading to adverse environmental impacts. But when the spare part can be printed, the object will last longer which is very good from a sustainability point of view.

Licensing, patent, trademark and copyright frameworks are strongly affected as 3DP induces an easy manner to reproduce objects especially in combination with 3D scanning. Therefore, regulatory frameworks have to be adjusted to integrate various aspects concerning the digitalization of objects and ideas. This includes considerations how the distribution of harmful technologies can be regulated or constrained through these frameworks.

Quantified results of the sustainability implications of 3DP concerning costs, energy and CO_2 emissions show that sustainability potentials occur over the entire life cycle of 3D-printed products. This amounts to cost reductions of 170–593 billion US $, avoided TPES of 2.54–9.30 EJ and avoided CO_2 emissions of 130.5–525.5 Mt by 2025 in the markets identified for 3DP. This represents about 5% overall reduction of the respective categories. Aerospace production, medical components and tooling represent manufacturing markets with the highest relative potential for 3DP. Fuel demands in aviation show the largest relative reduction potential through 3DP-induced lightweight design. Moreover, aerospace production has the largest potential to reduce decommissioning-related TPES demands and CO_2 emissions. Consumer products and automotive manufacturing represent the largest potentially applicable markets for 3DP as they are predicted to have a combined share of 86% in the total manufacturing market. But by 2025, 3DP is still considered a small niche technology in these markets due to problems in printing high production volumes.

3DP holds the potential to absolutely decouple energy demands and CO_2 emissions from economic activity once applied on large scale in industry. If critical technological parameters like production speed and availability of raw printable materials increase, then 3DP would be applicable to larger production series, implying that its sustainability potentials would significantly rise. Of course, one should be cautious as positive sustainability gains risk to be neutralized through an increasing overall activity ("Rebound effect"), especially if the sustainability gains are re-invested (Paech, 2012). In that case, sustainability gains contribute maximally to a relative decoupling.

Despite its early maturation phase, societal decision-makers should become aware of the sustainability potentials of 3DP as it represents a technology which can greatly lower the input and output intensities of industrial manufacturing. Sustainability policies on 3DP should focus on the following three aspects to harvest the sustainability potentials of 3DP: (1) technology, (2) labour and (3) regulatory frameworks.

Additional funds for research are needed to improve the technological capacities of 3DP. Funds are also needed for research on sustainability implications of 3DP from an LCA perspective, a micro-economic perspective or a bottom-up approach. Research is needed to understand the crucial determinants of direct and indirect energy use and CO_2 emissions in 3DP and how these can be reduced on a technological level and on a societal scale. The production speed (build rate) of 3DP represents a central aspect in research as it is directly connected to the applicable size of production volumes. Faster 3DP processes would be applicable to larger production series in an economically feasible manner and offer significant sustainability potentials. Furthermore, the range of applicable materials has to be broadened to enable printing of advanced materials, high-performance alloys, nano-materials and hybrid material structures. Cost drivers in machinery costs have to be identified and strategies to reduce machinery costs should be developed, as machinery costs represent the largest share in overall 3DP production costs. Strategies should be developed for the logistics sector on opportunities to benefit from 3DP-induced changes in supply chains (e.g. focus on localized structures).

Changing supply chains induce the need for more information technology-related skills in labour. This includes both a paradigm shift in design-thinking as well as the need to increase training and education in digital manufacturing. Therefore, educational systems and programs have to be adjusted to meet these new knowledge demands. This can furthermore be considered an opportunity to compensate for the elimination of manual work in manufacturing due to the high degree of automation in 3DP.

Regulatory frameworks have to be adjusted to new technological environments, in which the digitalization of objects and ideas is of great importance. This includes the establishment of clear legal rules and regulations concerning 3D scanning, digital blueprints of objects and online distribution of ideas.

Concluding, 3DP represents a manufacturing technology with a large sustainability potential, especially if it becomes applicable to mass production markets and if social impacts are fully addressed.

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Update

Energy Policy

Volume 85, Issue , October 2015, Page 511

DOI: https://doi.org/10.1016/j.enpol.2015.03.007

Energy Policy 85 (2015) 511

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Corrigendum

Corrigendum to "A global sustainability perspective on 3D printing technologies" [Energy Policy 74 (2014) 158–167]

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The authors regret that there was an error in 2 of the formulas on p. 160 of the article.

The formula on energy (2.2) should read: $\Delta E = GDP_{3DP} * \Delta E_{3DP} * (TPES/GDP)$

The formula on CO_2 (2.3) should read: $\Delta CO_2 = GDP_{3DP} * \Delta CO_{2,3DP} * (CO_2/GDP)$

The authors would like to apologize for any inconvenience caused by them to the Editors and readers of this journal.

DOI of original article: http://dx.doi.org/10.1016/j.enpol.2014.08.033

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http://dx.doi.org/10.1016/j.enpol.2015.03.007