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Perspective

The potential of 3D printing in facilitating carbon neutrality

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ABSTRACT

At present, dramatically reduction of fossil fuel usage is regarded as a major initiative to achieve the carbon neutrality goal. Nevertheless, current energy policies are unlikely to achieve the climate goal without sacrificing economic development and people's livelihood because fossil fuels are currently the dominant energy source. As an environment-friendly manufacturing technology, three-dimensional printing (3DP) is flourishing and is considered beneficial to energy structure adjustment and industrial upgrading. Despite this, its potential to contribute to global carbon neutrality has not attracted enough attention. Herein, we explore the application of 3DP and its potential facilitating carbon neutrality from crucial sectors and applications including manufacturing, construction energy, livestock, and carbon capture and storage (CCS) technologies. The additive manufacturing and decentralized manufacturing characteristics of 3DP allow reducing greenhouse gas (GHG) emissions in manufacturing and construction sectors by optimized and lightweight designs, reduced material and energy consumption, and shortened transport processes. In addition, 3DP enables the precise manufacturing of customized complex structures and the expansion of functional materials, which makes 3DP an innovative alternative to the development of novel energy-related devices, cultured meat production technology, and CCS technologies. Despite this, the majority of applications of 3DP are still in an early stage and need further exploration. We call for further research to precisely evaluate the GHG emission reduction potential of 3DP and to make it better involved and deployed to better achieve carbon neutrality.

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Introduction

Climate change caused by anthropogenic emissions of greenhouse gas (GHG) to the atmosphere is largely irreversible for very long periods even after emissions stop. The Glasgow Climate Pact, a global agreement aiming to maintain temperature increase at 1.5 °C above pre-industrial levels and reduce GHG emissions was adopted recently by nearly 200 countries. To achieve this target, dramatically reduction of fossil fuel usage is regarded as a major initiative globally as it is the largest source of current GHG emissions. Despite this, governments are projecting to increase more fossil fuel production than clean energy to stimulate economic recovery after the COVID-19 pandemic (SEI, 2021). Apparently, regular pathways for achieving carbon neutrality will inevitably result in the limitation of current energy policy and sacrifice of economic and people's livelihood. In addition to the exclusively concerning energy sector of current policies, extra attention also need to be paid to other high GHG emission sectors such as industrial manufacturing, construction, transportation, and livestock. Therefore, it's crucial to find innovative alternatives to reconcile energy policy, economic development, and carbon neutrality strategy.

Three-dimensional printing (3DP), also known as additive manufacturing, has been rapidly developed as a sustainable and environmental-friendly manufacturing technology. It owns inherent benefits such as energy and material saving, freedom of design and fabrication, one-piece fabrication of multiple materials, and decentralized production. Studies have pointed out that 3DP is beneficial to the energy structure adjustment, circular economy strategies, and the promotion of industrial structure transformation and upgrading (Nascimento et al., 2019). And 3DP has been considered to promote the fourth industrial revolution together with new digital technologies such as artificial intelligence, machine learning, Internet of Things, and smart logistics (Okwudire and Madhyastha, 2021). Up to now, a few specific case studies have investigated the impact of 3DP on GHG emissions in manufacturing and construction sector (Table 1 and Fig. 1). Despite this, research on its potential to contribute to global carbon neutrality is still in the early stage and has not attracted enough attention, especially in other sectors.

1. Manufacturing transformation and coordinated emission reduction

As an environmentally friendly manufacturing technology, the potential of 3DP in facilitating the reduction of GHG emissions of the manufacturing industry cannot be ignored (Table 1 and Fig. 1). It has been estimated that using 3DP to replace traditional manufacturing can reduce the energy consumption and CO_2 emissions of industrial manufacturing up to 5% by 2025 (Gebler et al., 2014). Compared with traditional manufacturing methods, the additive manufacturing style of 3DP can significantly reduce the consumption of raw materials and energy during the manufacturing procedure. Its decentralized manufacturing form is closer to the consumer side and can reduce the carbon footprint by the transportation of raw materials and final products over a short distance. In particular, the excellent versatility and democracy of 3DP allows ordinary people to manufacture a variety of products on the same printer without extensive technical training and with almost no switch time. Its advantages of distributed and democratized manufacturing has also been proved in the early stage of the COVID-19 pandemic (Wang et al., 2020). As an example, studies have reported that 3DP enables dramatically reduction of GHG emissions associated with metallic components production in aerospace (such as bracket, seat buckle and fork fitting), medical and tooling through optimized and lightweight designs, less material consumption, cost-effective manufacturing of complex geometries, and shortened transport processes (Gebler et al., 2014; Huang et al., 2016; Tang et al., 2016). A considerable reduction of aircraft fuel consumption can also be realized due to the lighter weight of the 3D printed parts (Gebler et al., 2014; Huang et al., 2016). It's estimated that U.S. market-wide aircraft industry will realize cumulative GHG emission reductions of 92.1 - 215.0 million metric tons CO_2-equivalent/year through 2050 under a rapid additive manufacturing adoption scenario (Huang et al., 2016). Meanwhile, the GHG emissions of 3D printed plastic products is highly related to material fill percentage and the existence of clean energy supplies such as photovoltaic power. A material fill percentage of 100% may lead to higher GHG emissions than conventional manufacturing (Kreiger and Pearce, 2013). It cannot be ignored that the production capacity of 3DP is limited, which makes 3DP more suitable to complement traditional industrial mass manufacturing rather than completely replace it. Therefore, the environmental impact and life cycle assessment of 3DP for manufacturing needs to be further explored in terms of design, fabrication, material, and participate pattern.

2. Potential of 3DP in construction sector

The construction sector is responsible for approximately 38% of current global GHG emissions, 40% of energy use and 12% of potable water use (Agusti-Juan and Hubert, 2017). As the world's population continues to increase and the largescale urbanization in developing countries, the immense demands for more buildings, infrastructures, and concrete use are inevitable. Therefore, the carbon footprint of the construction sector is expected to continually grow until the middle of this century (Khan et al., 2021). Conventional construction technologies require large usage of cement, formworks and reinforced materials, which are labor- and capital-intensive with high global warming potentials. Besides, construction owns a higher rate of injury and death than any other industries. To meet the demand of sustainable strategies and GHG emission reduction, digital fabrication (especially 3DP) is regarded as an innovative construction technology. 3D concrete printing has been receiving great interest and attention with more structure freedom, high automation, and less capital and material consumption. Some case studies have dedicated to investigating the global warming potential associated with 3D concrete printing over conventional technologies (Table 1 and Fig. 1). For example, a prefabricated bathroom unit constructed using 3DP achieved approximately 85.9% less CO_2 emissions compared to different construction methods

Table 1 – Summary of current studies addressing the impact of 3DP on GHG emissions in manufacture and construction sector.

Applications	GHG emissionsvariation	Description	Refs	Major barriers or challenges
Plastic products (block)	-80.8%∼+34.6%	Related to material fill percentage and the existence of photovoltaic power. The lowest GHG emissions were realized with solar photovoltaic power and 0%, 100% and 15% fill of material for block, spout and juicer, respectively. The highest GHG emissions were happened without solar photovoltaic power and 100%, 100% and 15% fill of material for block, spout and juicer, respectively.	(Kreiger and Pearce, 2013)	Needs to adjust material fill percentage for different productions and improve the social acceptability of 3D printed products.
Plastic products (water spout)	-28.6%∼+100%			
Plastic products (juicer)	-58.1%∼+9.7%			
Aerospace fuel	-9%∼-35%	Lightweight designs and high energy saving potentials of 3D printing. The lowest GHG emissions were obtained in the established model with high market potential, change in cost intensity, change in energy intensity, and change in CO_2 emission intensity. The highest GHG emissions were obtained in the established model with low market potential, change in cost intensity, change in energy intensity, and change in CO_2 emission intensity.	(Gebler et al., 2014)	Up to date, 3DP is primarily applied in low volume production series, customized or and high-value products.
Aerospace production	-8%∼-19%			
Medical components	-5%∼-19%			
Tooling	-3%∼-10%			
Total manufacturing	-5%			
Aircraft engine bracket	-58%	Optimized structure and less material consumption	(Tang et al., 2016)	3DP is only applied in manufacturing small components.
Bracket	-89%∼-94%	Lightweight geometries of metallic aircraft components and a reduction in airplane fuel consumption due to the lighter weight of the 3D printed parts. Data values were estimated from available literature values, the lowest GHG emissions reduction were calculated by subtracting the high 3DP values from the low conventionally manufacture values, and the highest GHG emissions reduction were calculated by subtracting the low 3DP values from the high conventionally manufacture values.	(Huang et al., 2016)	Technical challenges including machine productivity, geometric repeatability, residual stress, and high surface roughness need to be overcome.
Bionic bracket	-82%∼-90%			
Engine cover door hinge	-76%∼-84%			
Seat buckle	-26%∼-92%			
Fork fitting	-23%∼-86%			
3D printing filaments (polycarbonate)	-28%	No ABS pellet making process	(Gaikwad et al., 2018)	E-waste plastics were only available to Fused filament fabrication type 3D printers.
3D printing of sand molds	-30%∼-40%	Optimized part design and reduced metal and related-energy consumption. The author didn't give a clear explanation about the range.	(Sivarupan et al., 2019)	A large cross-sectional area job-box were necessary to extend 3D sand mold printing from small to large scale production scenarios.
1 m^2 of wall	-21.2%∼+81.4%	Depended on reinforcement steel volume fraction and wall thickness. 3D printing is suitable for complex structures. The lowest GHG emissions were obtained with a minimal reinforcement steel content of 0.5% and a lower wall thickness of 0.1m. The highest GHG emissions were obtained with a reinforcement steel content of 1.5% and a wall thickness of 0.1m.	(Agusti-Juan et al., 2017)	Most studies focused on small-scale processes. The implementation of 3DP in the construction sector requires quantitative assessments.

(*continued on next page*)

Table 1 (*continued*)

Applications	GHG emissionsvariation	Description	Refs	Major barriers or challenges
1 m^2 of wall (concrete)	+27.2%	High presence of cement in the 3DP concrete wall. More use of electricity for the 3D cob printing operation. 3DP concrete mixes performs better than the conventional concrete. The lowest GHG emissions were obtained with cement and fly ash ratios of 19.5% and 7.7%, respectively. The highest GHG emissions were obtained with cement and fly ash ratios of 25% and 7.1%, respectively.	(Alhumayani et al., 2020)	The high-cement content of 3DP concrete and the use of electricity for the 3D printing operation of 3DP cob remain to be overcome.
1 m^2 of wall (cob)	+85%			
Concrete mixes	-13%∼+5.7%			
1 m^2 external load-bearing wall	-24.6%∼+27.5%	Depended on the existence of reinforced columns and beams and the content of cement. The lowest GHG emissions were realized using an alternative concrete mixture and without reinforced concrete columns and beams. The highest GHG emissions were realized using 3DP method with reinforced concrete columns and beams.	(Mohammad et al., 2020)	Develop more sustainable printable concrete material. Thoroughly test the integrity of printed structures and buildings. Drive policy to adopt 3D concrete printing as a viable technology for building construction.
Prefabricated bathroom unit	-85.9%	Less formworks of 3D printed wall, the production process of formwork is energy-intensive	(Weng et al., 2020)	Lack of applications in constructing large-scale structures.
A concrete cylindrical-silo model	+23.7%∼+29%	Depend on cement content in 3D printing concrete construction. The highest GHG emissions were realized with recycled-aggregate ratio of 0%, the lowest GHG emissions were realized with recycled-aggregate ratio of 100%.	(Han et al., 2021)	Need reductions in cement content in future technological advancement.
A single-storey house	-47%	No steel reinforcement in the 3D printed walls, reduced emissions related to the production, manufacturing, transportation, and assembly of reinforcement materials	(Abdalla et al., 2021)	Lack of applications in constructing large-scale buildings.
A two-storey building	-32%	No steel reinforcement in the 3D printed walls, reduced emissions related to the production, manufacturing, transportation, and assembly of reinforcement materials	(Batikha et al., 2022)	A high level of unpredictability with the 3D printable concrete mix and its constituents, which increases the total project cost. The printers are relatively expensive, depending on the size and the degrees of freedom provided.

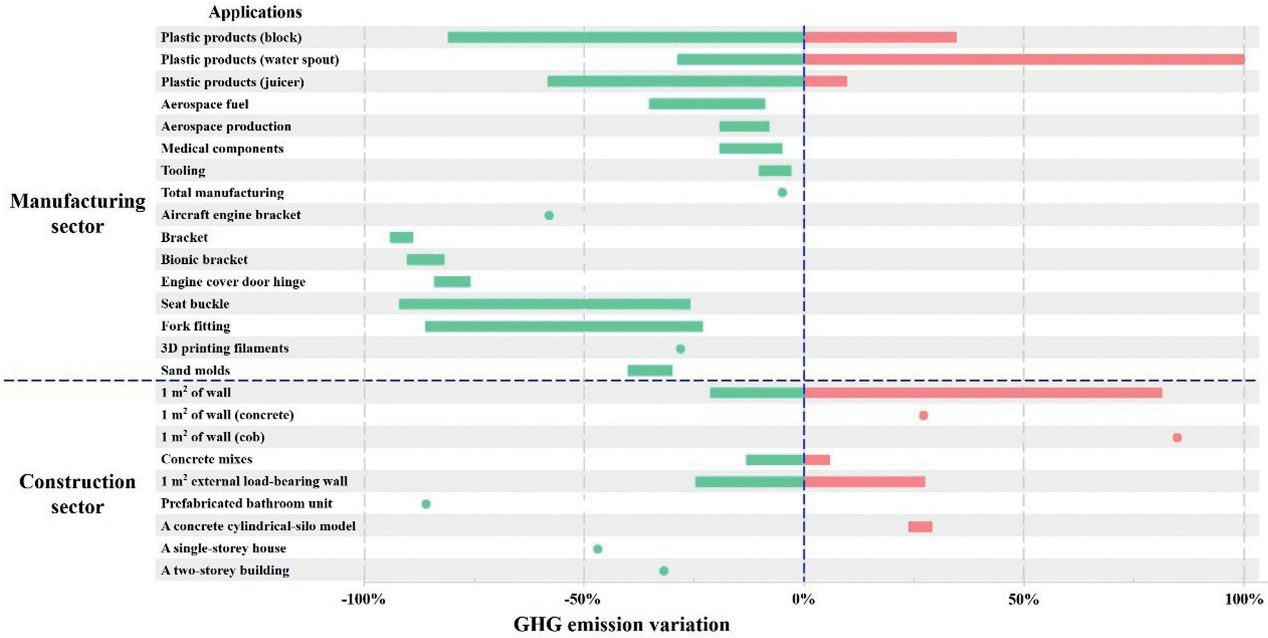

Fig. 1 – The impact of 3DP on GHG emissions in specific case studies in manufacture and construction sector.

(Weng et al., 2020). The GHG emission reduction mainly attributed to less formworks and steel reinforcement of 3D printed walls, whereby the GHG emissions related to the production, manufacturing, transportation, and assembly of reinforcement materials are largely reduced. Nevertheless, the higher content of cement and more use of operation electricity for 3D printing may lead to the increase of GHG emissions (Alhumayani et al., 2020). Optimizing concrete content and developing novel 3D printable eco-material may overcome these issues (Liiv et al., 2018). In general, it is essential to further assess the global warming potential of 3DP in construction.

3. Potential of 3DP in energy sector

The fossil fuels usage accounts for 80% of current global energy supplies and is the largest source of worldwide GHG emissions. Hence, in addition to reducing energy consumption and improving energy efficiency, it's urgent to develop clean energy and low-carbon technologies including hydrogen, solar, wind, and biomass energy to substitute fossil fuels. 3DP offers a promising strategy in designing and fabricating novel devices and catalysts such as electrodes, batteries, supercapacitors, and other devices for energy-related applications. 3DP holds distinct advantages of accurately controlling the geometry and architecture of customized complex 3D structures from the nanoscale to macroscale and fast prototyping with functional materials in a cost-effective manner (Fu et al., 2017; Liang et al., 2022). For example, 3DP can realize precisely developing of monolithic catalysts with customized structures for methanol steam reforming reaction. These catalysts can be used for in-situ hydrogen production of fuel cell vehicles with better performance and enhanced mechanical stability during driving (Liang et al., 2022). The advantages of 3DP provide great opportunities for obtaining enhanced power and energy density and will allow researchers to rethink the design of future energy-related devices. 3D printed electrodes and electrolysers with hierarchical porous structure and light weight have also been demonstrated to have high efficiency for water splitting to generate hydrogen (Chisholm et al., 2014; Peng et al., 2020). With the rapid development of functional printable materials, 3D printed energy-related devices using metal-organic frameworks, graphene oxide, carbon nanotubes, and other materials exhibited great performance (Fu et al., 2017). 3D multi-material printing technology which can manufacture different materials within the same part has been proved experimentally. This advanced 3DP technology can help to develop safe, customizable, low-cost and high-performance batteries and other related devices. Besides, 3DP also contributes to developing substitution technologies such as biomass utilization and energy recovery and utilization (Kucherov et al., 2017).

4. Potential of 3DP in livestock

The livestock sector has been dramatically expanded over the past decades worldwide while its land use is equivalent to about 30% of the global land area. It involves direct GHG emissions from enteric fermentation (especially methane emissions from ruminants), manure management, and feed production, as well as indirect GHG emissions and carbon sink reductions caused by pasture desertification and deforestation (Tuomisto and de Mattos, 2011). The impact on terrestrial carbon sinks together with GHG emissions, especially extensive CH_4 and N_2O emissions, highlights the importance of livestock in achieving carbon neutrality. Considerable attention needs to be paid to the prospect of low-carbon technologies. Cultured meat production is an alternative strategy as it can significantly simplify the entire commodity chain and its GHG emissions are mainly associated with the use of fuel and electricity, which can be reduced by using renewable energy. In addition, the application of cultured meat production can significantly reduce related land use and facilitate the restoration of pasture and farmland to forests, thereby increasing carbon sinks. A former study has estimated that cultured meat production could reduce 78%-96% GHG emissions and 99% land use compared to conventionally meat production in Europe (Tuomisto and de Mattos, 2011). Regarding this, 3D bioprinting is one of the innovative technologies that can be deployed in the near future and significantly change the entire food system, especially for cultured meat production. The extraordinary scalability and controllability of 3D bioprinting can easily modify the texture of cultured meat through the precise assembly of muscle/adipose cells' ratio, proteins, fibers, and nutrients, thereby realizing the diversity of nutritional values, organoleptic properties, and shapes (Kang et al., 2021). This is especially important for the production of mammalian cell-based meat that is close to real meat. Steak-like cultured meats with desired types and compositions including fiber, muscles, adipose tissues, and blood capillaries have been realized by 3D bioprinting (Kang et al., 2021).

5. Strategies to improve carbon capture and storage (CCS) technologies

While fossil fuels will be continually used and cannot be completely avoided in the short future, current emissions already account for two-thirds of the available budget for keeping warming to below 2 °C (Rogelj et al., 2016). So in addition to reforestation to increase carbon sink, it's urgent to develop negative-emission technologies such as carbon capture and storage (CCS) technologies to remove GHGs from the atmosphere. Non-biological CCS technologies have the potential to reduce 85%-90% CO_2 emissions from point and energy-intensive emission sources such as fossil-fuel power facilities and cement plants and are expected to reduce 20% worldwide CO_2 emissions from the energy sector (Haszeldine, 2009). However, non-biological CCS technologies have not yet been deployed on a large scale due to the high cost, unsustainability, and limited emission mitigation benefits. In this regard, 3DP can easily realize the development of new designs and advanced functional materials for non-biological CO_2 separation, adsorption, capture, and storage that cannot be realized by conventional manufacture methods (Kim et al., 2020). Biomimetic CCS technology is also promising and environmental-friendly for the mitigation of atmospheric CO_2 which utilizes purified photocatalytic enzymes such as carbonic anhydrase (CA) and organisms such as bacteria and algae with enhanced photosynthesis ability (Chen et al., 2012; Sharma et al., 2020). This is because organisms and purified enzymes can be easily cultured, synthesized, and applied on an industrial scale through biological and genetic engineering. However, biomimetic CCS technology is still under development due to the low stability of CA, difficulty to maintain the biological activity of organisms, and low efficiency of CO_2 sequestration. In this aspect, 3DP has the potential to facilitate new combinations and refinements of biomimetic CCS devices. 3DP can realize the precise manufacture of complex biomimetic structures and the use of functional materials containing living bacteria for printing (Dudukovic et al., 2021; Gladman et al., 2016). For example, a 3D printed tree-like cellular fluidic device is developed with the potential to improve CO_2 capture rates (Dudukovic et al., 2021). The gradual application of 3DP in other sectors such as desalination and wastewater treatment applications is also inspiring for achieving carbon neutrality (Chowdhury et al., 2018; Yanar et al., 2020).

6. Priority actions

Although 3DP was reported with the potential to reduce GHG emissions in the manufacturing and construction sector in most of the case studies, it was also confirmed that 3DP could increase GHG emissions in the rest studies. Except for the manufacturing and construction sector, the majority of applications of 3DP in other sectors are either in the experimental demonstration or prototype stage. So in order for 3DP to better serve carbon neutrality, a priority series of research are necessary including following:

- More life cycle assessments and case studies to precisely evaluate its GHG emission reduction potential not only in manufacturing and construction sector, but also in other crucial sectors.
- In-depth studies to investigate in which sectors, in what proportions, and forms are suitable for 3DP to prior participate and deploy, to better facilitate carbon neutrality while realizing energy structure adjustment, industrial transformation, and low-carbon economy.
- Explore innovative strategies and options for climate-change mitigation with 3DP and other digital technologies beyond current exclusively concerned pathways of energy sector.

In summary, as an intelligent and green manufacturing technology, 3DP is becoming an indispensable part of future industrial manufacturing and our daily life. And the carbon reduction potentials of 3DP in various situations are still unknown and need further exploration. While the decentralized manufacturing and small-scale production feature of 3DP are not suitable for all sectors and product chains. In-depth studies are needed to explore and stimulate the potential of 3DP to better achieve carbon neutrality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

Abdalla, H., Fattah, K.P., Abdallah, M., Tamimi, A.K., 2021. Environmental footprint and economics of a full-scale 3D-printed house. Sustainability 13 (21), 11978.

Agusti-Juan, I., Hubert, G., 2017. Environmental design guidelines for digital fabrication. J. Clean Prod. 142, 2780–2791.

Agusti-Juan, I., Muller, F., Hack, N., Wangler, T., Habert, G., 2017. Potential benefits of digital fabrication for complex structures: Envitonmental assessment of a robotically fabricated concrete-wall. J. Clean Prod. 154, 330–340.

Alhumayani, H., Gomaa, M., Soebarto, V., Jabi, W., 2020. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. J. Clean Prod. 270, 122463.

Batikha, M., Jotangia, R., Baaj, M.Y., Mousleh, I., 2022. 3D concrete printing for sustainable and economical construction: A comparative study. Autom. Constr. 134, 104087.

Chen, P.H., Liu, H.L., Chen, Y.J., Cheng, H., Lin, W.L., Yeh, C.H., et al., 2012. Enhancing CO_2 bio-mitigation by genetic engineering of cyanobacteria. Energy Environ. Sci. 5 (8), 8318–8327.

Chisholm, G., Kitson, P.J., Kirkaldy, N.D., Bloor, L.G., Cronin, L., 2014. 3D printed flow plates for the electrolysis of water: an economic and adaptable approach to device manufacture. Energy Environ. Sci. 7 (9), 3026–3032.

Chowdhury, M.R., Steffes, J., Huey, B.D., McCutcheon, J.R., 2018. 3D printed polyamide membranes for desalination. Science 361 (6403), 682–685.

Dudukovic, N.A., Fong, E.J., Gemeda, H.B., DeOtte, J.R., Ceron, M.R., Moran, B.D., et al., 2021. Cellular fluidics. Nature 595 (7865), 58-+.

Fu, K., Yao, Y.G., Dai, J.Q., Hu, L.B., 2017. Progress in 3D printing of carbon materials for energy-related applications. Adv. Mater. 29 (9), 1603486.

Gaikwad, V., Ghose, A., Cholake, S., Rawal, A., Iwato, M., Sahajwalla, V., 2018. Transformation of E-waste plastics into sustainable filaments for 3D printing. ACS Sustain. Chem. Eng. 6 (11), 14432–14440.

Gebler, M., Uiterkamp, A., Visser, C., 2014. A global sustainability perspective on 3D printing technologies. Energy Policy 74, 158–167.

Gladman, A.S., Matsumoto, E.A., Nuzzo, R.G., Mahadevan, L., Lewis, J.A., 2016. Biomimetic 4D printing. Nat. Mater. 15 (4), 413-+.

Han, Y.L., Yang, Z.H., Ding, T., Xiao, J.Z., 2021. Environmental and economic assessment on 3D printed buildings with recycled concrete. J. Clean Prod. 278, 123884.

Haszeldine, R.S., 2009. carbon capture and storage: how green can black be? Science 325 (5948), 1647–1652.

Huang, R.Z., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., et al., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. J. Clean Prod. 135, 1559–1570.

Kang, D.H., Louis, F., Liu, H., Shimoda, H., Nishiyama, Y., Nozawa, H., et al., 2021. Engineered whole cut meat-like tissue by the assembly of cell fibers using tendon-gel integrated bioprinting. Nat. Commun. 12 (1), 5059.

Khan, S.A., Koc, M., Al-Ghamdi, S.G., 2021. Sustainability assessment, potentials and challenges of 3D printed concrete structures: a systematic review for built environmental applications. J. Clean Prod. 303, 127027.

Kim, H.S., Hong, S.G., Yang, J., Ju, Y.J., Ok, J., Kwon, S.J., et al., 2020. 3D-Printed interfacial devices for biocatalytic CO_2 conversion at gas-liquid interface. J. CO2 Util. 38, 291–298.

Kreiger, M., Pearce, J.M., 2013. environmental life cycle analysis of distributed three-dimensional printing and conventional manufacturing of polymer products. ACS Sustain. Chem. Eng. 1 (12), 1511–1519.

Kucherov, F.A., Gordeev, E.G., Kashin, A.S., Ananikov, V.P., 2017. Three-dimensional printing with biomass-derived pef for carbon-neutral manufacturing. Angew. Chem.-Int. Edit. 56 (50), 15931–15935.

Liang, Z., Wang, G., Zeng, G., Zhang, J., Tang, Z., 2022. Highly controlled structured catalysts for on-board methanol reforming. J. Energy Chem. 68, 19–26.

Liiv, J., Teppand, T., Rikmann, E., Tenno, T., 2018. Novel ecosustainable peat and oil shale ash-based 3D-printable composite material. Sustain. Mater. Technol. 17, e00067.

Mohammad, M., Masad, E., Al-Ghamdi, S.G., 2020. 3D Concrete printing sustainability: a comparative life cycle assessment of four construction method scenarios. Buildings 10 (12), 245.

Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Lona, L.R., et al., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context A business model proposal. J. Manuf. Technol. Manag. 30 (3), 607–627.

Okwudire, C.E., Madhyastha, H.V., 2021. Distributed manufacturing for and by the masses. Science 372 (6540), 341–342.

Peng, M.W., Shi, D.L., Sun, Y.H., Cheng, J., Zhao, B., Xie, Y.M., et al., 2020. 3D printed mechanically robust graphene/cnt electrodes for highly efficient overall water splitting. Adv. Mater. 32 (23), 1908201.

Rogelj, J., den, Elzen, M., Hohne, N., Fransen, T., Fekete, H., Winkler, H., et al., 2016. Paris agreement climate proposals need a boost to keep warming well below 2 degrees C. Nature 534 (7609), 631–639.

SEI, IUNEP, 2021. The Production Gap Report 2021.

Sharma, T., Sharma, S., Kamyab, H., Kumar, A., 2020. Energizing the CO_2 utilization by chemo-enzymatic approaches and potentiality of carbonic anhydrases: A review. J. Clean Prod. 247, 119138.

Sivarupan, T., Upadhyay, M., Ali, Y., El, Mansori.M., Dargusch, M.S., 2019. Reduced consumption of materials and hazardous chemicals for energy efficient production of metal parts through 3D printing of sand molds. J. Clean Prod. 224, 411–420.

Tang, Y.L., Mak, K., Zhao, Y.F., 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. Journal of Cleaner Production; 137, 1560–1572.

Tuomisto, H.L., de, Mattos, M.J.T., 2011. Environmental impacts of cultured meat production. Environ. Sci. Technol. 45 (14), 6117–6123.

Wang, D.Y., Zhang, J.P., Liu, Q., Chen, B.L., Liang, Y., Hu, L.G., et al., 2020. 3D Printing challenges in enabling rapid response to public health emergencies. Innovation (New York, N.Y.) 1 (3), 100056.

Weng, Y.W., Li, M.Y., Ruan, S.Q., Wong, T.N., Tan, M.J., Yeong, K.L.O., et al., 2020. Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. J. Clean Prod. 261, 121245.

Yanar, N., Kallem, P., Son, M., Park, H., Kang, S., Choi, H., 2020. A New era of water treatment technologies: 3D printing for membranes. J. Ind. Eng. Chem. 91, 1–14.