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Review

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The role of PGMs in decarbonizing the atmosphere: additive manufacturing in perspective

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Abstract. Platinum Group of Metals (PGMs) has been at the forefront of emission control in autocatalysts and could be the driving force behind the net-zero agenda, by providing emission-free energy sources. The literature has revealed that the versatility of additive manufacturing (AM) could be used to produce intricate hierarchical structures that increase the active catalytic sites of PGMs in autocatalysts, fuel cells (FCs), and batteries with improved operational efficiency. FCs and batteries with lower PGM loads have proven to perform better than conventional manufactured energy devices with higher PGM loads. The inherent hyperlocal-on-demand nature of AM could be used to disrupt the conventional multiple energy-consuming carbon-intensive supply chain to decarbonize the atmosphere. The synergy between AM and PGMs has contributed greatly to the increase in operational performance of FCs and batteries, compelling several nations to start migrating their energy systems to eco-friendly energy systems.

Keywords: Autocatalyst / greenhouse gasses / 3D printing / fuel cells / batteries / hydrogen economy

Abbreviations

PBF	Powder Bed Fusion
BJ	Binder Jetting
DED	Directed Energy Deposition
PV	Photopolymer vat
FB	Furan Binders
ME	Material Extrusion
DLF	Directed Light Fabrication
SL	Sheet Lamination
SLA	Stereolithography
MJ	Material Jetting
LPBF	Laser Powder Bed Fusion
LENS	Laser Engineered Net Shaping
UAM	Ultrasound additive manufacturing
DMLS	Direct Metal Laser Sintering
3DLC	3D Laser Cladding
SDL	Selective Deposition Lamination
LDW	Laser Deposition Welding
LOM	Laminated object manufacturing
FDM	Fused Deposition Modelling
EBAM	Electron Beam Additive Manufacturing
DLS	Carbon® Digital Light Synthesis
DOD	Drop-On Demand
SLS	Selective Laser Sintering
SB	Solvent-based Binders
SLCOM	Selective Lamination Composite Object Manufacturing
UVB	UV Binders
FFF	Fused Filament Fabrication
PSL	Plastic Sheet Lamination
EBM	Electron Beam Melting
PB	Polymer Binders
CAM-LEM	Computer-Aided Manufacturing of Laminated Engineering Materials
NPJ	NanoParticle Jetting
CBAM	Composite Based Additive Manufacturing
SLM	Selective Laser Melting
CFF	Composite Filament Fabrication
DLP	Digital light processing
WAAM	Wire Arc Additive Manufacturing
PJ	PolyJet
WB	Water-based Binders

1 Introduction

WHO (World Health Organization) [1] reported that about 3.7 million premature deaths occur worldwide every year due to outdoor air pollution, with emissions from the

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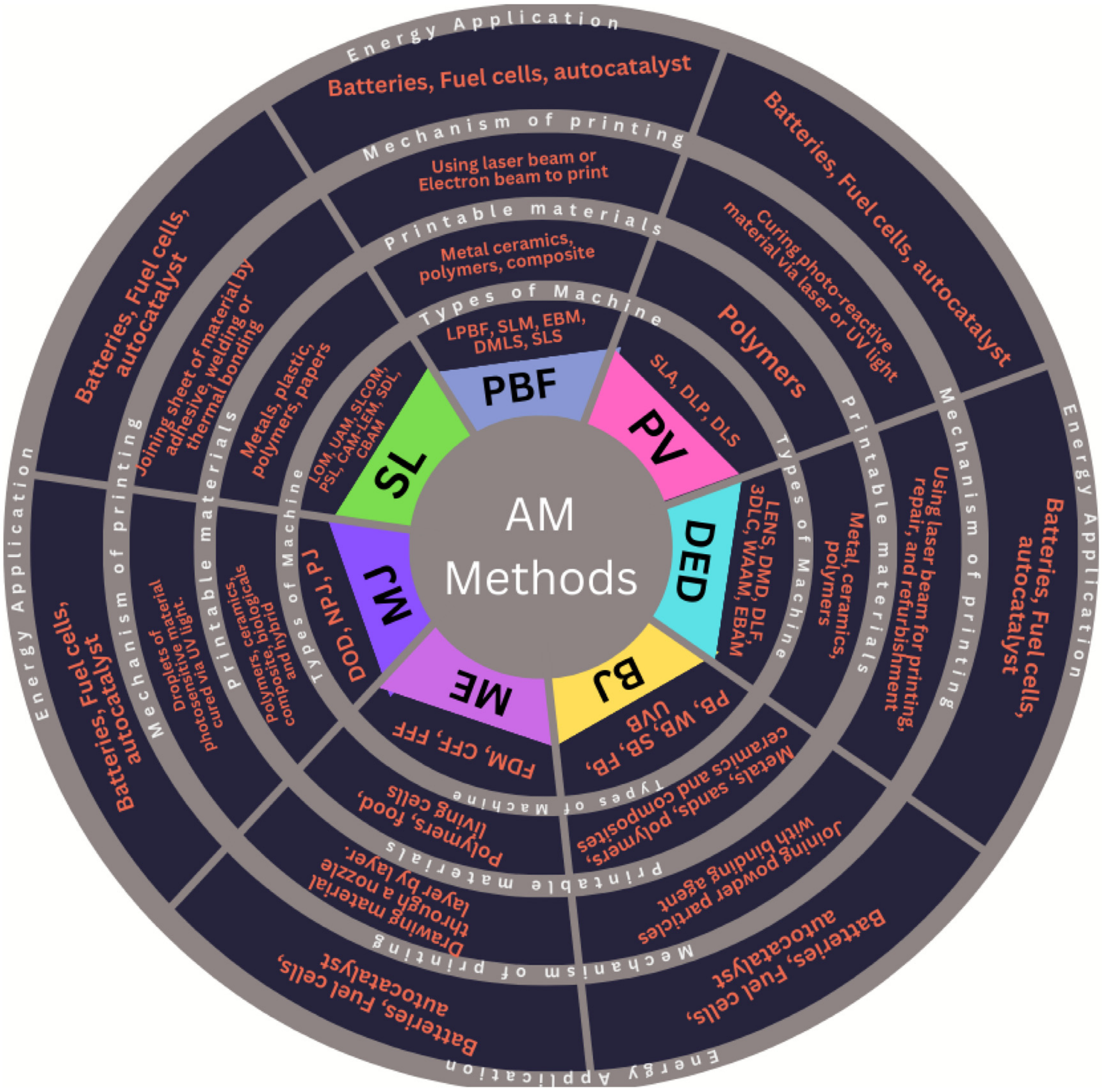

Fig. 1. Classification of AM methods based on machine types, printable materials, and mechanism of printing.

transportation industry contributing significantly. The report indicated that about 92% of the global population is exposed to harmful air [2]. The external cost of these harmful gas emissions ranges from €330–940 per year. The direct cost of releasing these harmful emissions to the atmosphere is about €24b per year, due to illness-causing low productivity, reduction in crop yield, increased medical cost, and high mortality [1]. To provide solutions that would prevent the dire irreversible environmental and socio-economic consequences of global warming [3] due to the release of harmful gasses into the atmosphere; most leading countries gave estimated dates to place a complete ban on the use of internal combustion engines (ICEs) which is one of the principal contributor to greenhouse gas emissions [4]. This critical decision was taken after the Paris collation in an attempt to ensure global warming does not exceed 1.5°C by 2050 to protect the planet [5,6].

Platinum group of metals (PGMs) and additive manufacturing (AM) which is generally referred to as 3D printing has emerged as game changers to curb the release of harmful gases from on-road and off-road transportation systems [7]. PGMs (platinum, palladium, rhodium, ruthenium, osmium, and iridium) are precious metals that have demonstrated unrivaled catalytic properties [8], making them the ideal for cleaning up the exhaust of ICE systems which have led to the discovery of catalytic converter [8,9]. Catalytic converter which is also referred to as an autocatalyst is cylindrical or elliptical made from ceramic or metal with a honeycomb internal configuration coated with a solution of chemicals Al_2O_3 including platinum, rhodium, and/or palladium normally mounted in a stainless-steel canister and installed in automobile exhaust line to convert pollutants from the combustion chamber to harmless gases [10]. The autocatalyst converts harmful emissions (Hydrocarbons – HC, carbon monoxide – CO, and oxides of nitrogen – NOx) which are generated during the fuel combustion into water, CO_2, and nitrogen. The filters in the autocatalyst are coated with PGM alloys to burn off fine particulates (soot) produced during the combustion process and regenerate the filters to ensure the continued elimination of harmful fuel particulate matter (PM) from the exhaust which normally causes lung and

Table 1. Harmful gasses produced from tail gas of ICE vehicles and their adverse effects.

Harmful gas	Adverse effects
Carbon monoxide (CO)	Carbon monoxide (CO) displaces oxygen from the blood. It is fatal at high concentrations and exacerbates heart disease at lower concentrations.
Hydrocarbons (HC)	Hydrocarbons (HC) are carcinogens and form photochemical smog in the atmosphere.
Oxides of nitrogen (NOX)	Oxides of nitrogen (NO_X) contribute to acidic rain, the formation of ozone, and photochemical smog in the atmosphere.
Particulate matter (PM)	Particulate matter (PM) can cause cardiovascular and lung diseases due to soot particles, and metallic and sulfate particles from the tail gas and engine lubricate.

(Data sources [26,27]).

cardiovascular disease if not prevented and release into the atmosphere [11]. The internal configurations of the catalytic converter with interconnected honeycomb structure make AM an ideal candidate to increase the operational efficiency of the autocatalyst [12].

AM is a renaissance of the manufacturing industry in the fourth industrial revolution and has the capacity to produce components of catalytic converters, fuel cells (FC), and batteries with improved operational efficiency to power the transportation industry with little-to-no harmful emissions [7,13]. AM could be used to produce components of propelling systems such as batteries and FCs with controllable pore morphology, chemical distribution, and geometrical control at multiple lengths at micron/nanoscales [14]. Manufacturing components of FCs, batteries, and converters at nano-, micro-, and macro scales is very important because the electrochemical and physiochemical interactions of these systems are influenced by the basic building blocks at the molecular and supermolecular scales [15]. Using the versatility of AM to produce higher hierarchical structures with controllable microstructures and geometry provides increased surface-to-volume ratios that require less catalytic loading (PGMs) but higher intensifications at a lower cost [16]. This was demonstrated by Baena-Moreno et al. [17] using a novel 3D-printed structure with a complex gyroid geometry for a catalytic converter. The gyroid 3D complex geometries provided a 14% improvement in CO_2 conversion compared to the honeycomb structures manufactured using conventional methods (eg. casting, forging, sheet forming, extrusion, etc.) [18] of manufacturing. This improvement was attributed to the higher turbulence and the improved heat transfer conductivities provided by the 3D-gyroid highly interconnected substrate. This observation attests to the superior manufacturing capabilities of AM which could contribute to a reduction in carbon emissions *(Note: greenhouse gas and carbon emissions would be used interchangeably to imply harmful emissions).* As a result, it is reported that the AM technology could contribute 27% reduction in greenhouse gas emissions [19]. AM technology is generally classified into seven categories [20] depending on the type of machine, material feedstock for printing, and the mechanism of printing (Fig. 1).

The selection of a particular AM method depends on the intended application and the material to be used [21]. Generally, all the methods can be used to produce customized 3D structures with intricate geometrical configurations with high density, and precision – opening a window for producing components with different properties based on the intended industrial applications [22]. PBF machines use laser or electron beam to print metal, ceramics, polymer, and composites with great dimensional accuracy while DED machines are mainly known for their unique ability to repair/refurbish damaged components. MJ, BJ, and ME are known to print 3D structures using UV light, binding agents, and drawing of materials through nozzles respectively [23]. SL process is for laminating dissimilar materials while VP one of the earliest AM processes uses UV light for curing materials layer-by-layer. The various AM methods have demonstrated their agility by eliminating materials wastage and producing interconnected intricate 3D structures with geometrical precision, reducing manufacturing cost and time, increasing operational efficiency, and lowering energy consumption during the life span of products [23,24]. The reduce, reuse, and recycle (3 Rs) [25] inbuilt strategy of the AM process has systematically positioned the technology to revolutionaries the manufacturing industry geared towards reduction of carbon emission as stipulated in the Paris Collation [5]. Based on the Paris Agreement, the world has no option apart from cleaning up its act of carbonizing the environment, making PGMs and AM a hair's breadth of becoming ubiquitous approach to decarbonizing the atmosphere. The cumulative effect of the synergy between AM and PGMs could drastically reduce greenhouse gas emissions and accelerate the achievement of the net zero agenda.

The current research would therefore focus on the reduction of harmful gases in the transportation industry via the use of PGM and AM – discussing the contribution of AM in producing catalytic converters, FC, and batteries, the unrivaled contributions of AM to greenhouse gas emissions reduction, current challenges, and the way forward. The article would give an enlightening expert insight into the current research paradigm about how AM and PGM are contributing to the hydrogen economy to create a net-carbon world.

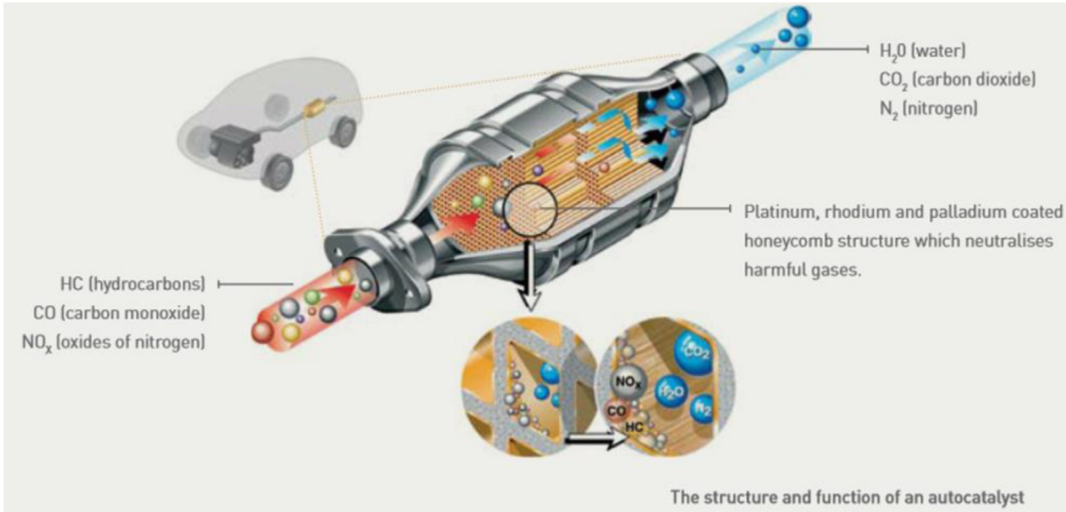

Fig. 2. Schematic representation of catalytic converter [26].

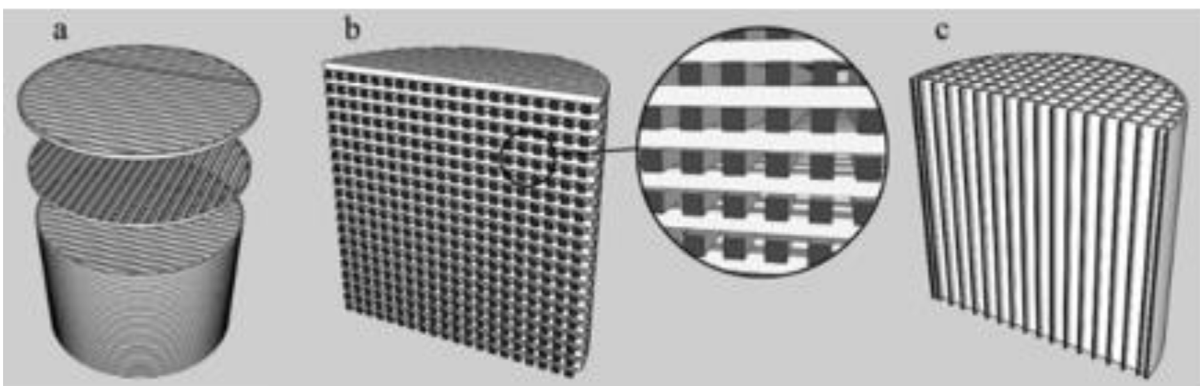

Fig. 3. 3D printed catalytic convertor substrate a) Rotated layers; b) Cross section of the rotated layers; C) conventional diesel oxidation catalyst substrate with straight channels structure [31].

2 Contributions of PGM and AM to the operational efficiency of autocatalysis

While it is indisputable that the invention of automobile has made the world a convenient place it equally contributed significantly to one of the world's man-made problems – climate change with all its negative consequences [8]. Fossil fuel energy systems (eg. Diesel or gasoline engines) produce harmful, toxic fumes (Tab. 1) which led to many health complications [26,27]; triggering the inversion of catalytic converters which have undergone many generational improvements to the current three-way Catalytic Converter (Fig. 2) which is mounted with oxygen sensors to control the remove of all the three major pollutants (HC, CO, and NOx) [8].

The catalytic converter is made up of parallel channels of a honeycomb monolith network thin-walled cell structure through which gases flow (Fig. 3c). The substrate is washcoat with Al_2O_3 to increase the porosity of the substrate which serves as a carrier for PGM active catalysts layer [28]. The wash coating technique was developed to increase the monolith surface area available to the PGMs to provide higher active catalytic sites which makes the AM process a prime candidate [29]. AM could be used to increase the active catalyst site to improve the catalytic conversion process as demonstrated by Baena-Moreno et al. [17] with the complex gyroid structure since the shape of the internal configuration of the catalytic convertor can substantially influence its operational efficiency. 3D printing of the catalytic converter's components (Figs. 3a-3b) could boost the conversion efficiency of the converter with a lower PGM load [30] requirement and the release of fewer unwanted by-products at lower energy consumption with an improved life cycle of the converter.

The interconnected porous 3D structure of the catalytic converters enables efficient mass and heat transfer provoking powerful conversion efficiency which has triggered a great research interest. Via the layer-wise process of 3D printing a catalytic converter substrate was printed and tested in a dual-fuel heavy-duty diesel engine as a methane oxidation catalyst [31]. The 3D printed structure is made up of rotated layers (Figs. 3a-3b) with interconnected networks of channels as opposed to the conventional diesel oxidation catalyst (DOC) with a straight channels structure (Fig. 3c) with a higher PGM

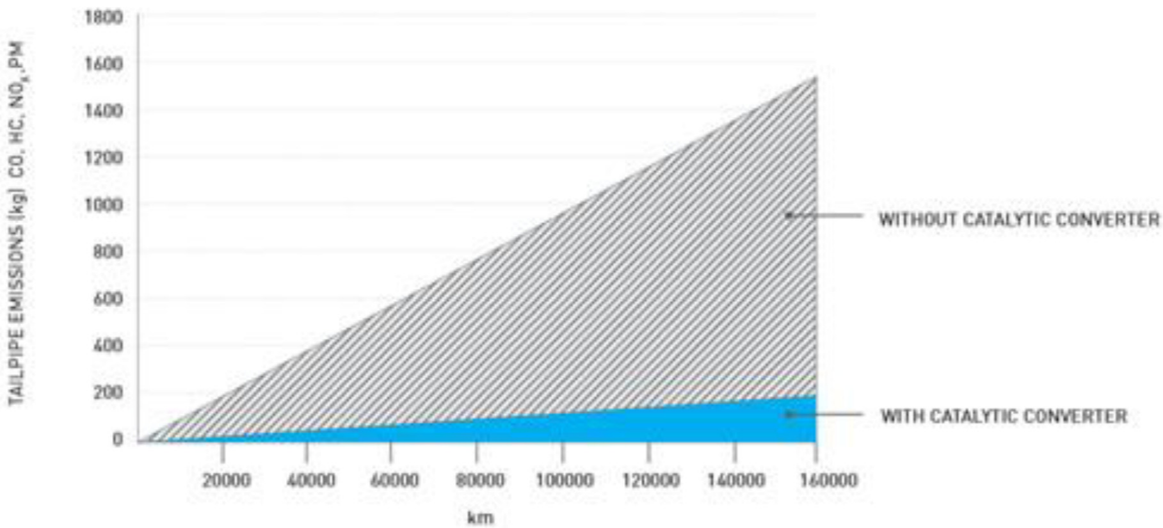

Fig. 4. Catalytic converter prevented the release of harmful polluting gases into the atmosphere (Data source: [26]).

load. At a high temperature of about 300 °C, the 3D printed structure recorded 31% and 45% conversion efficiency for methane (CH_4) and non-methane hydrocarbons (NMHC) while the conventional commercial control DOC converter which has a higher PGM loading indicated 24% and 38% for CH4 and NMHC respectively. Despite the lower PGM loading of the 3D printed catalytic converter, it performed exceedingly better than the higher load commercial DOC converter due to the intricately interconnected network channels. The interconnected rotated layers (Fig. 3a-3b) provide a larger surface area that enhances catalytic activity to promote the generation of higher internal turbulence to increase the rate of oxidation [31]. In related studies, the authors [29] went on further to 3D print a catalytic converter substrate with non-linear channel structures and compared its conversion efficiency with commercially honeycomb monolith extruded structure (Fig. 3c). The networks of non-linear 3D printed structures were offset at repeating angular adjacent layers of 30^0, 45^0, 60^0, and 90^0 oriented structures and washcoated with a PGM composite catalyst. The results indicated that the 3D printed substrate yielded a higher catalytic activity in methane oxidation as compared to the conventional commercial honeycomb catalytic convertor substrate. The 3D printed sample at an angle of 60 ° at an operational temperature of 510 °C demonstrated the highest conversion efficiency of 89.6% as opposed to 12.6% of the conventional honeycomb catalytic converter. The high conversion efficiency of the 3D printed substrate is due to the higher turbulence kinetic energy obtained in the 3D printed substrate. The high turbulence occurs due to the increased mass transfer as a result of the large surface area of the 3D-printed substrate. The printing of catalytic converter substrate monoliths with hierarchical porous structure prevents the active species from scattering in the reaction flow, providing abundant active catalytic sites, and permitting turbulent gas flow which cumulatively improves the catalytic performance of the 3D printed catalytic structure [32].

The synergy between substrate architecture of 3D-printed diamond-based lattice substrates catalytic converters was investigated by Kovacev [30] and compared to conventionally manufactured 400 Cell Per Square Inch honeycomb catalyst (Fig. 3c) for real exhaust gas fume. The 3D-printed diamond-based lattice substrates were coated with a theoretical PGM loading of 2.5 g and the conventional honeycomb catalyst was coated with a PGM loading of 7 g [33] and their light-off behaviour was analyzed in a diesel exhaust environment. It is reported that the 3D-printed structures demonstrate a better light-off temperature for carbon monoxide (CO) and oxidation of unburnt and cracked hydrocarbons.

Wei et al. [34] noted that the relationship between mechanical properties and geometries of 3D printed objects has been extensively studied however the chemical properties and catalytic functions of 3D printed objects a rarely studied. The authors prove that a hierarchical interconnected network of 3D printed structures could themselves simultaneously serve as chemical reactors and catalysts – making them self-catalytic reactors which could assist in improving the conversion efficiency of catalytic converts at lower PGMs load. Intricate 3D structures have the capability to establish multiple control functions themselves to fine-tune the active catalytic product distribution sites to enhance the conversion process leading to the release of less harmful gases to the atmosphere. In the view of Rosseau et al. [35] the current effort of 3D printing of catalytic converters has solely focused on material feedstocks and chemical reaction processes within the printing process without giving proper consideration to increasing the intensification to improve the efficiency of the conversion process. Using engineered phase separation, a micro-structure of the catalyst converters were developed with great control over the 3D printed structure at multiple length scales. The layers approach provides a higher active catalytic site increasing intensification and improving energy conversion efficiency compared to current converters [36]. The author mentioned

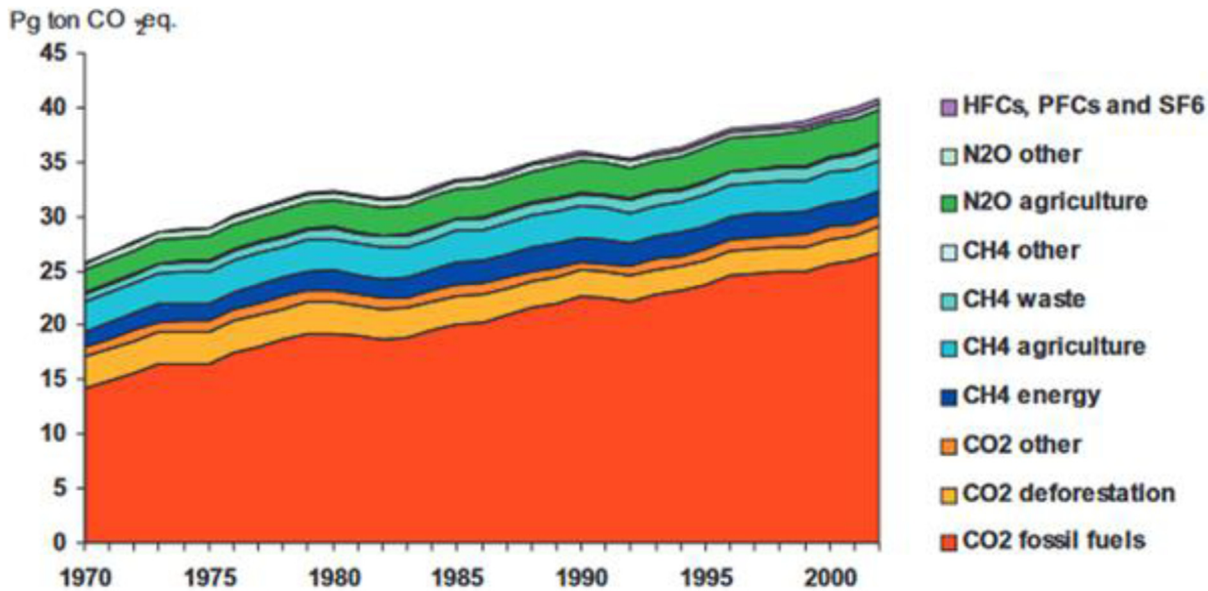

Fig. 5. Global emission of greenhouse gasses (Data source [37]).

that research should focus on factors such as mixing behavior, heat and mass transfer, and pressure drop which are very paramount at the industrial scale. Research should focus on these areas to increase the intensification of the device and not only on optimization of the aspects regarding chemistry and materials science.

The laudable research investigations presented suggest that fine-tuning of 3D printed hierarchical interconnected structures could be customized for a particular application, gradient structures could be produced to establish control functions for self-catalytic reactors [34], the material feedstock could also be tailored to achieve a particular thermal response which could all cumulatively assist in manufacturing low-emissions vehicles.

Although the AM process has improved the conversion efficiency of catalytic converters, the results still fall short of the Paris Collation Agreement [6]. Nonetheless, WHO reported that a catalytic converter could prevent 1.3 tonnes of toxic and harmful polluting gases from a vehicle which have covered 160,000 km not to being released into the atmosphere [26]. The catalytic properties of PGMs have dramatically abatement the release of harmful gases into the atmosphere (Fig. 4). The current report indicated that the efficiency of modern PGM autocatalysts reduced emissions to the extent that emissions by 1 car sold in the 1970 s is equivalent to emissions produced by 100 modern cars in 2023 [26].

As already noted, the catalytic converter is an antipollution device that triggers a chemical conversion of pollutants gases into less harmful substances such as carbon dioxide, nitrogen, and water vapor. Carbon dioxide (CO_2) from burning fossil fuels is the major contributor to greenhouse gas emissions and accounts for about 79% of emissions (Fig. 5) [38]. As a result, greenhouse gas emissions continue to increase by 1.3% per year, reaching the current value of >45 $GtCO_2$ eq in the 2020 s [39,40]. If the current rate of global warming continues it would be impossible to keep global warming below 1.5 °C by 2050 as requested by the Paris Agreement [41]. The huge contribution of the transportation industry to global warming via ICE is what has provoked the tightening of the regulations on emissions and proposed ban on ICEs by 2050 according to the Paris Agreement.

Almost 100% of all modern ICEs are fitted with autocatalysts relying on PGM alloys to abate harmful emissions from the real exhaust fume [26]. However, after the Paris Collation, the new regulations required more than a 50% reduction in NO_X and more than 70% reduction of CO for current powertrain systems fitted with autocatalysts [26]. This obligation required an alternative approach since the catalytic converter does not eliminate carbonization of the environment but only reduces harmful emissions with its accompanying CO_2 – requiring improvement in the conversion process to further reduce the harmful gases or completely eliminate the release of the harmful gases to the atmosphere to the acceptable levels [26,28]. The search for a suitable approach has led to the emergence of electric vehicles *(fuel cell electric vehicles – FCEVs and battery electric vehicles – BEVs)* which PGMs have a central role to play in manufacturing the next-generation electric vehicle powering systems.

The main challenge of using PGMs in catalytic converters is their high price which has forced automakers to continually search for ways to reduce PGM loads in converters or find alternative alloys at a lesser cost. The literature reveals that a host of other catalysts containing nickel, iron. copper, and cobalt [8] were tried but could not meet the long-term activity and durability required for modern-day emission control systems especially at low temperatures (about 40 °C) [36] forcing automobile industry to keep on using platinum in the autocatalyst despite its huge cost. Emission is highest during cold starting of a

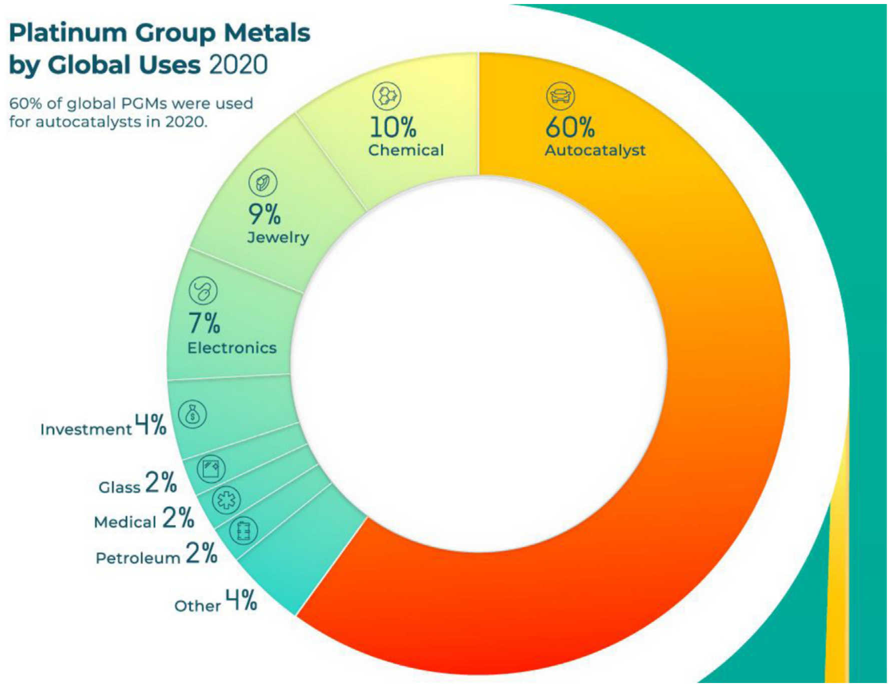

Fig. 6. The percentile usage of PGMs by various industries (Data source: Platinum group metals [42]).

vehicle (*the first 30 s of starting a vehicle pollutants such as carbon monoxide could build up on the catalyst reducing its efficiency*) [9] which makes PGM alloys the ideal for manufacturing autocatalysts since they are able to ignite the reactions at low temperatures (40 °C) [36] breakdown the harmful particles before exiting the combustion system into the atmosphere.

However, due to the proposed ban on ICEs, the demise of the PGM industry was contemplated since the major use of PGM is the autocatalyst (Fig. 6). Through research and development, PGMs are expected to play a central role in the future fields of transportation and power generation. The global desire to decarbonize the environment demands that the transportation industry use powering systems that can provide zero-carbon emission and PGMs have already demonstrated their unparalleled catalytic properties. The emerging concept of electric vehicles (EVs) would increase the demand for PGM [43] with its benefits for the environment. This paradigm shift has eased the major concerns among investors about the future of PGMs as the world is eager to ban the use of ICE engines, which is the major beneficiary of PGMs (Fig. 6). The possible use of PGMs in FCs and batteries have ease these fears and it is now projected that the demand for PGMs in the transportation industry would increase as the world prepares for the transition from the ICEs to EVs. It is indicated that the demand for PGMs would increase by 12% in 2022 and 11% in 2023 which is driven by the desire towards the attainment of higher technology readiness levels to decarbonize the atmosphere. Zhang et al. [44] estimated that the global reserve of PGM would meet the short-term needs (2020–2030), the medium-term needs (2020–2050), and the long-term needs (2020–2100), beyond 2100 it might be insufficient if alternative approaches are not found by that time.

3 Contributions of PGMs and AM to the operational efficiency of fuel cells

Through an electrochemical reaction, a fuel cell converts chemical energy into electrical energy without any mechanical or thermal activities [45]. Generally, a fuel cell comprises of an electrolyte that is packed between an anode (fuel) and a cathode (oxidant) [46]. The electrolyte and operating temperature are the distinguishing features between different types of fuel cells [10]. The major types of fuel cells that have reached commercial-level maturity include [47]:

PEMFC – Proton exchange membrane fuel cells rely on PGMs for efficient operation.

PAFC – Phosphoric acid fuel cells rely on PGMs for efficient operation.

DMFC – Direct methanol fuel cells rely on PGMs for efficient operation.

SOFC – Solid oxide fuel cell.

MCFC – Molten carbonate fuel cell.

AFC – Alkaline fuel cell.

Low-temperature (<90 °C) fuel cells such as PEMFC, PAFC, and DMFC require noble metals, typically platinum, as a catalyst at the two electrodes to encourage reactions [46]. On the other hand, high-temperature fuel cells such as SOFC and MCFC are powered via hydrogen-rich fuels (ethanol, ammonia, natural gas) and can tolerate

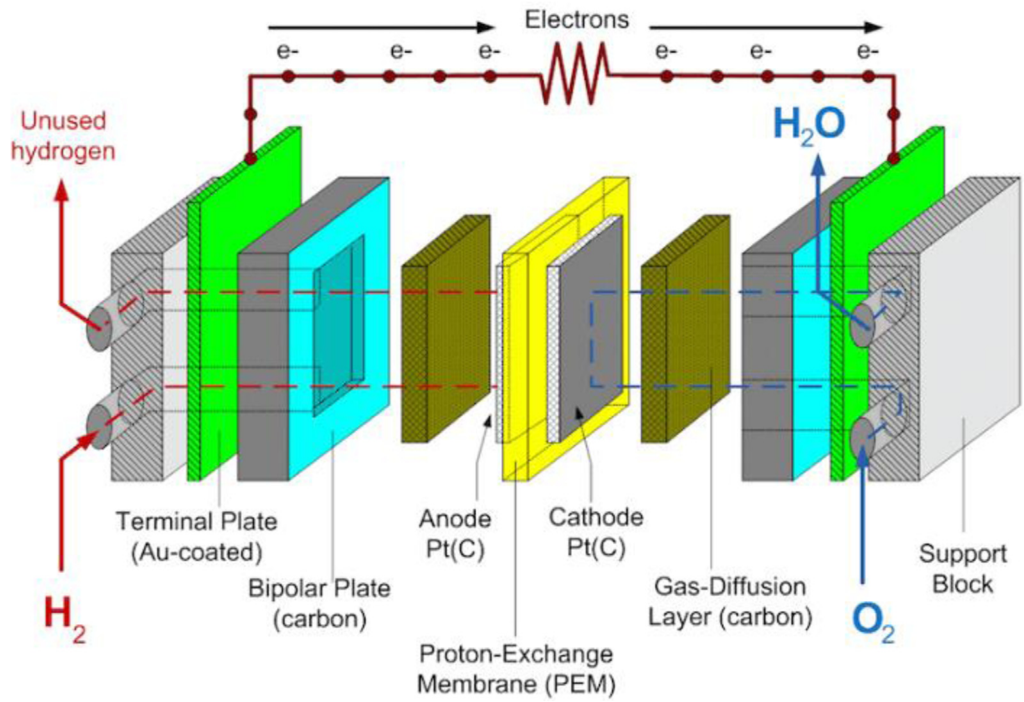

Fig. 7. Main components in PEM fuel cell [51].

medium-purity hydrogen (99.5%) [48]. Although AFC can also operate at low temperatures (60–80 °C) they lack the necessary performance and durability to be used in most combustion systems [49]. As a result, Proton Exchange Membrane Fuel Cells (PEMFC) are in high demand due to their unique capabilities to operate at relatively low temperatures (40 °C to 90 °C) [36,50] and pressure (1 to 2 bars) [48] with reliability, durability, and tolerance due to the unique mechanical catalytic properties of PGMs. Research and implementation have been ongoing to simplify the production process and the cost of PEMFC and AM have a significant role to play to increase the operational efficiency of FCs.

A typical Proton Exchange Membrane (PEM) fuel cell consists of a membrane electrode assembly (MEA) sandwiched between the bipolar plates of the anode and cathode (Fig. 7), into which flow channels are grooved, a detailed presentation of PEMFC is presented by Holdway and Inderwildi [46]. The MEA is made up of a proton exchange membrane (PEM), catalyst layers (anode and cathode), and gas diffusion layers (GDL) for both the anode and cathode electrode sides (Fig. 7). As presented in Figure 7, the PEMFC can basically be described as a stack of several cells that are assembled layer-by-layer suggesting that AM could be used to produce the various components (layers) monolithically.

Mo et al. [52] used electron beam melting (EBM) process to print Ti6Al4V liquid/gas diffusion layer (Fig. 7) with multifunctional parameters and the performance was compared with conventional woven and sintered liquid/gas diffusion layers and reported an 8% increase in operational efficiency. The increase in operational efficiency is due to the highly interconnected hierarchical circulatory systems nature of the 3D printed gas diffusion layer. The EBM process permits control over the pore size, pore shape, and pore distribution which leads to a significant decrease in ohmic losses and a corresponding increase in operational efficiency. The low-cost 3D printed Ti6Al4V GDL demonstrated greater resistance to corrosion than the conventional woven/sintered GDL due to the inherent protective titanium oxide thin film layer under the passivation or re-passivation process. The authors predicted a possibility in the future of using the emerging hybrid and multimaterial additive manufacturing approach to produce a complete FC monolithically. Calignano et al. [53] use the selective laser melting and fused deposition modeling to produce FC that generates 2500 mW m−2 power density due to the precision of the geometry of the cell morphology in the range of 100 μm that enhanced permeability to ensure high thermal/electric conductivity [12]. The result was compared to the conventional control fuel cells that generate 816 mW m^{-2} [54]. A carbon-based substrate in a GDL (Fig. 7) of a Tubular High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFC) was replaced with a 3D printed 316L stainless steel porous-thin-walled interconnected hierarchical network by Agudelo et al. [55]. The LPBF HT-PEMFC samples of varied porosity (14% and 16%) demonstrated a 329.25 mW m^{-2} peak power density for the 16% porous structure which is higher than the control conventional FC (69 mW m−2) [56]. Scotti et al. [57] produced thermally and chemically inert and long-lasting 3D printed GDL using 316L stainless steel. The LPBF FC produced a maximum current density of 1089 mAcm^{-2} and 238 mW m^{-2} power density – demonstrating 65% practical efficiency compared to conventional fuel cells of the same series. Researchers at Clemson University [58] 3D printed the anode and cathode of a protonic ceramic fuel cell and

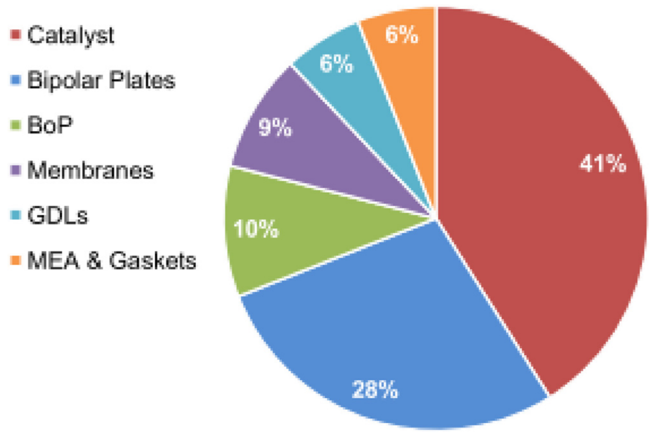

Fig. 8. a) Automotive fuel cell component cost distribution based on 500,000 fuel cell systems produced per year (Data source: US Department of Energy (DOE) [64]). Where BoP means balance of plant, which represents all components of a fuel cell system except the stack itself.

reported that the AM approach offers greater precision, consistency, and affordability compared to the classical methods of production of protonic ceramic cells. The efficient low-cost cell has a large active area of 15.7 cm^2 attributable to the AM method and produces 2.45 W at 650 °C, a maximum power density of 197 $mW\,cm^{-2}$. Bian et al. [56] used the AM process to print porous carbon anode structures and compared their performance with conventionally produced carbon cloth anode fuel cells under the same conditions. The 3D printed porous lattice network hierarchical structures yield a maximum power density of $233.5 \pm 11.6\,mW\,m^{-2}$ while the conventional carbon cloth anode yields a maximum power density of $69.0 \pm 4.7\,mW\,m^{-2}$ representing more than a 200% increase in operational efficiency. Another study by the authors – Bian et al. [59] on a 3D printed anode revealed a 12.3-fold higher power density compared to conventional copper mesh electrodes. He et al. [60] reported an unprecedented $10{,}608 \pm 1{,}036\ A/m^3$ current density for a 3D printed electrode and $10.8 \pm 2.2\ A/m^2$ for the conventional control carbon-felt bio-anode under the same electrochemical conditions. The unprecedented current density is attributed to the high surface area of the 3D-printed electrode.

Another important component of the FC is the bipolar plate which enables even distribution of pressure exerted on the stack cells, uniform distribution of gas through the interconnected channels, draining of water from the gas networks channels, current conduction between the individual cells, and providing mechanical support for the cells. Jin [61] uses the LPBF process to print a bipolar plate with a triple serpentine flow field with austenitic SUS 316L powder. The 3D-printed microchannel flow field improves fuel cell performance. A performance capacity of 1.2052 A/cm^2 was recorded as opposed to 0.7888 A/cm^2 for the control sample – representing a 52.8% improvement for the 3D-printed bipolar plate. It is required that flow field plates (FFP) should be impermeable to gases to arrest any leakage of reactants. In addition to the reactants' flow field channels, FFPs may also contain cooling channels. Water as the by-product of FC has the potential to negatively affect the performance of the cell. Vivek and Muthukumar [62] use a 3D printing process to redesign the flow field channel with an active area of 25 cm^2 to change the flow parameters to improve the operational performance of the FC. Changing the outlet water management flow resulted in an optimum power density of 1.5556 W/cm^2 with a corresponding current density of 2.82837 A/cm^2 producing an optimum voltage of 0.55 Volts at a temperature of 50 °C. AM technologies could be used to incorporate fuel, oxidant, and coolant channels whose shapes are critical to the working of the PEM, thus 3D printing has a significant contribution to the development of hydrogen economy. The cooling channels that can be incorporated into the FFP would enhance the thermal management process which would favour the preferred cold start nature of PEM FCs. Thus, AM manufacturing process could be applied to reduce the cost, material, and time spent on manufacturing PEMFC. To demonstrate the capability of AM to optimize the performance of PEMFC, Herzog et al. [63] use topology optimization software and LPBF process to fabricate the end plate (thermal plate – Fig. 7) and reported a 48% reduction in weight with an increased in electric stack power output. The AM-optimized end plates ensure effective homogenous pressure of the serial stack cells. The topology-optimized endplate produced a maximum electric stack power of 107.8 W at 45 A.

The current price ($61/kW) for mobility fuel cells still surpasses the estimated $30/kW target of the US Department of Energy (DOE) by 50%. To make the fuel cells more competitive in the long term, there is a need to reduce the cost of the membrane assembly (MEA). Since the high price of FC is due to PGM (catalyst) (Fig. 8) which is mainly a material cost and may not fall with the number of systems produced per year, it is essential to lower the amount of the catalyst (PGMs) used while maintaining durability. The experimental work of Wang et al. [65] proves that 3D printing process could reduce PGM load (Fig. 9) which could lead to a 35% cost reduction of FCs.

Willert et al. [66] 3D print Catalyst-Coated Membranes of a PEM cell without using any intermediate substrates. The catalyst loading for the cathode was 0.2 mg_{Pt} and the anode loading was 0.08 mg_{Pt} indicating the low PGM loading via AM process which would dramatically reduce the high cost of producing FC which could lead to its widespread rapid adoption. The FC with a low PGM load outperformed the conventional FC by demonstrating a 15% higher electrochemical power density. With continuous research, the versatility of AM would contribute greatly to migrating from ICEs to the eco-friendly hydrogen economy [3]. Historically about 90 g of PGMs is required to produce a FC. However, due to persistent research and improvement about 30 g of PGM is required to produce FC currently compared to 3–7 g required for a catalytic converter in a fossil fuel diesel passenger vehicle [67]. Bosch [67] has announced a technology breakthrough that would enable them to use only about a tenth (3 g) of

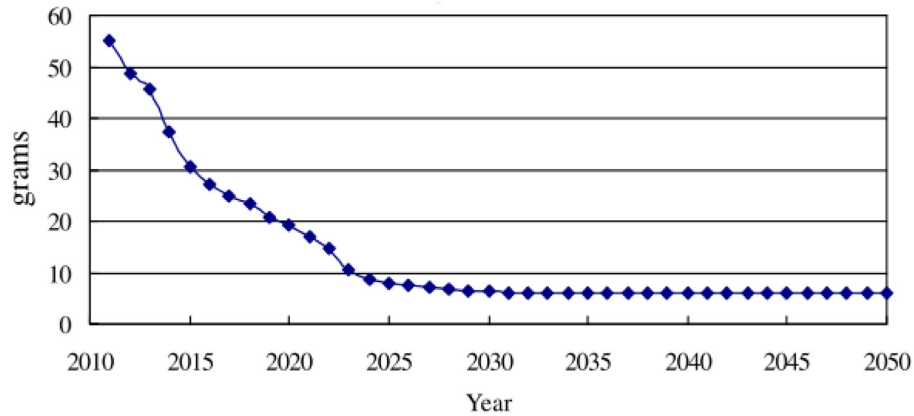

Fig. 9. Projected changes in *PGMs* (g/FCEV) as a function of time (Data source: US Department of Energy (DOE) [33,64]).

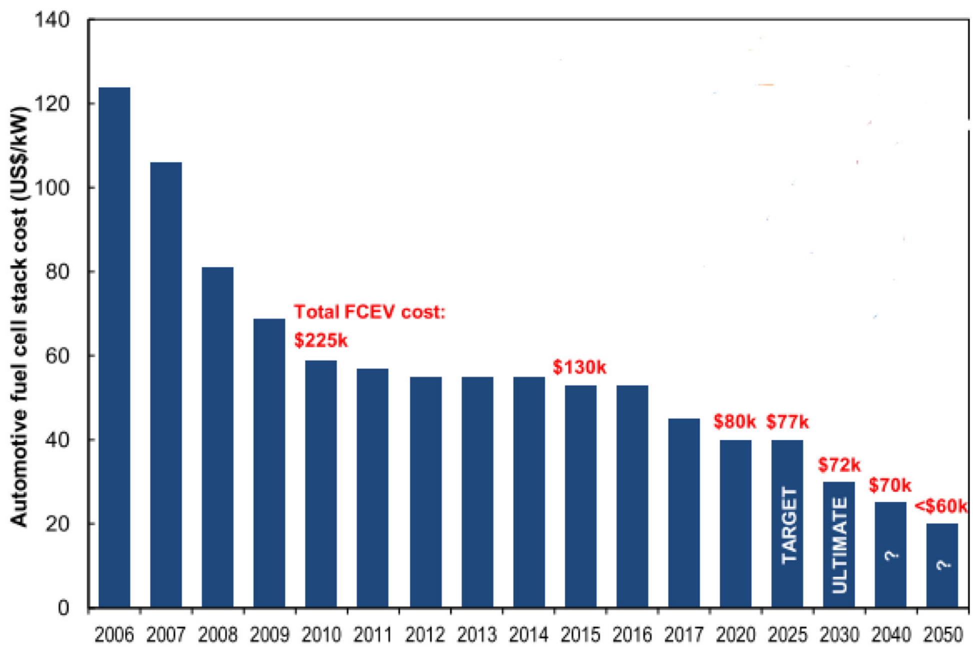

Fig. 10. The progressive decline and projection of FC stack cost (Data source: US Department of Energy (DOE) [64]).

the PGM used in current fuel cell (30 g) vehicles, which would compel the high price of FC to reduce drastically (Fig. 10).

Toyota has also indicated that reduction of PGM loading in its FCEV from 30 g to 10 g in its next version of electric vehicles [67]. Reverdiau et al. [33] noted that with a higher catalyst surface area, the PGM loading could be reduced – and AM could be used to increase the active catalytic surface area [68]. It is reported that the cost of producing a FC was reduced from $15,000 to $500 via the 3D printing process by eliminating the multiple assembly steps of clips, clamps, gaskets, sealants screws, reverts, etc. [69] which have simplified the production process and reduce the manufacturing footprint – contributing to the reduction of greenhouse gas generation [60,70].

Apart from the high material cost (PGMs) (Fig. 8), the machining of the flow plates in electrolyzers and FC to distribute liquid and gaseous reagents contributes to the high cost of the technology. Chisholm et al. [71] use AM process to print a lightweight, low-cost silver-coated electrolyzer. A voltage of 161.2 mV was recorded, and the authors noted the performance was excellent in terms of efficiency, internal resistances, and current-voltage response. A hybrid 3D printing process of SLM and FDM was used to print electrodes and the liquid/gas diffusion layer components of a water-electrolyzer using multimaterials. The electrodes were printed from steel while the diffusion layers were printed with polylactic acid (PLA) thermoplastic filament. The assembled hybrid 3D-printed electrolyzer demonstrated excellent water-splitting capabilities [72]. The greater optimization and ruggedness in 3D printed electrolyzers' interconnected intricate structures could act as a catalyst for substantial change in the shift to zero emissions agenda. With the advancement in nanotechnology, great strides have been made in reducing PGM loading in electrolyzers while maintaining

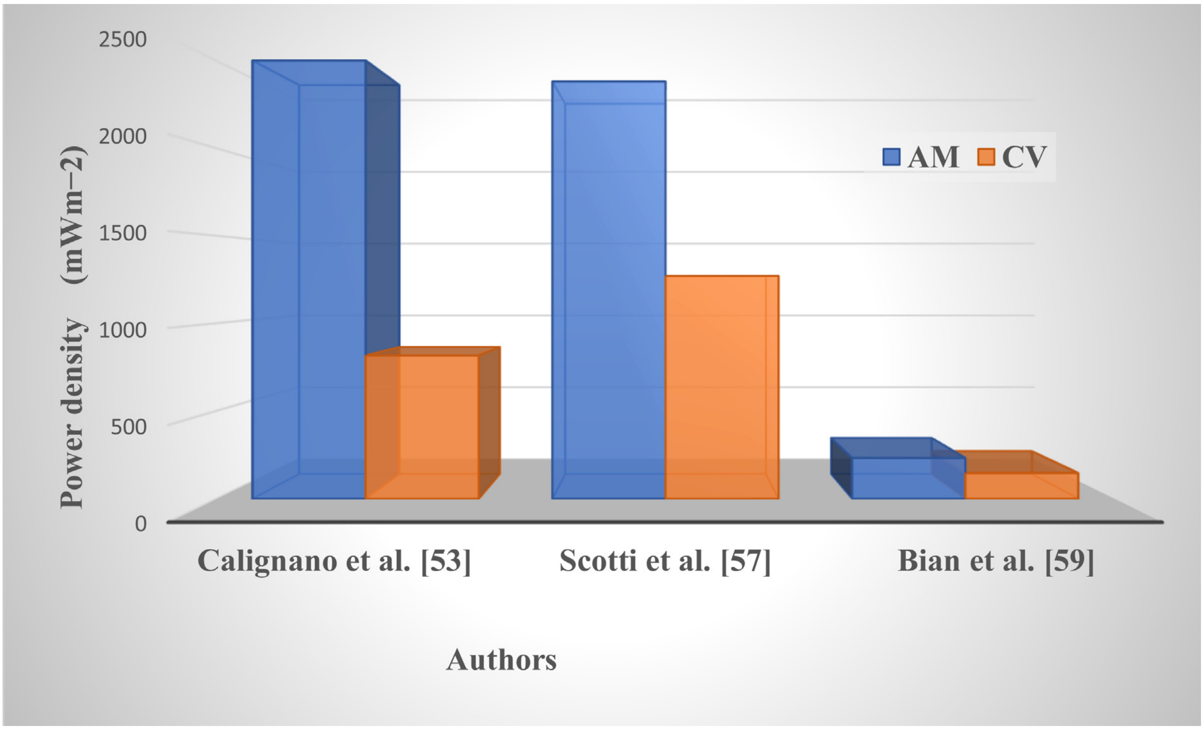

Fig. 11. Increase in operational efficiency of AM fuel cells compared to conventional (CV) manufactured fuel cells.

sufficient activity sites and stability. Bhattacharya et al. [73] employed the method of making computer chips to reduce PGM loading in an electrolyzer. The authors indicated that their approach resulted in producing electrolyzers that could rival commercial platinum electrocatalysts, which current capacity ranges from 1 to 20 MW [74].

The cumulative research outputs (Fig. 11) have empirically proven that the unique superior manufacturing capabilities of AM process could tremendously improve the operational efficiency of FC. Hence PGMs and AM are expected to lead the transition from the fossil fuel-based economy to the "Hydrogen Economy" [3] which is focused on using hydrogen to power transportation and power generation sectors of the economy.

4 Contributions of PGM and AM to the operational efficiency of batteries

Similar to Fuel cells, batteries are electrochemical devices that convert chemical energy to electricity. The main difference between FC and batteries is that FC can only convert energy but do not have the ability to store the energy. Batteries can convert energy and store energy which gives them the added advantage of dual functions [81]. Lion Battery Technologies [82] have indicated that energy density *(It is the measure of the amount of energy a battery contains in comparison to its weight or size)*, cyclability *(It is the number of times a battery can be recharged before it reaches its end of life)* and discharge capacity *(It is the measure of the maximum amount of energy the battery can store and deliver)* of modern batteries can be improved via PGM and AM (Tab. 2). A collaboration between Platinum Group Metals, Lion Battery Technologies, and Florida International University [83] has led to groundbreaking results in manufacturing lithium-air and lithium-sulphur batteries that have received three patents for the next-generation PGM battery with carbon nanotubes at the cathode and only 10 grams to 12 grams of PGMs at the cathode. The inventors reported that the performance efficiency of the batteries in terms of recyclability, energy density, and discharge capacity is more than ten folds compared to the current lithium-ion batteries at a lower cost and significant power-to-weight advantage due to the layer-wise process (Tab. 2). The lithium-air battery weight 144 kg and costs US$63 per kWh and the lithium-sulphur battery also weight 188 kg and costs US$71 per kWh compared to the conventional Tesla Model 3 lithium-ion battery that weight 371 kg and costs US$150 per kWh [83]. The lithium-air and lithium-sulphur batteries are stair-stepped change that relies on PGM and AM to unlock ten times the magnitude of improvement in a power-to-weight ratio (energy density), charge-discharge cycle at a lower cost which could create a surge of great interest in BEVs since their discharge capacity and reliability would improve at a less charging frequency with a higher range [83]. The proof-of-concept lithium-air and lithium-sulphur batteries demonstrated energy densities as high as 750 per kWh compared to 247 per kWh batteries used in Tesla vehicles [84]. The research team indicated that the development of the batteries is in the transition stage from the lab to the production of commercial prototypes. The prototypes demonstrated a 70% retention after 300 cycles and the team is working to improve the cyclability of the batteries to 500+ cycles [85]. The main challenge of modern lithium-ion batteries is the trade-off between power and weight which

Table 2. Performance of 3D printed batteries vs conventional manufactured (CV) batteries.

Fabrication methods			Comments	References
AM	CV			
Electrode performance (mAh g-1)	Electrode performance (mAh g-1)	Current density (C)		
158.3	152	0.3	The precise streamline of the 3D-printed porous network structure of the electrodes improved the movement of the charges in the ink flow field triggering a higher performance capacity.	[75]
451.1	339.4	0.1	The rigorous geometrical precision of the 3D printed comb-like interconnected channels enhanced the electrochemical properties of the electrode to outperform the conventional cast electrode.	[76]
150.21	103.38	10	The exceptional performance of the printed cathode was due to the porous networks of hierarchical structure that enhance the electrolyte diffusion to provoke a higher electrochemical performance.	[77]
147.4	140.8	0.3	The precise streamline of the 3D-printed porous network structure of the electrodes improved the movement of the charges in the ink flow field triggering a higher performance capacity.	[75]
145.8	138.3	0.3	The precise streamline of the 3D-printed porous network structure of the electrodes improved the movement of the charges in the ink flow field triggering a higher performance capacity.	[75]
140.67	90.64	20	The high operational output of the 3D printed cathode was due to the porous networks of hierarchical structure that enhance the electrolyte diffusion to provoke a higher electrochemical performance.	[77]
117 ± 6	110 ± 5	2.0	Due to the geometrical precision that yields a higher aspect ratio the 3D samples demonstrated a higher energy and power density.	[78]
82	61	10	The electrochemical performance of the batteries was increased due to the well-interconnected network of interdigitated hybrid 3D structures.	[79]
87	24.1	2	The hierarchical intricate porous 3D structures improve the electrolyte diffusion of the cell leading to the high-performance output of the 3D printed batteries.	[76]
~82	~60	10	The precise control of the interconnected hierarchical solid content of 3D-printed electrodes improves the performance output of the batteries.	[80]

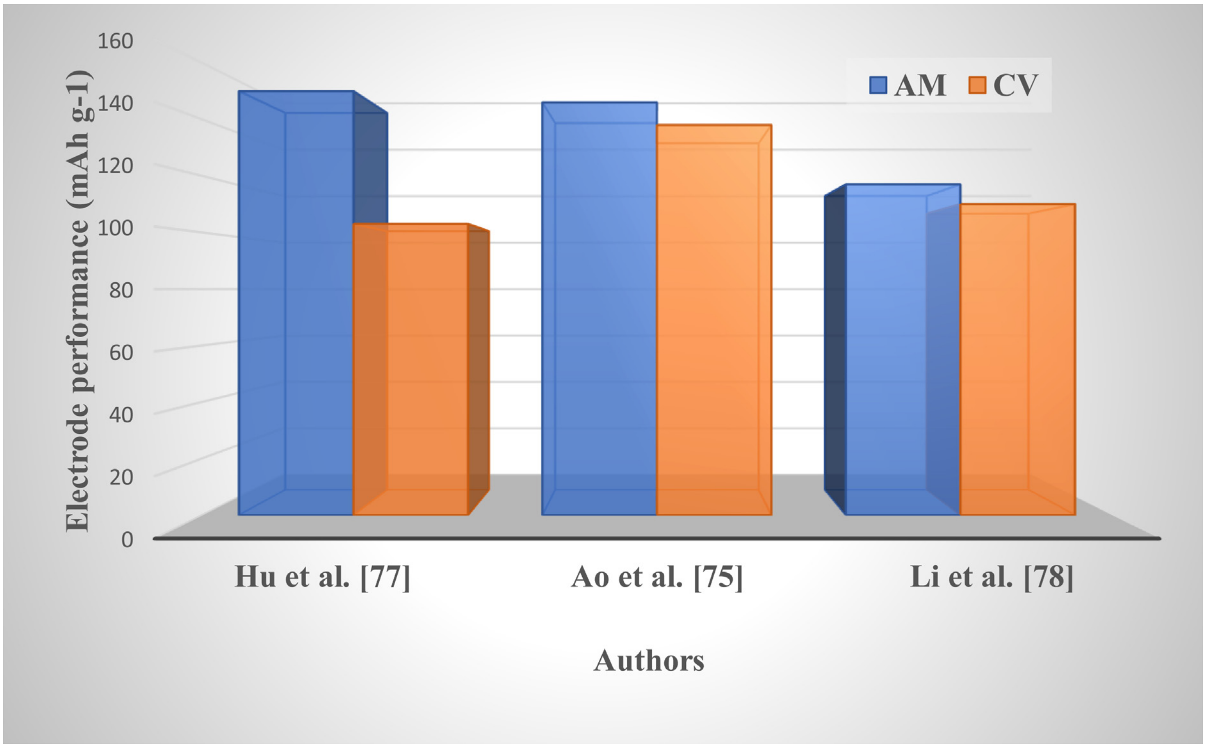

Fig. 12. Increase in operational efficiency of AM batteries compared to conventional (CV) manufactured batteries.

Table 3. The trade-off between BEVs, FCEVs, and ICEs.

	Conditions	BEVs	FCEVs	ICEs
Greater is desirable	Range	֍	֍֍֍	֍֍֍
	Efficiency	֍֍֍	֍֍	֍
	Refueling/recharging speed	֍	֍֍֍	֍֍֍
	Durability	֍֍	֍֍֍	֍֍֍
	Acceleration	֍֍֍	֍֍֍	֍֍
Lower is desirable	Capital cost	££	£££	£
	Infrastructure cost	££	£££	£
	Recharging/fuel cost	£	£££	££
	Repair/maintenance cost	£	£	£££
	Emissions	**֍**	**֍**	**֍֍֍**

(Data source: Pollet et al. [95]).

makes AM a prime candidate to improve the energy density of the emerging lithium-air and lithium-sulphur batteries while minimizing their weight.

Using material extrusion Li et al. [78] 3D printed the electrodes of $LiMn_2O_4$ battery with a high aspect ratio that would improve the mass loading of the batteries. The 3D-printed battery produces 117 ± 6 mAhg−1 performance capacity as opposed to 110 ± 5 mAhg−1 for the conventional manufactured control sample. The exceptional performance of the AM battery was due to the interconnected hierarchical network channels that permit a higher electrolyte diffusion. The performance of ink-jet 3D printed Li-ion batteries was compared with physical vapor deposition (PVD) batteries by Delannoy et al. [86]. The 3D-printed Li-ion batteries exhibit a higher performance value (145 mAh g−1) that is higher than PVD Li-ion batteries electrochemical performance discussed in the literature (<100 mAhg-1) [87]. The performance of a conventionally tape-casted electrode was compared to a tri-modally hierarchical porous 3D-printed electrode by Xu et al. [76]. The operational efficiency of the AM electrode was 451.1 mAh g–1 compared to 339.4 mAh g–1 of the tape-casted electrodes. Fused deposition modeling of a 3D printed lithium battery produced by Vernardou et al. [88] with graphene pyramids electrode demonstrated 265 mAh g−1 high electrochemical capacity due to the easy transfer of Li^+ ions across the 3D printed pyramid electrode interface.

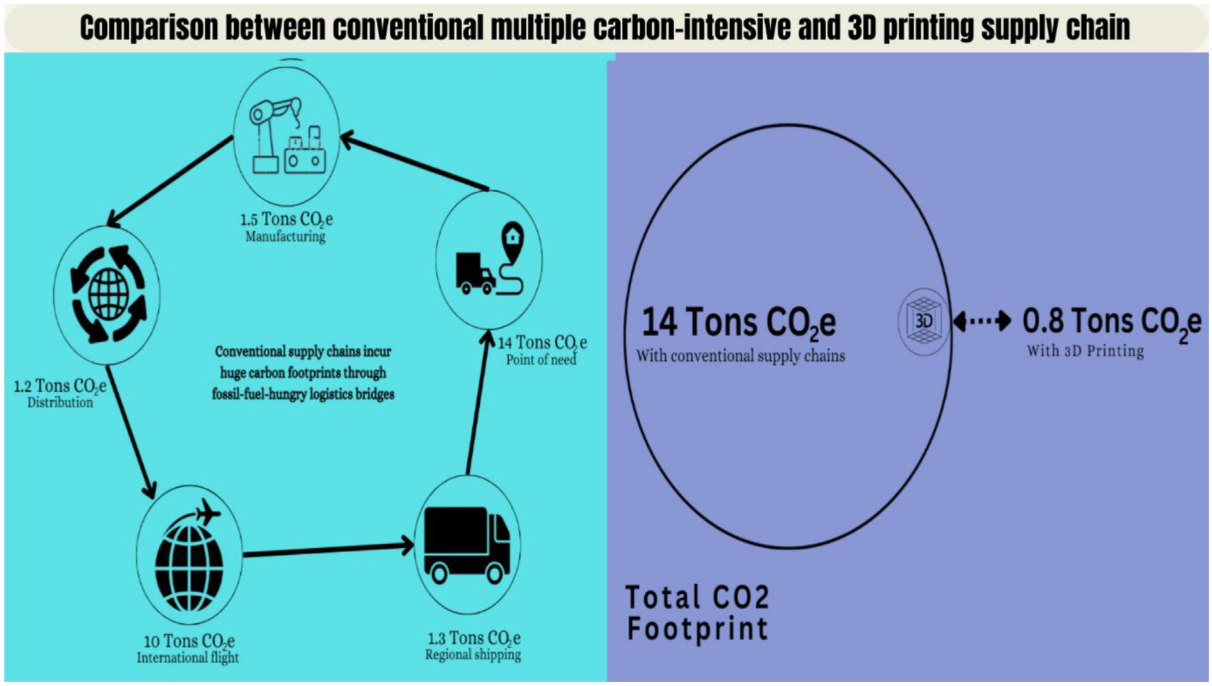

Fig. 13. a) Comparison of carbon emissions between the conventional energy-consuming multiple carbon-intensive supply chain and on-demand printing AM (Data source: Markforged [98]).

Even though modern lithium-ion batteries were good and a great step forward in the evolution of batteries they suffer from short battery lives, overheating, and long charge-rate capability which cannot power the current energy-hungry vehicles for a long range. PGMs and AM could be used to produce longer-life batteries with the required capacity for vehicles to enable the migration from ICEs to EVs. As every nation harkens to the clarion call and adapts their national grid to green energy to power BEV, it is important to use the versatility of AM to make available cheaper, lighter, and more powerful 3D printed batteries with cyclability and long battery life [89].

As demonstrated above and also presented in Table 2 and Figure 12, AM processes were able to print clog-free electrodes with higher electrochemical performance – but the fluidity of the feedstocks required that each printed layer is dried before the next layer could be printed which made the whole AM process of printing liquid/gel core batteries not the mainstream choice for battery fabrication. To overcome the difficulties associated with printing gel/liquid core batteries solvent-free batteries (green batteries) were proposed [90] about a decade ago. Through rigorous research and development, Sakuu Inc [91] a battery manufacturing company was able to produce 'first-of-its-kind" green batteries (Solid-state batteries) in 2022. BJ and MJ 3D printing methods were used to produce the solid-state batteries with 800–1000 Wh/L high energy density. Due to the layer-wise printing the green batteries could form part of the structural components of the final products [91,92]. The electrolyte and electrode materials were precisely controlled by the AM process ensuring higher energy and power densities of the solid-state batteries. The solid-state lithium proprietary multi-material batteries were printed with interconnected thermal transport channels, sensors, and customized fixtures. The 3D-printed green batteries demonstrate better energy density, recyclability, and discharge/charging capacity [93]. The factory footprint of the printed green battery was reduced by 44%, the capital expenditure was less by 23%, the operational activities were reduced by 69% and the overall production cost was reduced by 33% – demonstrating the superior manufacturing capabilities of AM in lowering cost and reducing manufacturing chain to decarbonize the environment. Due to these contributions of AM and PGMs leading the emergence of green batteries, it is projected that by 2040 the sale of EVs will rise to about 56 million representing about 57% compared to the 2% sale in 2019 [94], accelerating the attainment of net-zero agenda.

As presented in Table 3, apart from the high initial capital cost – migrating from the fossil fuel-polluting ICE systems to BEVs and FCEVs systems would not only provide an eco-friendly medium of powering systems but also increase efficiency and higher power outputs (acceleration). The contributions of PGMs and AM have improved the operational efficiency of batteries and fuel cells (Tab. 2, Figs. 11–13) and have ignited a great faith in eco-friendly energy sources such as the hydrogen economy [3], compelling several nations geared towards migrating their energy systems to eco-friendly energy sources such as the hydrogen economy [96]. It is worth mentioning that according to the Hydrogen Council [97] to achieve the net zero agenda, greenhouse gas emissions should be reduced by 60% by 2050. The council is optimistic that by 2030, 25% of off-road transportation would be powered by hydrogen while about 400 million cars, 5 million buses, and 20 million heavy-duty trucks would be powered by hydrogen.

5 Unrivaled contributions of AM towards harmful emission reduction

The "zero-inventory" capabilities of AM might make it unrivaled to any other technology currently [99,100] regarding emissions reduction. As schematically demonstrated in Figure 13 the major reason why the transportation industry contributes significantly to greenhouse gas emissions is due to the hungry fossil fuel logistics of multiple carbon-intensive supply chain bridges that need to be crossed before a product reaches the end user. AM has the capacity to disrupt the conventional multiple-step supply chain approach due to its on-demand printing strategies (Fig. 13), eliminating the long networks of shipments that contribute excessively to greenhouse gas emissions. Through digital manufacturing strategies, AM could serve as its own "virtual warehouse" [101], and products would be manufactured when needed. From Figure 13 it could be observed that apart from using subtractive methods of manufacturing that contribute excessively to greenhouse gas emissions via material wasting – the greenhouse emissions during transportation could even exceed the greenhouse gas emissions during the entire production process. AM could disrupt the multiply energy consuming supply chain through virtual warehousing strategies and eliminate the weakness [102] *(eg. Trapping of cargo ships at harbours delaying delivery of goods to the end users timeously and shutdowns due to pandemics such as Covid-19)* of the conventional supply chain. The inherent hyperlocal nature of AM would prevent huge carbon emissions (Fig. 13) from on-road and off-road long chains of transportation networks. The consolidation of several components into one printed product by AM would also reduce global logistical activities – reducing greenhouse gas emissions. AM has demonstrated its unrivaled capacity of decoupling the production processes from the long global logistics networks which contribute significantly to greenhouse gas emissions. The distributed digital production nature of AM supports shorter lead time and eliminates the long supply chain networks [98] while offering on-demand printing through a decentralized network of AM nodes to address localized needs.

In a digitalized AM economy, blueprint CAD files can be teleported to the required sites for printing. Avoiding the inherent fragility and brittleness in the classical transportation network which was exposed during the Covid-19 pandemic [99]. The localized automation nature of AM permits the manufacturing of customized products according to the needs of geographical locations. The rapid prototyping nature of AM also permits several interactions according to the satisfaction of local end-users before the final product is printed and commercialized to avoid unnecessary rejections – decreasing manufacturing footprints [103]. The digitalized nature of AM made it possible to integrate the manufacturing process with artificial intelligence (AI) for data mining which would usher in process automation with the possibility of eliminating multiple test runs and defects in build components [104]. The synergy between AM and AI would enable manufacturers with the capability to accurately predict scenarios in real-time, and augment the manufacturing process to increase the efficiency of the process to reduce carbon emissions [105]. This would ensure components are printed right the very first time ensuring repeatability, quality, and longevity of products which lead to less parts replacement and reducing landfill waste. The digitalization of the process would provide researchers, government bodies, and industry practitioners the opportunity to optimize the processes to increase the efficiency of using AM technology to decarbonize the atmosphere [106]. The capability of AM to print worn-out parts/worn-down sections without printing the entire product can contribute significantly to the reduction of carbon emissions. For example, using the conventional method of manufacturing – if the landing gear of an aircraft is damaged the whole gear needs to be manufactured. However, AM methods such as DED could be used to repair the damaged component of the gear without manufacturing the whole component. The recycle, reduce, and reuse (3 Rs), approach of AM would increase the life span of the components, reduce carbon footprint, and reduce landfill waste drastically by 40% [107]. According to the estimation of the International Renewable Energy Agency (IRENA) there would be about 1 million tonnes of spent FC waste by 2050, 2 million tonnes of lithium-ion battery waste by 2030, and 78 million tonnes of solar panel waste by 2050–if repairing/recycling techniques are not in place to recycle these devices. The German EVs Powertrain Solutions – Bosch have already indicated that AM has the capacity to avert these devastating estimations via its 3 Rs manufacturing principles, which would reduce the cost of EVs and the adverse effects of mining *(greenhouse gas emissions, air and water pollution, deforestation, degradation of the land, distraction of habitats)* materials for producing FCs and batteries. Bosch [108] has invented a technology that can recover about 95% of PGMs from FC and batteries at the end of their service life. The recovery process is eco-friendlier than all the previously invented methods. Such a circular economy [109] strategy built into the manufacturing process via AM approach would enable Bosch to repurchase FC stacks and batteries when their useful life expires. These recycling processes are expected to start when the very first budge of FCEVs and BEVs batteries may reach the end of their service life by 2030 [108].

Due to the digitalized nature of AM, the future blueprint of EV energy systems would use AI to monitor the operations of EV battery components to determine when maintenance, repair or recycling should be conducted [108]. This blueprint usage would ensure a stable supply chain, a reduction in carbon footprint in manufacturing EV energy systems, and a reduction in selling prices; since PGMs account for more than 50% of the cost of e-mobility systems. Unlocking the dematerialization and light-weight printing process of AM [110] does not only prevent wasting of material resources but also the energy needed for extracting and processing raw materials, which would translate into accelerating the net-zero agenda. The lightweight of AM structures implies less fuel consumption, less carbon emission, and less distribution costs. For example, a kilogram reduction in aircraft weight would save 2,500 liters of aviation fuel. Replacing an aircraft component with topology-optimized AM parts that would have a service life of two decades would save approximately 50,000 liters of aviation fuel which corresponds to 126,000 kg of CO_2 emissions [111]. A 45% reduction in weight was recorded for a seat-belt buckle of Airbus A380 produced via AM process saving over 3,000,000 litters of aviation fuel. Boeing 787 turbine blades were topology optimized and produced using AM process. A 30% reduction in weight was recorded as well as 80% less carbon emission, 50% noise reduction, and 20% rise in propelling efficiency [112]. The literature has demonstrated that material usage could be reduced by 35–80% [103] and supply chains by 25% [113] through dematerialization and topology optimization strategies. The above scenarios indicate the extraordinary capabilities of AM technology in accelerating the net-zero agenda. The versatility of 3D printing was used to print a mini catalyst element for X-43 aircraft [114,115] with intricate configurations that maximize the exposure to the catalyst while reducing the space occupied by the unit contributing to a reduction in aircraft weight. The 3D printed mini catalyst element not only assists in reducing carbon emissions but also serves as a cooling unit to control the temperature of the aircraft at an altitude by the intricate cooling channels beneath the exterior skin of the aircraft [116]. The introduction of the 3D-printed substrate has paved the way for manufacturing hierarchical porous structure which provides abundant active catalytic sites with low PGM loading.

6 Challenges and the way forward

3D printing is not a silver bullet and there are some downsides of the technology which is attracting great research attention. One of the major challenges of the AM processes to print FC and battery components is maintaining the geometrical accuracy of the final build components according to the CAD file's exact dimensions [117]. Using LPBF Lin et al. [118] printed a bipolar plate of an FC with an intricate shape termed wine-glass shape and reported that the final product deviate from the geometrical dimensions of the CAD file. According to the authors, the degree of the staircase effect [119] increased the surface roughness of the samples considerably. The agility of the 3D-printed samples for high-value engineering applications could be affected by their surface quality. However, the intricate nature of most AM products makes it difficult to implement some post-processing techniques such as matching. Although rescanning has been identified as one of the methods to resolve issues of surface quality of AM components, the effect of the double exposure on the mechanical integrity of AM products is not yet known [120]. The high rate of heating and cooling of some of the AM processes induces micro-cracks, residual stresses, and porosity that affect the performance of the printed parts which is susceptible to leakage of gaseous/liquid contents of FC and batteries [121].

Another major challenge that faces AM build samples is the heterogeneous nature of the solidified molten pool morphology, microstructure, and mechanical properties of the final built components [121]. It is generally noted that the mechanical properties of AM-built components demonstrate positional variations, making it very difficult to ensure repeatably of the products under the same built conditions. There are variations even within each unit's building block (single layer) and multiple layers which makes it challenging to standardize the process and determine the optimum parameters that could be used to obtain repeatable mechanical properties [120]. The effects of the built orientation, built chamber conditions, and post-processing activities (stress-relieving/heat treatment requirements) to homogeneous the microstructure even worsen the reproducibility of AM components as compared to wrought samples [122]. The variation of AM fatigue results builds under the same conditions due to surface defects, lack of fusion, trapped gas, un-melted powder particles, etc. that serve as crack initiation points have made it very complicated for AM to enter the mainstream of manufacturing methods for FC and batteries despite its superior capabilities of manufacturing complex geometrical structures. These challenges could only be addressed by understanding the governing principles that detect the molten pool and the solidification behaviors [120].

Controlling the molten pool and understanding the solidification mechanism via in-situ monitoring techniques such as the use of pyrometers, highspeed cameras, near-infrared thermal semiconductor cameras, photodiodes has been the major research focus for about a decade [16]. Multiply techniques have been used to generate adequate data that could assist in formulating parameters that could enable the reproducibility of surface quality and mechanical properties of 3D-printed components. The heterogeneity in the microstructure and mechanical properties make it difficult to predict the behavior of 3D-printed samples for high-temperature applications [123]. Applications of a material in a harsh environment at high temperatures for high-value engineering applications require accurate predictability [124]. Numerical modeling methods, lattice Boltzmann methods, volume of fluids method, statistical methods, molecular dynamics method, and finite element modeling were also used to gain insight into the melting/solidification mechanism to evaluate the entire 3D printing process to obtain parameters *(laser/electron/UV input parameters, machine parameters, build chamber parameters, material parameters)* that could be used to produce the samples with homogenous microstructure and non-disperse mechanical properties with repeatability [125–128]. All these methods could not provide the required results and research is ongoing to understand the physics that govern the microstructural evolution, temperature evolution, molten pool dimensions, rapid melting and solidification, residual stress, and chemical redistribution among others. Further research is required to understand the underlying principles that govern the entire 3D printing process to ensure repeatability of built components loaded with PGMs to enhance the confidence of the manufacturing industry in the technology.

One major research failure is conducting mechanical testing for AM-built components loaded with PGMs in uniaxial testing instead of multiaxial testing detentions; since the components would be used in multiaxial mode

[110]. The situation is even worse by conducting the uniaxial test at or near room temperature [16] while most of the components would be used at high temperatures. This mismatch between laboratory research and the actual application of 3D printed components has limited the practical understanding of how the built PGMs loaded FC and batteries would behave in service.

Machine-based challenges such as slow printing rate (<100 mm3/h), and size of the build chamber are still receiving considerable research attention [129]. AM process is not completely wasteless due to the support structure requirements to prevent deformation during printing. The disposal of these support structures or converting them to reusable feedstock should be taken into consideration. It is established that recycled feedstocks produce a lower-grade component that could not meet the current and future standards [130] – indicating the existence of a research gap. This could lead to more mining of PGMs to produce BEV and FCEV powering systems. Therefore, strict regulations must be put in place to ensure a responsible mining of precious metals (PGMs).

The limitations of 3D model software are another challenge that needs to be overcome to push AM technology into the mainstream as a prime choice for producing PGM-loaded FCs and batteries. The current CAD files *(standard tesselation language, object file format, additive manufacturing format, polygon file format, etc.)* [131] have the capacity to provide information regarding the geometry of components but cannot provide the corresponding information about the mechanical properties of the component [132]. The emerging software *(3D manufacturing, fabricatable voxel, simple voxels, 3DFLOW, etc.)* that can provide information about the geometry and material properties of components cannot be used to perform solid modeling tasks [133]. There is a need for software that can perform thermodynamic calculations and process simulations that govern the molten pool behaviors, geometry, microstructural evolutions, and solidification process concurrently with the printing process and predict accurately the mechanical properties of the final printed product. The software should be able to discreetly vary the composition/distribution and directionality *(x, y, z – Cartesian coordinate)* of PGMs in FC and batteries in a 3D space. The absence of data based on the properties of different multimaterials to feed into the software for the calculations is another challenge [134]. Every new material developed (*eg. Alloys)* have different thermophysical properties and must be determined. Issus of cross-contamination during multimaterials printing is still at the laboratory stage. Since the AM process is unconventional, its challenges are very unique and require a net set of ideas to address the current challenges of the technology.

The lack of a universal global consensus validation framework for AM components has bred skepticism among industry practitioners about the integrity of AM components. It is envisaged that due to the rapid prototyping strategy of AM, its certification processes would be faster than the classical method certification/standardization process [23]. Despite the unique added value of AM technology, it is considered secondary to most incumbent technologies which have been tried and tested for decades and centuries for printing batteries and FCs. As a new technology, AM certainly carries risks that most manufacturers cannot demystify without a regulatory body that sets standards for qualifying and certifying AM-built components for FC and battery production. Questions regarding intellectual property (IP) for printing of spare parts without authorization from copyright owner/s have no answer/s. The aforementioned limitations of AM cannot outweigh its great advantages. AM should be the way forward for printing PGM-loaded energy devices to accelerate the migration from the energy-hungry pollution IEC systems to an eco-friendly technology to achieve the net-zero agenda.

7 Conclusion

PGMs are just not precious metals they are unsung heroes of emission control from traditional fossil fuel engines to futuristic battery and hydrogen electric vehicles and are projected to remain relevant in the pursuit of creating a net-zero carbon world. PGM and AM, have the capacity to disrupt the existing IEC markets and open up entirely new markets that could provide emission-less energy systems and can grow to a large scale on the back of the attractiveness of EVs. Among all the FCs, it seems PEMs are the most mature technology and have demonstrated significantly improved system performance and durability than the other types of FCs and have attracted industrial applications. Although lithium-ion batteries have taken center stage for BEV, they may soon be replaced by PGM-based emerging lithium-air and lithium-sulphur batteries that have demonstrated ten-fold superior operational efficiency due to the higher catalytic sites provided by AM methods with lightweight at a lower cost. The zero-inventory and the digitalized nature of AM, cum its integration with AI is poised to streamline the AM process and disrupt the manyfold carbon-intensive supply chain to accelerate the achievement of the net-zero agenda.

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Conflits of interest

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Data availability statement

The raw/processed data required to reproduce these findings can be shared on request.

Author contributions statement

Thywill Cephas Dzogbewu and Deon Johan de Beer contributed to the Conceptualization, data validation, formal analysis, investigation, data curation, writing –original draft preparation, writing –review and editing, visualization, project administration, and funding acquisition.

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