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Engineering and Economic Aspects of Additive Manufacturing in Energy Related Industries

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Abstract: Additive manufacturing is the buzz word these days and many companies are leaning on this technology to leap forward in un-chartered design space that promises to give better performance at impossible to reach design goals with the current manufacturing methods. This paper addresses recent developments that have occurred in Energy related businesses with the adoption of 3D printing, also known as Additive Manufacturing (AM). It covers what and why of additive manufacturing; what constitutes energy and AM industry; current activities in AM for energy; AM for different energy sectors; AM processes; AM applications; selected patents in additive manufacturing associated with energy applications; and economic and financial aspects of AM in energy related industries. In this review paper it was noted that in-spite of phenomenal growth in AM, it seldom replaces traditional production methods due to associated constraints. Many companies are finding complimentary AM processes along with subtractive manufacturing techniques to meet the market demands. However, AM is particularly advantageous and attractive compared to traditional manufacturing methods for low volume complex geometry parts. Many times, complicated internal features produced using AM are not evident to an observer and an AM component with touchups may be indistinguishable from existing components with its external appearances alone. But note that inner details may differ significantly in AM made parts with tangible performance benefits over conventional parts. Some of the patented ideas presented here provide an insight into the inner complexities in geometry that can be achieved with AM to get distinct advantages that are nearly impossible to achieve economically from conventional machining. We notice, new engineers coming out of universities are already exposed to design techniques for additive manufacturing and they are also more trained on relevant numerical techniques than their predecessors graduated a decade ago; thus, new engineers are more open to embrace this technology. This paper provides not only the engineering aspects, but also includes the business and invention side of the AM pertinent to the energy industry. Hopefully, this article helps the AM community to get updated with different features of new development in energy industry and brings up new ideas to apply AM for achieving better performance from existing as well as new products.

Keywords: Additive Manufacturing; Energy Industry; Wind Energy; Solar Energy; Gas Turbines; Batteries; Fuel-Cells; 3D printing; Turbine Airfoils.

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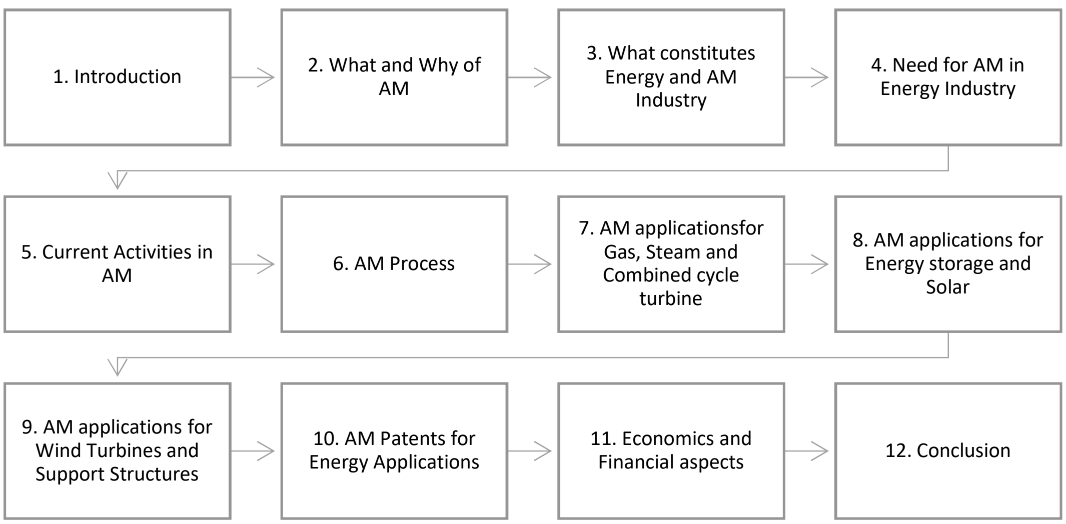
1. Introduction:

We are at an interesting time to observe unfolding of a new era of not only manufacturing but the design of components with a different mindset, an additive focused mindset instead of subtractive thinking. For example, in cast and drill design, one selects the discrete size of a drilled hole to match the drill bit. Moreover, in casting the designer must keep the liquid metal flow path and solidification direction in mind while designing a component. In AM, those requirements are relaxed as manufactured holes and internal hollow channels could be built-in while the component is being printed. Further, the designer can better optimize for the strength and weight requirements of the application without being constrained by the tooling and associated tolerances. Briefly put, AM is a manufacturing process that builds a component from nothing to something. Conventional machining starts with a cast or forged shape that is usually significantly bigger than the final product and it chips away material to provide the final shape. In contrast, AM starts with a build plate with nothing on it and builds the final part one layer at a time. So, an AM device can produce a multitude of shapes and geometries provided the component size is within the machine's operating range.

Most review publications in additive manufacturing adopt appealing images collected from marketing sources but do not provide the inner technology. This paper takes a different approach by undertaking a deeper investigation into the inner workings of AM with a business perspective that a display of components does not provide. Some publications have more than 150 references and yet are less than eight pages long. This paper tried to refrain from such wide but shallow discussion and attempted to provide the reader with a smooth journey through the current status of AM in Energies business. Following flow chart shows a roadmap for the chapter layout in the current work:



In the current paper, authors strived to provide a detailed overview of information most pertinent to the AM for energy applications without going into any specific mathematical formulations and numerical analyses. Make no mistake that success in AM has come from breakthrough in science and technology. Further, accurate production of AM components is inherently dependent on complex computer coding, material science knowledge, and optimization techniques at various levels, sophisticated steering mechanisms for laser and other high energy sources, and precision robotic manipulators. Instead of providing hundreds of secondary references which covers those various aspects of AM, this article utilizes selected primary references related to energy applications and provides enough details for an interested reader to gather more information as needed. The chapters are separated as common introductory discussions followed by detailed AM activities in different industries. A discussion on manufacturing is not complete without economic and financial viewpoints, and that is added near the end of this paper. What is lacking is a pricing model for a project or a job. Unfortunately, the knowledge available in that topic is proprietary and cannot be disclosed here. This discussion addresses the issues pertinent to not only the research community, but also newer and as well as experienced professionals to provide a broader view of the AM landscape so that they can be more productive, can guide themselves in this complex technology dependent business world, and can cross-pollinate ideas from one sector to the other.

A reader interested in the general illustration on additive manufacturing can benefit from Thompson et al. [1]. It is one of the most cited publications listing several additive commercial and research products. They provided a pictorial review of the worldwide activities on additive manufacturing in 24-pages with 374 references and 59 figures. However, there is more to AM than pictures of finished products and that is the theme of this current work. The limitation of the current presentation due to lack of space is omission of algorithms; machine learning based intelligent systems; inspection and automation. Other than that, this review paper has covered most of the energy sector's AM technologies and related economical aspects available to date.

2. What and Why of Additive Manufacturing:

If we consider the current popularity of additive manufacturing, the natural question to ask is why and why now. Humans have caused one miracle after another; we can fly safely from one side of the globe to the other, complete important tasks, and come back within half a week, and it is getting faster. We have hundreds of equivalent horsepower packed in small metal engines and have machines to help with daily chores. When it comes to AM, the adage of "necessity is the mother of invention" can be applied here as well. Many technologies which would ultimately culminate in the development of AM such as servo motors and machine programming languages, which are precursor to G-code and CAD/CAM systems were spurred by the demands of World War II. Early 1980s witnessed first patents filed in Japan, France and USA nearly at the same time, for layer-wise fabrication of 3D objects by selectively adding material. However, inventions by Charles Hull from USA resulted in first commercial stereolithography machine SLA-1 and incorporation of AM giant, 3D systems. Most AM processes involve the following stages for part production [2]: a) CAD modeling and conversion to STL , b) STL file manipulation, c) Slicing and support structure generation, d) File transfer to AM machine, e) AM machine set up, f) 3D print, and g) Post processing. Advances in various aspects of computing technology such as processing power, graphics capability, machine control, networking and integration have helped with improving all these stages and led to faster AM processes with better part quality. The result is 3D printing technology as we see it now.

Next question that logically gets asked is, can additive replace the conventional manufacturing. Obviously one can see that it has not yet, and experts argue that it will not totally replace conventional manufacturing within the foreseeable future. But speed of progress is not predictable, as who would have thought we will carry a wireless phone, camera, internet enabled computer with us all the time. Industrial AM machines are expensive and need sophisticated concentrated power sources and precision robotic movements. As the market for these machines increases and initial restricting patents expire, machine prices are bound to decrease, and they are progressively becoming ubiquitous as the years pass by. Because AM builds a thin layer at a time, the build time can be slow and may not be suitable for large production volumes. But when the production volume is low and customized parts are being desired, AM is a strong contender over traditional machining. The advantages are, no initial tooling costs, tool setup time and, no detailed cost evaluations are needed based on the machining steps. The costing of a product is simpler in AM and it is based primarily on four items- build time, material used, post machining support removal, and inspection.

Technology trend in AM was studied by Niaki et al. [3], who investigated additive manufacturing (AM) by studying in-depth the economic sustainability of AM technology and bringing out the contextual factors that drove its superior performances in comparison with conventional manufacturing. They argued the justification of its adoption in rapid prototyping (RP) from an economic point of view. Their research attempted to evaluate the superior economic sustainability and higher potential profitability of AM technology for RP. Furthermore, they found two primary economic performance comparison criteria to be: energy consumption as a direct cost and profitability of investment. To get a reasonable economic observation, they conducted a survey involving 105 companies from 23 countries; and found that AM technologies contribute in cost reduction mostly in new product development and for low-volume production. For metal, AM not only could not compete with conventional manufacturing for mass production, but also was not suitable for larger batch production system with more than 200 parts in most cases. This was due to the economies-of-scale principles that arose from the inverse relationship between the quantity of production and fixed-cost per unit. In other words, the higher the quantity of a production, the lower the per-unit fixed cost. Since these costs were spread out over a higher number of goods, AM became less competitive for higher production volumes, since the cost per unit of mass production decreased; but AM per unit cost stayed about the same. The findings of this research lead to a conclusion that in general metal AM can be a suitable alternative to conventional manufacturing for low-volume (less than about 40 parts) production only. However, the outcome may depend on the capacity of machine, material properties, and required quality levels. In contrast, AM enabled an economy-of-one, which meant there was a possibility for cost-effective production of a single customized or complex design, while it was much expensive when using conventional manufacturing. Since AM does not need any tools or predefined molds, it can reduce the cost of iterative new product development processes.

AM in metal is developing as an alternative to conventional manufacturing of high-value components creating new opportunities to increase better outcome for the marketplace but technology still needs improvement to become commercial large scale success (see Tosi [4]). AM in plastic is different and can be cost effective even in larger production volumes. This is especially true where injection molding is involved. Injection molding die is expensive, and AM can be competitive by removing the need for designing and making a die. On the other hand, AM can build a die more cost effectively than conventional machining for high production volumes. Another review paper by Ford and Despeisse [5] discussed the AM benefits and its sustainability. They also have included examples from recent commercial product development and illustrated a few success stories with AM technologies. One example given was an aircraft engine fuel nozzle, which has been discussed later in this paper.

Currently, AM requires significant skill and engineering to keep machines running to make quality parts. However, recent trends in AM research indicate that AM could benefit with advances in the artificial intelligence and smart algorithms possibly resulting in lower number of engineers required to operate AM machines in the near future. There are several articles that discuss artificial intelligence (AI) and machine learning applicable to the additive manufacturing domain. Yao et al.[6] used a hybrid machine learning technique to develop dendograms that helped inexperienced design engineers to design for additive. Baturynska et al.[7] used machine learning with finite element analysis to optimize the powder bed fusion based AM. Inspired by biological neurons, the development of convolutional neural networks (CNN) provided an alternative to the stochastic process of evolution in a form that was applied in a parallel computing environment by Gu et al.[8]. They used 100,000 different microstructures and obtained the best formation for a given component using AI. Gobert et al.[9] used AI based defect detection on finished products by AM. Process monitoring in additive manufacturing (AM) is crucial for success and they proposed ideas to automate and speed up the inspection process. Zhu et al.[10] used prescriptive deviation modeling method coupled with machine learning techniques for predicting shape deviations in AM. Authors argued favorably that AI can make additive manufacturing processes less time consuming than they already are and can add more accuracy to the 3D printing process. It was also mentioned that the use of computer vision can analyze existing physical products with reverse engineering and improve internal design even if the original drawings and details were not available. AI can accelerate the product development and improve AM processes to minimize the time-to-market for new products. AM is a good fit for AI as both are heavily dependent on numerical techniques and optimizations. There are many research activities in AI for AM and this field is emerging. Additive manufacturing professionals should pay close attention to machine learning as that can be disruptive and bring the operating cost down significantly for AM.

AM arguably is perceived as a cleaner and greener technology compared to the conventional machining. Some authors [2,3] have pointed out that there is typically less material waste in AM as there is almost nothing being machined away as scrap. However, this is not completely true. Most of the AM processes require removable support structures depending on the part configuration and most of the times these support materials are not recyclable without further processing. Even in powder-based AM processes, there can be waste generation in the form of by-products due to material vaporization from high power laser and inability to re-use powder after certain cycles. It is worth noting that the material cost is usually insignificant compared to the engineering and machine time. Huang et al.[11] summarized AM opportunities to improve human health and quality of life. They observed energy usage increased in AM, but hazardous waste was minimized (Table 1). The virgin material usage was also significantly low in AM compared to conventional machining. They discussed AM applications in customized surgical implants and assistive devices in the healthcare industry. According to authors, researchers are now investigating the use of AM to produce scaffolds for tissue engineering applications and drug delivery devices. Because AM is well suited to produce customized products, it is expected to play a significant role in personalized healthcare to improve the safety, quality, and effectiveness of healthcare for the general population. Lessons learned from these developments can also be applied to manufacturability of components related to energy production and transportation. However, we are talking about different AM processes and lessons learnt from one may not be easily usable in another. But many automotive components use sophisticated kinematics and material to material interactions like medical applications that can be better designed with AM. Moreover, after market repair parts manufacturers can use these adaptable AM techniques learnt from medical appliances to print custom make parts on demand.

Table 1. Comparison of energy usage and environmental impact (data [11])

Process	Energy use (kg CO2 per component)	Water usage (kg per component)	Landfill waste (kg)	Virgin material use (kg per component)	Hazardous waste (kg per component)
Casting	1.9	0	n/a	2	n/a
Flexline Machining	2.4	0.08	1.512	2	0.0064
AM	13.15	0	0	0.65	0

There are indirect benefits from AM, like reduced environmental impact for manufacturing sustainability. Compared to conventional machining processes, AM is more efficient in terms of fresh material consumption and water usage. Usually it does not require the use of coolant and other auxiliary process materials, and thus produces less pollution to the terrestrial, aquatic, and atmospheric systems. It also requires less landfill. Therefore, AM is expected to become a key manufacturing technology in the sustainable society of the future. Another beneficial aspect is, simplified supply chain increases efficiency and responsiveness in demand fulfillment. AM is conducive to innovative design and enables on-demand manufacturing. As a result, the need for warehousing, transportation, and packaging can be reduced significantly. With proper supply chain configuration, it is possible to improve cost efficiency while maintaining customer responsiveness. There is an immediate need for building at site for military components; but it is not feasible yet because these machines are not user friendly and require significant expertise to deliver quality components. With the advent of personal AM machine, the dream may come true where customers can obtain desirable products economically whenever they want and without significant shipping charges and delays.

Currently, AM is helping the existing machine shops to get additional business that requires AM followed by conventional machining. Feedback from the industry indicated that machine shops with AM capability can up-sale conventional machining by comparing the cost on two manufacturing techniques. There will be a time, when minimal additional cleanup machining will be needed after AM processes, but we are not there yet. Some can argue that this discussion is not necessary; however, as a peer reviewed archival publication, this article needs to address not only the current trend but provide some baseline for the next generation. Currently, the best AM process available is building layer by layer. Will that be the norm twenty years later? Perhaps not, perhaps a 3D component will be built at the same time for all locations, drastically reducing the build time, and that is why this discussion is useful to build perspective related to current status of the AM technology and clarify the baseline for future readers. As of today, AM machine shops require trained engineers to run the production and that reminds the days of emerging CNC machines. Prior to 90s CNC machine shops required engineers and special software coding at the machine to serve the needs of customers. Today, CNC machines can be operated without an engineering degree or any coding experience. Eventually AM will mature and will become user friendly thus reducing the needed operator skills. Hopefully this review paper captures all the major achievements to date and helps build the next step of progress.

3. What Constitutes Energy and AM Industry

To address energy applications, we need to understand what is meant by energy business. If we look at the energy sector at the stock market, the definition of energy business as perceived by engineers not necessarily aligns with the financial world. For example, Vanguard Energy Index Fund's (ticker: VDE) top holdings are Exxon Mobil, Chevron, ConocoPhillips, Schlumberger, Phillips 66, EOG Resources and Marathon Petroleum. Energy Select Sector SPDR Fund's (ticker: XLE) top holdings are very similar to VDE. iShares Global Clean Energy ETF (ticker: ICLN) discloses top holdings as: Siemens Gamesa Renewable, Vestas Wind Systems, Xinyi Solar, SolarEdge Technologies, Minas Gerais, Meridian Energy, Ormat Technologies, and First Solar. Whereas, Invesco Global Clean Energy ETF (ticker: PBD) has top holdings as: Bloom Energy, Crop Energies, Renewable Energy Group, Tesla, W-Scope, eREX, and West Holdings. It can be observed that the definition of energy market is vast, and a variety of industries are included. The sub-classification of these energy-based industries are fuel extraction, energy harvesting, energy production, energy distribution, and energy conversion.

Similarly, the Additive Manufacturing perspective is also very different from financial view to the engineering view. The financial world sees 3D software modelling companies as part of the AM. The 3D Printing ETF (ticker: PRNT) shows top holdings as: SLM Solutions, HP, Renishaw, MGI Digital

Graphic, Straumann Holding, ExOne, and 3D Systems. In this article, we will be emphasizing on utilizing AM in energy production and conversion industries. Specific focus will be on aerospace, solar, wind, battery storage, prototyping, and repair of large and expensive thermally hot equipment. Note that there are many components being developed for pipe fittings and structural support, which we exclude from the scope of this article. We will discuss applications related to the energy business and not the infrastructure.

It is worth noting that a major part of AM constitutes algorithms and computer modeling. 3D numerical model technology is essential, and most AM processes involve a distinct pre-processing stage whereby the part geometry is translated into a process-specific printing plan. This plan is developed in layers or slices of the original part geometry by a set of algorithms collectively known as a "slicer". Commercial slicing programs explicitly generate laser or electron beam paths and do not consider the impact of resulting geometric part features (e.g. thin walls, small corners, round profiles) which can result in critical voids leading to part failure. Even if software made for specific hardware is part of AM, there is not enough room to discuss them in detail in the current scope of this work. But important publications are included for completeness of this review paper. Slicing algorithms are discussed in Tata et al. [12]; and Adams and Turner [13] improved on slicing algorithms with an implicit slicing algorithm. When optimized patterns were overlaid onto each part layer, the mechanical properties of the part was improved, and the presence of undesirable voids and flaws were reduced or eliminated. These software services are integral part of the AM technology and cannot be neglected. Unfortunately, these algorithms are protected as trade secrets and production level details are not publicly available.

4. Need for AM in Energy Industry

Summary of important publications related to AM's impact on the energy business are discussed in this section. Verhoefa et al. [14] studied projected energy use in 2050 for six economic sectors and the influence of additive manufacturing on the energy demand based on Shell's energy consumption analysis. Figure 1 shows the proportion of energy usage in different sectors adopted from their work. It is clear that the transportation and the residential economic sectors were the top two energy users. Additive manufacturing is penetrating both these sectors and will become an irreversible part of the economic cycle. The fastest growing sector for AM is perhaps the service sector that involves spare parts and customized components. AM can also help with in-situ repairs that will be part of the service sector. For example, the wind energy components and solar firms are exposed to elements of weather and will get surface damages in five to ten years. Development in AM will possibly repair those parts at site without dismantling the major components.

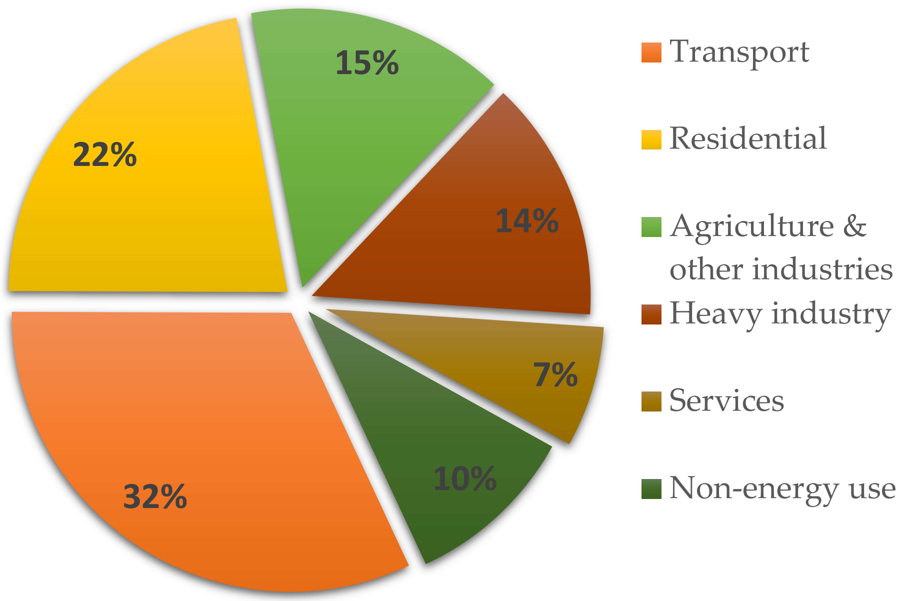


Figure 1. Energy use by different business segments projected to 2050 (data [14])

Figure 2 shows, the energy demand reduction with the inclusion of AM was highest in heavy industries followed by transport; and the least influence of AM was observed on services. In this figure 'S' represents Scramble and 'B' represents Blueprints. According to PeakEnergy, the definitions of these terms are: "Scramble: it is where key actors, like governments, make it their primary focus to do a good job for their own country. So, they look after their self-interest and try to optimize what they are trying to do within their own boundaries. Blueprints: it is international initiatives, like Kyoto, like Bali, or like a future Copenhagen. They start very slowly but before not too long they become relatively successful. This is a model of international cooperation." Broadly speaking, Scramble scenario means players are competing and Blueprints scenario means involved players are collaborating. The 'H' is high AM impact and 'L' is low AM impact. The figure indicates that with higher impact AM scenarios, the energy usage reduction is an order of magnitude greater than lower AM impact scenarios. These were provided by Verhoef et al.[14] and they observed, Scramble with high (SH) AM impact showed manufacturing closer to point of use, less long-distance freight transport, but limited new product design by AM. Blueprints with high (BH) AM impact showed manufacturing near the point of use with business justification, supply chain disintermediation with less intermediaries, reduction in the time to market, and mass customization. Scramble with low AM impact showed, no major changes in the supply chain, reduction of inventories in some sectors, minor changes in product design area. Blueprints with low AM impact showed, no significant changes in supply chains, some sectors better suited for AM with prototyping of main application by AM.

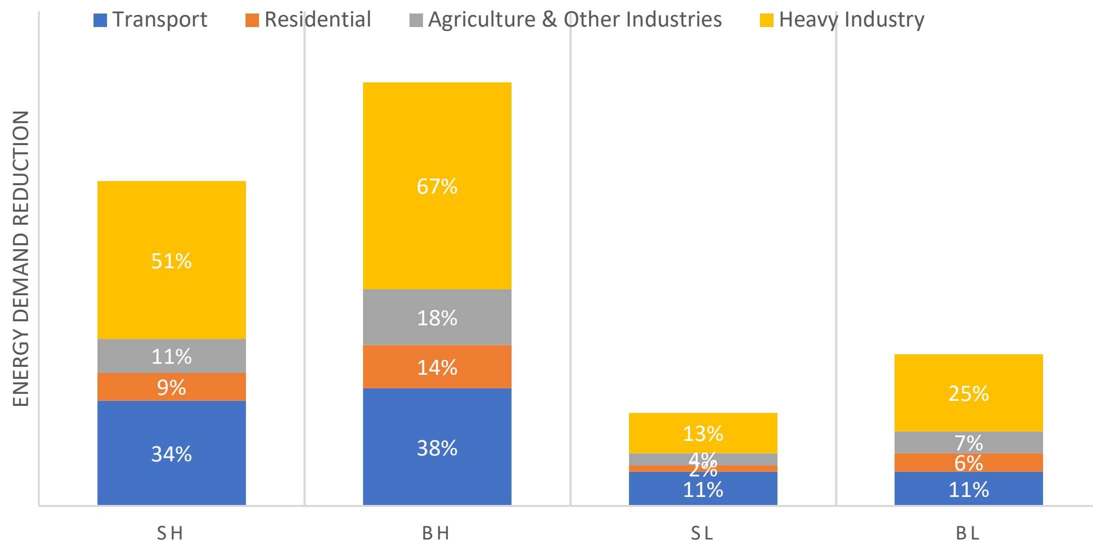


Figure 2. Energy demand reduction in four scenarios (data [14])

In a blog post in 2018 titled "3D printed solar panels: Meet the renewable energy revolution," Gaget [15] remarks that 3D printing was becoming a major asset for the energy industry and that the impact of additive manufacturing on renewable energy was important because of the rising concerns over climate changes. Author indicated that renewable energies were becoming important and that fossil fuels were progressively running out. However, why there was a need of AM was not discussed. Even though that post was an arguable topic due to a sharp drop in fossil fuel prices since 2014 and author failed to establish the need for AM in renewables industry. However, it was accurately pointed out that 3D printed solar technologies to harvest Solar energies, was one of the key potential AM applications. Market dynamics indicate that recent development of electric cars, wind turbines, and solar panels has accelerated. But most of these devices are expensive and they need to be improved for their strength to weight ratio; and that is an area where AM is known to be very useful. GlobalData Energy estimated that the impact of additive technology in solar panels could reduce manufacturing cost by 50% while increasing the efficiency by 20% compared to the traditional solar panels. 3D printed solar panels were found to be super-thin, lightweight, sturdy, and could easily be transported to installation sites with reduced chances of damage.

The energy industry is proactively using renewable innovations and better efficiency of established technologies to reduce emissions. Fortunately, energy industry is not the only place where this is being addressed. This new renewable philosophy is widely referred to as the "circular economy", an umbrella term that refers to a wide range of practices involved in slashing waste, raising efficiency and even redefining economic growth itself. Waste is becoming a concern in many industries, as the classical way of doing business is modified towards a more sustainable vision for the future. Wootton in a GE press release in 2019 has discussed the research objectives of cooperative research and development agreement (CRADA) with Arcam EBM emphasizing on: improve process reliability of EBM technology through the use of in-situ process monitoring and closed loop control; expand the technology to new materials systems, specifically Nickel-based superalloys; and validate microstructure and properties of Titanium Ti-6Al-4V materials fabricated with increased deposition rates. The CRADA, which covers all GE Additive equipment, materials and engineering services capabilities, focused on developing and implementing novel additive technologies into commercial products including process simulation methodologies, in-situ monitoring, and quality control, on both EBM and direct metal laser melting. It also emphasized on materials modeling, development of industrial methodologies, and commercialization of equipment and processes.

In the near future, AM can enable in-situ manufacture of turbine components that are designed for the unique needs and resources of a particular location. There is an opportunity for AM to provide wind turbine spare parts of the discontinued models, for which the manufacturer may have limited quantities to service the repairs. Earlier in 2017, Siemens completed its first full-load engine test for AM gas turbine blades, produced entirely using additive manufacturing technology. Siemens is in the process of developing additive manufacturing solutions not just for turbine blades (rotating), but also for turbine vanes (stationary), burner nozzles (combustor), and radial impellers (compressor parts). Langnau[16] discussed the range of advantages AM technologies could offer for the wind industry. Author pointed out that as the AM technologies become more mature, reliable and standardized, the supplier-chains could be streamlined and the production could be more localized, thus reducing the transportation times and costs. That justifies the implementation of AM in the wind industry. Author also speculated that AM could speed up part and component development time by up to 75%, reduce material resources by up to 65%, and reduce gas emissions by up to 30%. Author highlighted the specific advantages to the wind energy industry due to AM's ability to manufacture a large part in one step, thus eliminating joining processes needed for production techniques with smaller subcomponents. In addition, AM can repair a small section of a large expensive component without full part replacement.

RCAM Technologies developed a technique to additively build ultra-tall low-cost concrete wind turbine towers that were manufactured onsite. This project was funded by the California Energy Commission Grant EPC-17-023 and would reduce technological and economic barriers to upgrading, repowering, and expanding wind power generation in California by enabling cost effective deployment of taller towers built onsite. RCAM's vision for wind energy is to develop land-based and offshore wind turbine towers and substructures up to 200m tall at half the cost of conventional tall tower technologies. RCAM Technologies' team, partners, and advisors have been carefully selected to provide world-leading expertise in key disciplines needed to dominate industrial concrete additive manufacturing markets.

Oak Ridge National Laboratory is a big supporter of AM technologies and it concluded that AM benefits to Aerospace cannot be ignored. Their design-to-manufacture AM processes showed the potential to dramatically reduce buy-to-fly ratio from a previous industry average of 8:1 to nearly 1:1. AM reduced material and energy requirements while accelerating the fabrication time of highly complex components. For example, a heat exchanger is a device that allows different fluid streams to be heated or cooled. Carlota of GE showed that heat exchangers are beginning to be designed using additive manufacturing and the outcome is very different from conventional designs. It is possible that experts may need to rewrite the existing correlations with improved AM designs as AM design abilities offer better fluid path options to increase performance. GE and its partners explain that their printed heat exchangers can operate in extreme environments of up to 900°C and with operating pressure of 248 bar. Peter De Bock, thermal engineer at GE Research explains: "We use our extensive knowledge in metal management and thermal management and apply it like never before thanks to the power of 3D printing. Thanks to this method, we can now realize new architectural designs that were previously impossible. This will allow us to create a "UPHEAT" device that can operate cost-effectively at temperatures higher than those of current heat exchangers (+250°C)." In another disclosure, Thompson mentioned, GE Additive, which is a subsidiary of GE Aviation with test facilities in West Chester, is making aircraft engine parts so complex that better 3D printers are needed. It partnered with the U.S. Department of Energy's Oak Ridge National Laboratory, a leader in additive manufacturing, to design AM machines that can keep up with the complicated shapes being designed. This shows the need for a different design thought process to use AM effectively.

AM is having a wide range impact on energy storage technologies. For example, research teams that are working on next generation batteries are utilizing 3D printing technologies to create complex internal structures of batteries with increased capacity and flexibility in shape and size. 3D-printed lithium-ion batteries are making progress and American chemical society (ACS) observed that most lithium-ion batteries on the market come in traditionally manufactured shapes of cylinders or rectangles. As a result, an electronic device like a cell phone need to conform to given size and shape of the battery. This limits design options and puts additional constraints on the component layout. Theoretically, it is postulated that AM can fabricate an entire device with built in battery. However, polymers like poly lactic acid, commonly used in AM, are not ionic conductors; thus, creating hurdles for printed batteries. However, researchers are finding ways to inexpensively print batteries as standalone devices with unconventional shapes. Down et al. [17] reported the first entirely AM/3D-printed sodium-ion full-cell battery. They developed AM/3D-printing compatible composite materials with active materials like $NaMnO_2$ and TiO_2 within a porous supporting material. The AM/3D-fabricated device demonstrated a respectable performance even if it had nearly 80% thermoplastic support structures.

The disposal and recycling of plastic materials are some of the biggest challenges of 21st century. Few studies have reported recycling of thermoplastics via three-dimensional (3D) printing as novel primary and secondary recycling techniques. Singh et al. [18] observed that recycled or virgin thermoplastics as energy storage devices (ESD) is feasible with AM. They used Fused Deposition Modeling (FDM) and a feed stock filament comprising of advanced composite materials (thermoplastic: acrylonitrile butadiene styrene (ABS) matrix, reinforced with different proportions of chemicals/salts namely: MnO2, ZnCl2, NH4Cl and graphite). This study illustrated that dry cell comprising of minimum 40% by weight recycled thermoplastics can be prepared successfully having voltage potential at par with commercial dry cell. Another major advantage of using this novel route was that the ESD prepared was thermally more stable and could operate at up to 95 °C temperature while a typical Lithium ion battery is not safe to operate beyond 55 °C.

Researchers have strived in the last several decades to improve the performance of RF energy harvesters. Notably, Zhakeyev et al.[19] discussed about overcoming the low-energy-density problem in RF energy harvesting, and AM has emerged as an alternative to conventional fabrication techniques for that family of devices. AM has a very efficient solution for low-cost RF circuit associated with high resolution and a wide variety of printable materials. The inkjet 3D printing can produce high resolution conductive traces useful for electrical engineering applications. This conductive paste-based AM technology can build support circuits for sub-terahertz frequencies on different substrates including flexible materials. AM has already illustrated the capability to print basic circuit components like capacitors, inductors, antennas, diodes. The fused deposition modeling (FDM) enabled the fabrication of transducers and energy storage components.

Internal combustion engines dominate the individual transportation industry. Currently, aluminum alloys, being lighter compared to traditional materials, were considered as an environmentally friendlier solution. However, the energy required for the extraction of the primary materials and manufacturing of components were not considered while comparing the two products. Salonitis et al.[20]

found that a conflict exists around the substitution of traditional cast iron for automotive engine with lighter metals. They estimated the overall energy required for building an engine cylinder block with cast iron and aluminum alloys with "cradle-to-grave approach" that took into account the energy input at each stage of the component life cycle starting from the resource extraction from ore to the end-of-life discarding stage. Their results indicated that, although aluminum components contribute toward reduced fuel consumption during their use phase, the vehicle distance needed to be covered in order to compensate for the up-front energy consumption related to the primary material production and manufacturing phases was very high. Thus, the substitution of traditional materials with lightweight ones in the automotive industry should be very carefully evaluated. AM can play a big role in engine production with just-in-time manufacturing, and by weight reduction with innovative internal porous structures. By implementing AM, a manufacturer can eliminate the need for detailed long-term projections on batch manufacturing and inventory control. The same AM equipment can produce different engine blocks based on the demand of the day, if not by the hour. Moreover, cheaper or environmentally friendly materials can be used with innovative internal structures and added porosity to reduce component weight.

Population growth in cities and dependence on electrical appliances are resulting in significant increase in energy consumption. Keirstead et al. [21] found that energy use in cities can be optimized and reduced. They first developed an urban energy system model and then evaluated the state of current practice based on a review of 219 papers. They identified five key areas namely: technology design, building design, urban climate, systems design, and policy assessment. They also added land use and transportation modeling, which impacts energy usage in cities but have not been studied in detail before. They identified few challenges in developing a comprehensive model like available data quality and uncertainty, model integration among interactive systems, and local as well as federal policy adoptions. Results indicated that there is significant potential to improve energy usage in urban systems by predictive modeling and sensor-based coordination. To implement these integrated perspectives, it requires innovative designs that cannot be achieved without AM. The trend towards "Smart City" with digital workflow encourages adaptation of AM in many different aspects of future civilization.

If one has to pick winners from AM revolution, medical appliances will perhaps lead the pack. Shidid et al. [22] observed that AM in medical applications are growing most rapidly and there are new technologies being evolved in that area that can also be beneficial to energy markets. Authors argued that AM was not subject to traditional manufacturing constraints and it provided significant opportunities for the design of novel geometries and complex lattice structures with enhanced functional performance. AM can develop patient specific components and that is where it can be of unique equivalent usage for just in time parts for special machines. The same logic or production sequencing can be used in energy related industries. Compressive testing of AM built lattice structures showed 85% load carrying capacity of a bone and the compressive stiffness was indistinguishable from the stiffness of the original bone samples. This encourages bio-mimicking design features in energy market and one design with leaf like structures in a wind turbine has been discussed here. Some can argue that medical applications are so different that they are irrelevant for this discussion, but that will be a short-sighted view. Let us not forget that as of today medical sector is the winning horse of the AM market. It is a money maker, profitable and as a result, significant innovations are taking place in that sector at a faster pace than others. An AM professional should keep an eye on the developments made in the medical sector and select innovative ideas for the energy-based applications.

5. Current Activities in AM:

In an Overview of manufacturing processes using ISO/ASTM52900-15 standard, AM system was classified in seven different types: binder jetting, directed energy deposition (DED), material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [23]

- Binder jetting: a binder is selectively spread on a powder bed mostly based on ceramics.
- Directed Energy Deposition (DED): Concentrated power source melts and deposits feed material (mostly metal) on the target surface.
- Material extrusion: Similar to hot extrusion of plastic. However, the same process can also be used with modelable materials such as concrete, clay, organic tissue, or even food.
- Material jetting: A photopolymer is sprayed and then hardened with ultraviolet (UV) light.
- Powder bed fusion: Powder in a bed is locally heated until they melt together. Used on titanium, cobalt-chrome, as well as on nylon.
- Sheet lamination: Shaped sheets are fused together. Used with metal and plastics. Unlike other techniques, this may require some preformed tooling.
- Vat photopolymerization: A vat of photopolymer resin is exposed to locally intersecting or focused laser beam or high intensity light that caused hardening of the resin.

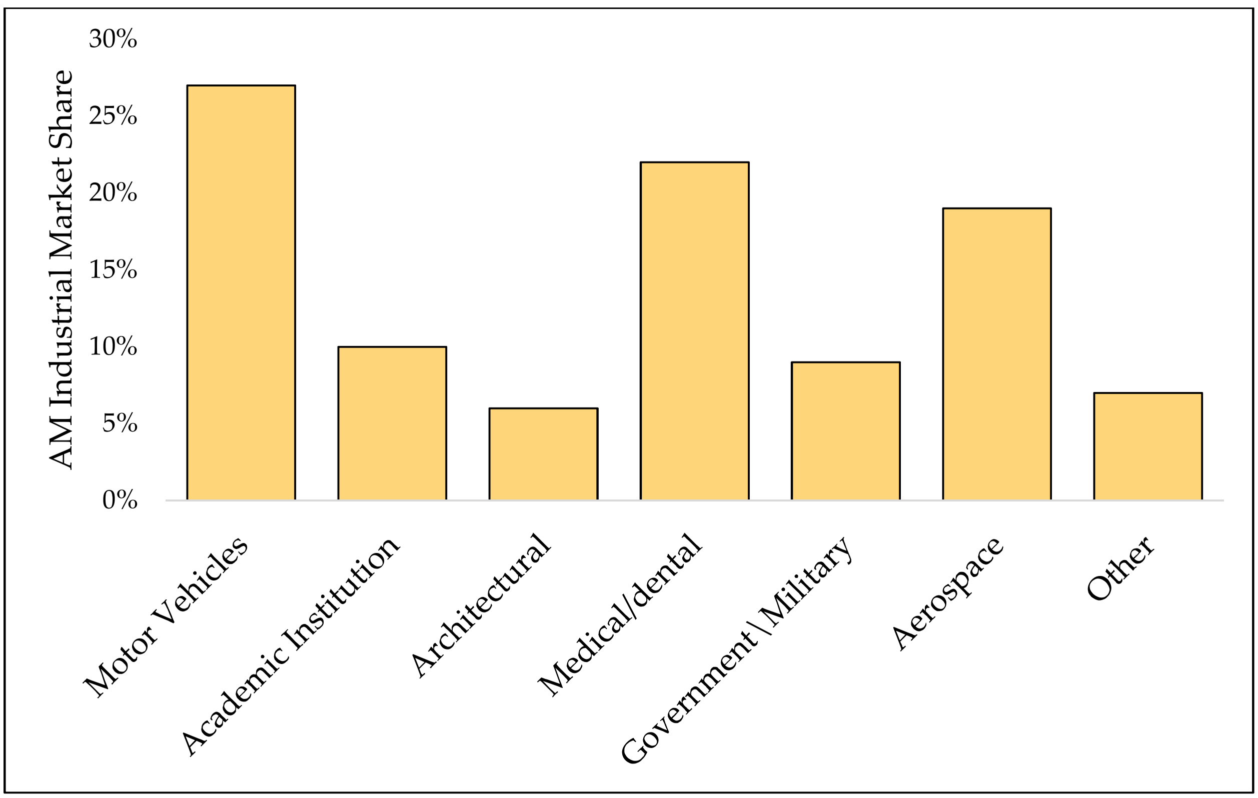


Figure 3. AM industrial market share (data [24])

Industrial market share for AM products is concentrated at motor vehicles, medical, and aerospace and the distribution is plotted in Figure 3[24]. Interestingly academic institutions contribute to 10% of the market share by research and development activities. Use of fast prototyping in senior design with Capstone projects have increased significantly. Energy related applications are usually in Aerospace and some automotive technologies.

AM industry's use of metal based materials grew from 28% in 2017 to 36% in 2018 as observed in Figure 4[25]. Plastics lead the type of materials followed by metals and resins in 2017, but in 2018 Wax and Ceramics stayed about the same at 10% in material mix while plastic usage percentage dropped. It can be argued that use of plastic is not growing, and it dropped from 88% to 65% of the overall product mix in one year ending in 2018. It seems, metal-based 3D printing is growing at the expense of other materials. Full Color Sandstone offers multi-color printing, making it the best material for figurines, architecture, medical models and other applications that require many colors. Although it's a great material for decorative models, it is not well suited for handling due to its low strength and brittleness.

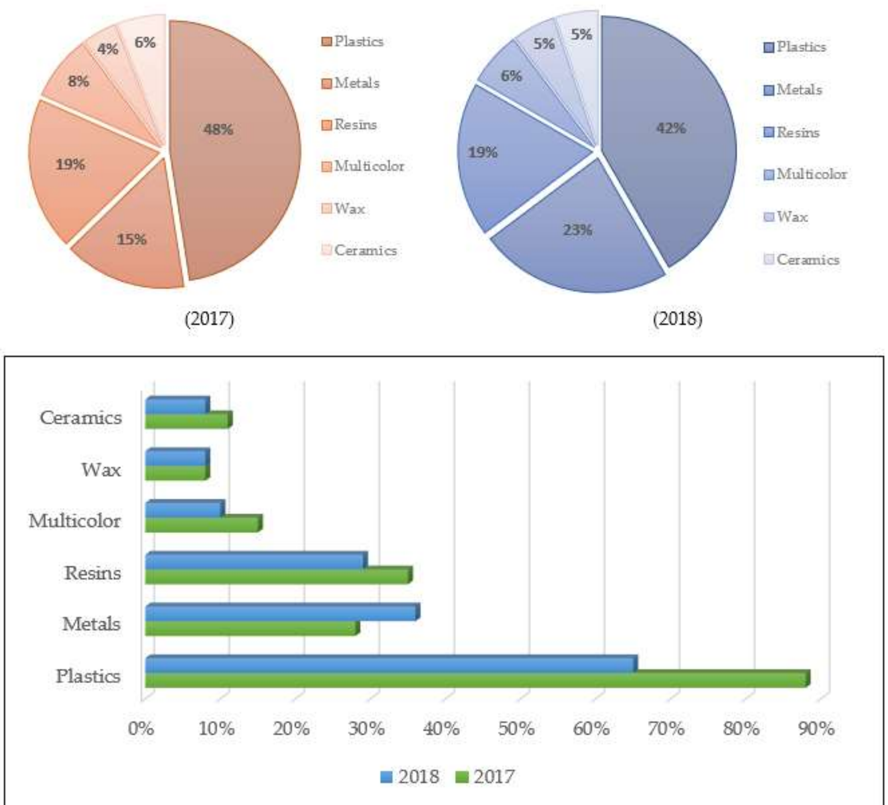


Figure 4. Change in material ratios in AM from 2017 to 2018, (data [24])

Williams and Jones [26] postulated that human civilization will expand beyond planet earth and AM will have a significant contribution in that expansion. Our civilization is energy dependent and it will make more sense to build components and machines out in another planet rather than carrying all components from earth. To achieve smooth operation, the documentation, operating steps, material development, part quality, and risk identification with a more rigorous process is suggested. This research group is working on solar powered AM technologies to use lunar dust (regolith) to build habitats, energy preserving, and energy harvesting equipment. Lessons learnt in earth environment are being extrapolated for outer space applications.

There are attempts to obtain special material characteristics not only with designer materials, but with shapes and sub-structures. For example, Carrillo et al. [27] developed honeycombs via 3D printing of a sustainable paste. The printing gel used was known to provide porosity to tungsten carbide samples, which increased specific strength due to reduced density. So, they created intentionally porous honeycomb sub-structure to get desired mechanical properties, but thermal deformations during additive manufacturing caused significant variations in the final shape of the samples. Hu et al. [28] used rapid prototyping concepts with Laser Engineering Net Shaping (LENS) and Ultrasonic Consolidation (UC) to fabricate heterogeneous objects with more than one material. These sub-structures with unmixed strategic materials were tuned for desired mechanical or thermal performance.

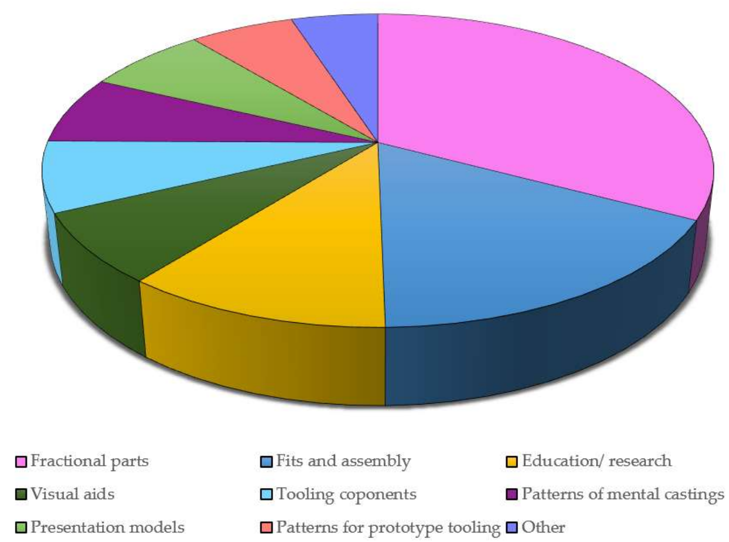


Figure 5. Use of additive technology in different business sectors (data [29])

AM is finding many different applications as the printers improve and easier to handle materials are discovered. Figure 5 shows that AM is used for not only component development but also for tooling, supports for fits and assembly. It can also be observed that education and research-based users are significant in proportion, and they typically use AM to develop prototypes and proof of concepts. The senior design classes in undergraduate curriculum frequently use the AM to test concepts and to support their ideas with a visual and tangible presentation.

Caterpillar has seen rapid prototyping supply over 50,000 models since 1990 to engineers and designers for fit-ups, casting aids, design verification and display models. In recent years, with the rise of the "innovation culture," 3-D printing enabled them to break out of those traditional areas with color, new materials, and new processes. Additively fabricated plastic parts provide good form and fit and follow up metals on strength and durability. Today, additive manufacturing is making huge strides through their factories in the form of tooling, gaging, and fixturing; not to forget an improved way to deal with low-production-volume items.

Oak Ridge National Laboratory (ORNL) made advances in large-scale additive manufacturing of composite structures that garnered recognition by Guinness World Records. This process is very different from AM with metal. ORNL polymer materials development team used 3D printing to design tools with less material without compromising their function. After ORNL completes verification testing, the aerospace giant Boeing plans to use ORNL's additively manufactured trim-and-drill technology in their company's new production facility in St. Louis, USA. There is an active symbiotic relationship between the two organizations with funding help from other federal departments. Boeing will provide feedback regarding their experience to ORNL on the tool's performance to improve the process further. The AM based tool will be used to secure the airliner's composite wing skin for drilling and machining before assembly. These interactions between government and for-profit companies are encouraging and show that multiple talent bases are required to design these complex processes. Work is progressing at break-neck speed and manufacturing processes are becoming dependent on the evolving AM.

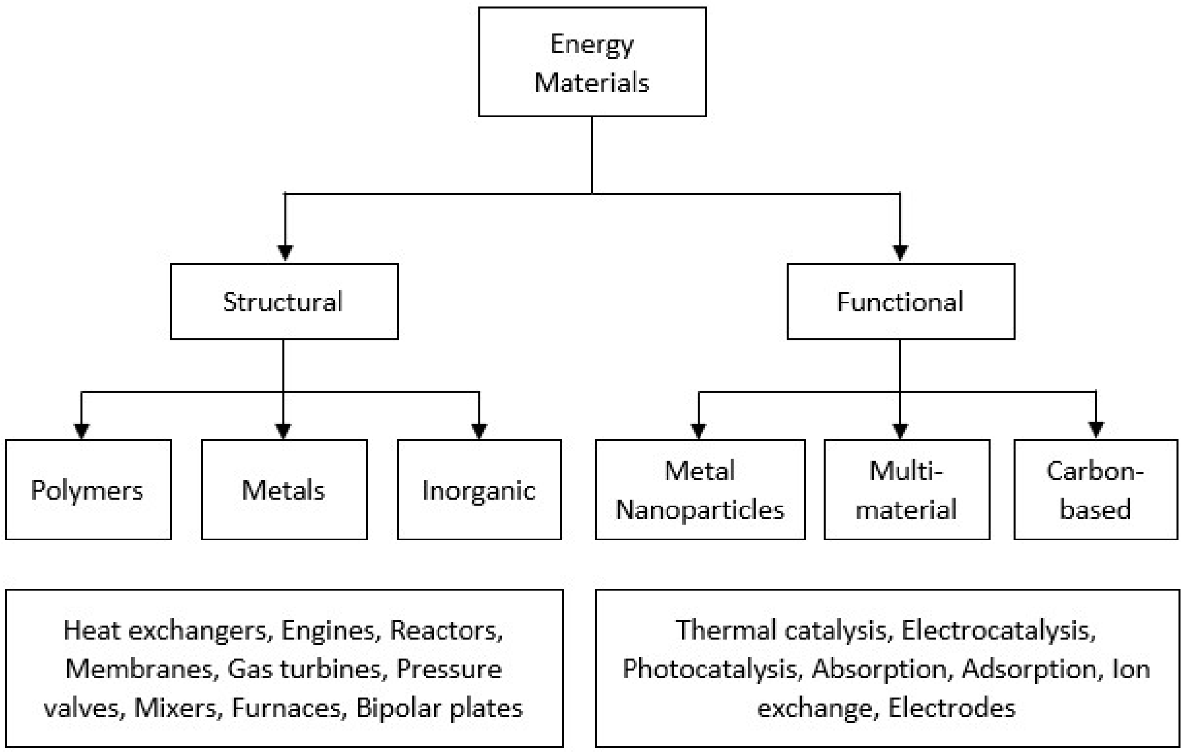


Figure 6. AM Energy applications (data [19])

Materials used in energy related components can be broadly classified in two categories based on applications - Structural and Functional. Figure 6 shows detailed classification with the materials falling under each of these categories and corresponding examples from the energy sector are provided. The principles of additive manufacturing (AM) have been explained in detail in numerous literatures, but few of them touched on the materials available for various applications, especially in energy field. Fu et al. [30] recently reviewed the research efforts on the use of DIW and development of graphene oxide (GO) based inks to fabricated structures for energy storage, electronic circuits and thermal energy applications. Consequently, it is necessary to clarify the materials that can be utilized in AM for the energy conversion and storage applications. There are a few extensive databases on the selection of commercial AM materials available. Notably, Senvol Database, a search engine for industrial AM machines and materials, provides material properties for 981 different ceramic, metal, polymer and composite materials used in commercial AM machines.

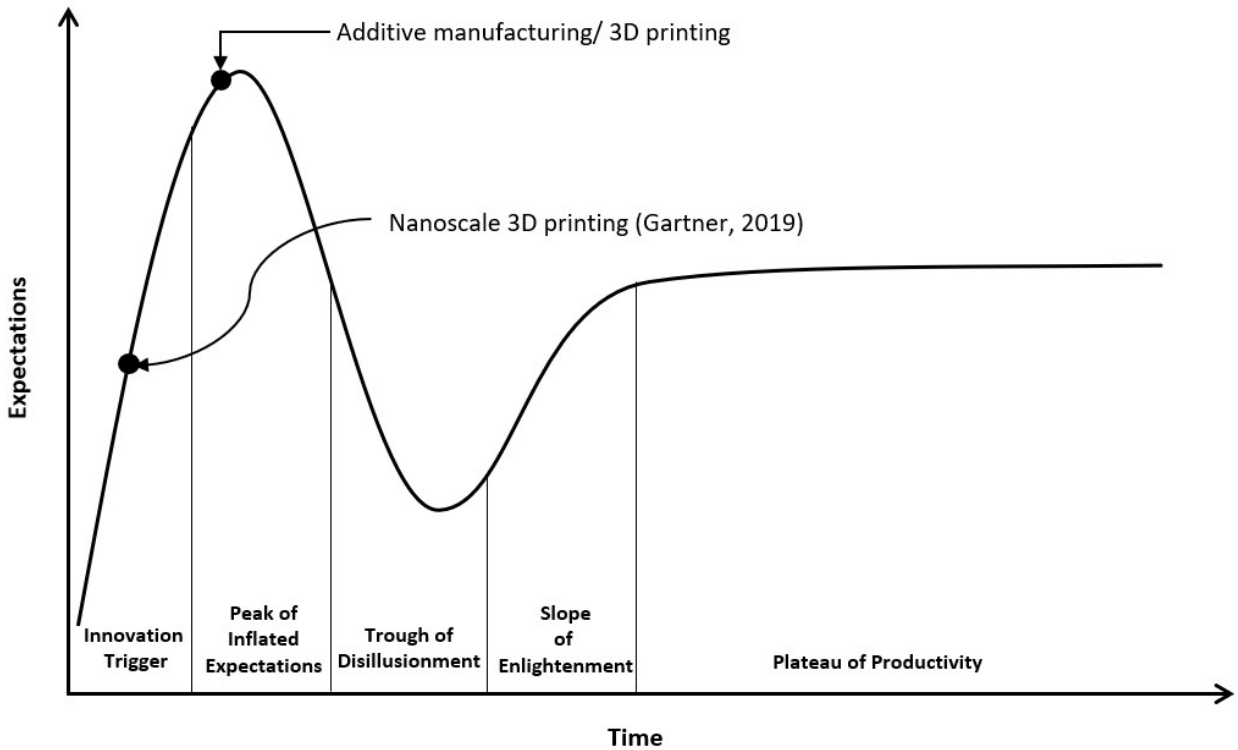


Figure 7. AM on the hype curve (data [31])

The hype cycle is a branded graphical presentation developed and used by Gartner, the American research, advisory and information technology firm, to represent the maturity, adoption, and social acceptance of specific technologies. The hype curve related to AM is illustrated in Figure 7. The hype cycle claims to provide a graphical and conceptual presentation of the maturity of emerging technologies through five phases. However, note that the Gartner hype cycle has been criticized for a lack of evidence that it holds, and for not matching well with technological uptake in practice.

The hype curve related to AM is illustrated with five domains in Figure 7.
1. Technology Trigger: A potential technology breakthrough brings in new opportunities. Commercial viability and usable commercial prototypes are not available yet at this stage.
2. Peak of Inflated Expectations: Some use of the new discoveries shows a potential product or process improvement. Larger companies start to take notice and investors find the technology to be worth considering
3. Trough of Disillusionment: Interest wanes as experiments and implementations fail to deliver or meet expectation. Investment continues only if the surviving providers improve their products to the satisfaction of early adopters.
4. Slope of Enlightenment: The concept of the technical applicability based on the early discoveries materialize. Next generation products appear and enterprises fund pilots. However, conservative companies remain cautious.
5. Plateau of Productivity: Major producers and users brace the new products. The economic pricing of demand supply pattern starts to form, and the product becomes widely available from a new concept to a more established customer base.

In 2015, it was argued that the additive manufacturing was at the peak of inflated expectations. In 2020, with the economy heading towards a "cool down", the hype curve location for AM is perhaps in the transition to disillusion from the peak expectations. It is difficult to predict the future or current status as this curve is mostly based on hindsight. We know the general cycle elements, but do not know exactly when they happen and for how long. Four essential technology elements and system integration for viable AM are: material development and evaluation, design for AM and related standards, solid modeling and process control, inspection, validation and certification.

Additive Manufacturing (AM) opens new opportunities for the economy and the society, and the global market for this technology is growing rapidly. However, quality assurance remains one of the main barriers for a broader integration of AM in the industrial sector. According to Al-Meslemi[32], most quality-related problems of AM were caused by uncontrolled variations in the production chain. By identifying the key controlling parameters or the Key Characteristics (KC) and introducing the proper process control protocol for these parameters, the effect of these variations can be predicted, and expensive monitoring, rework, repair and quality-related problems can usually be avoided. In addition, these KCs can also be used to achieve sustainability in AM. In addition to providing quality product that satisfies the client's requirements, the manufacturing resource usage (energy and material) can be minimized. Authors reviewed recent literature related to sustainability in AM and proposes a new approach into how the key characteristics, which are normally used to reduce variations in production, can give an insight to a sustainable AM. Quality control of AM is becoming more important as it is being used in critical missions and in high-strength high durability applications. Further, they identified four "sustainability goals": (i) reducing the time of manufacturing; (ii) reducing the cost of manufacturing; (iii) reducing the material usage; (iv) increasing the parts functionality. Then they discussed how the KCs influence "sustainability goals". For example: manufacturing time could be reduced by decreasing spacing between parts which is related to build environment. The novelty of their approach was from connecting KCs to sustainability goals as defined above. Usually these KCs are used for quality control and not for improving sustainability of AM process or part.

6. AM Process

Additive Manufacturing (AM) is a common name used in the industry based on the goal or objective of manufacturing process. In its current form, material is gradually added to get to the desired shape and functionality. How to add (process) and what material to choose that depend on the application, economics, tolerance, strength, appearance, and feasibility. AM in one industry can be very different from another, however there are opportunities for cross-fertilization of ideas from one business segment to the other. There are review papers available on these processes and therefore the details are not repeated here. Following discussion will provide the needed knowledge base for an interested reader to explore further.

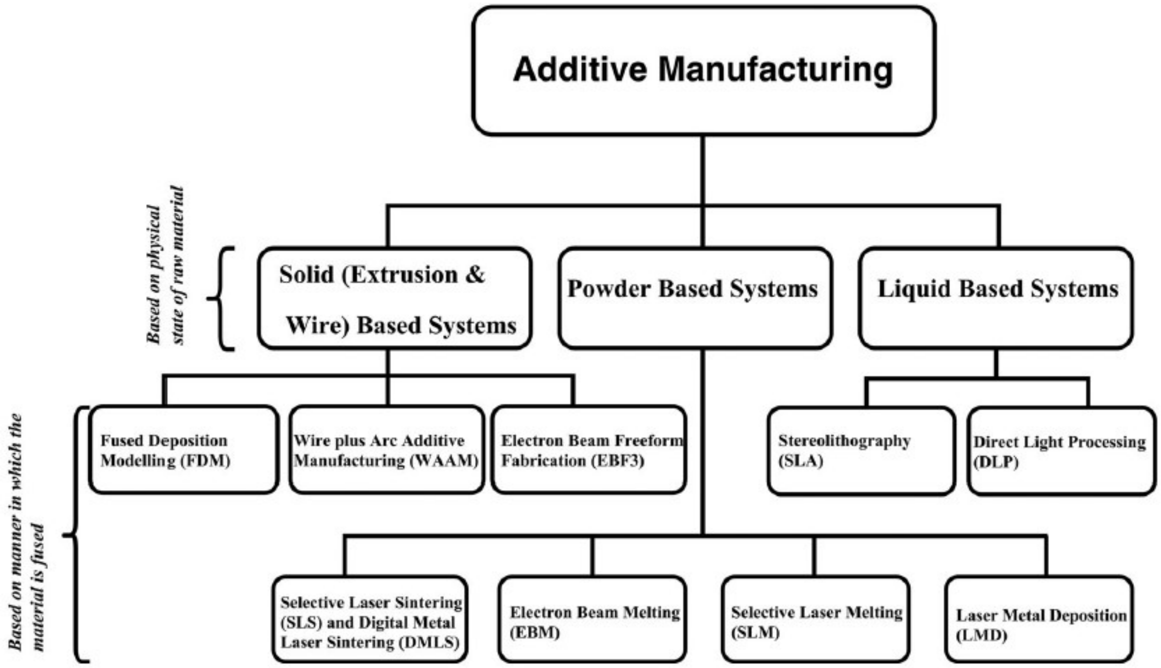


Figure 8. Classification of commonly used AM processes (data [33])

The AM processes can be broadly classified by the form of the raw material used. Joshi and Sheikh[33] created a process classification chart based on materials used in aerospace industry as shown in Figure 8. They considered wire feed, powder, and liquid as the common forms of the feed material. This is not an exhaustive list but covers most of the applications discussed here.

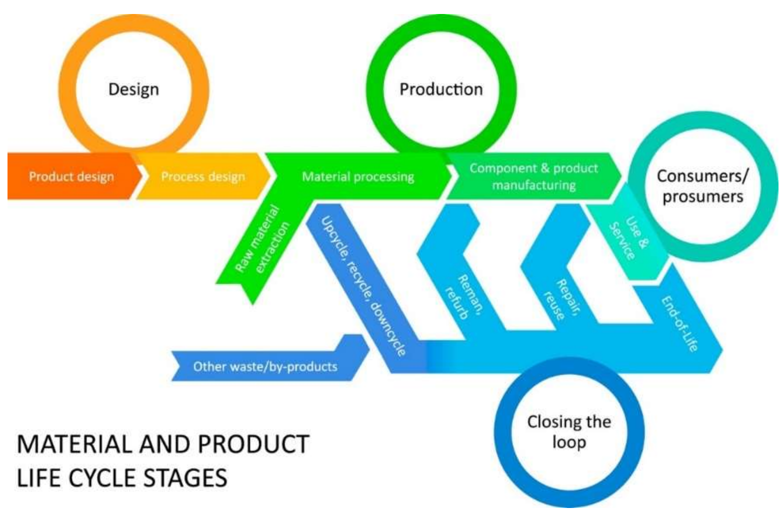


Figure 9. Life cycle perspective for identifying sustainability benefits of AM.[5]

The AM process is by nature more flexible as it starts with an empty space, and therefore adaptable to sustainability and recyclability of material. Ford and Despeisse[5] discussed how AM opens up design space by allowing greater freedom in geometries with simpler assemblies and fewer materials. They demonstrated how this could provide benefits over the four stages of product life cycle; product and process design; material input processing; make-to-order component and product manufacturing; and closing the loop, see Figure 9. They have included several real-life examples to illustrate those aspects.

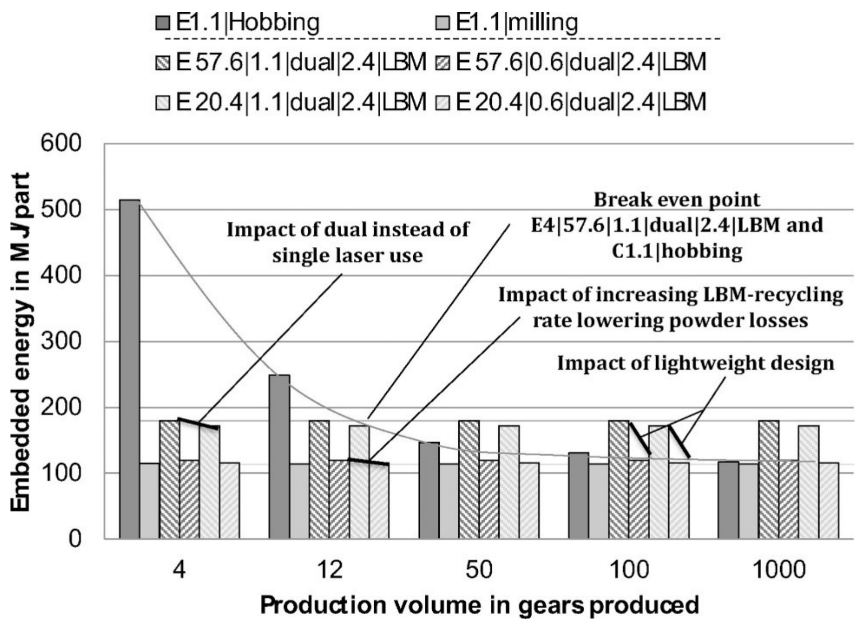


Figure 10. Comparison of total embedded energy calculation of different Gear production scenarios.[34]

Figure 10 shows an analysis of Gear production with different manufacturing techniques. Test production volumes were 4, 12, 50, 100, 1000. LBM: Laser Beam Melting of metal powder. There are two designs: 1.1 kg and lower mass 0.6 kg. The lower mass 0.6 kg has the functional strength of the gear and is designed for additive, which cannot be economically produced by conventional methods. Argon usage for powder atomization is estimated conservatively to 2 m^3 of argon/kg powder. As further investigations show, that production volume has no significant impact on Specific Energy Consumption (SEC), average values for SEC-LBM were set to 95.49 MJ/kg for dual laser mode and 165.62 MJ/kg for single laser mode. This shows that dual laser mode was advantageous as most of the machine auxiliaries like motors and heating were shared by the laser sources doubling the solidification rate. Hence, total manufacturing time for LBM should be minimized in order to minimize the electrical energy demand. Also, based on the results, a dual laser source was recommended for further investigations. Furthermore, a comparison is made between different scenarios of hobbing (a special technique of gear cutting) and milling. For LBM, scenarios with different recycling rates were considered. At low manufacturing volumes, hobbing had a comparably high embedded energy due to extensive tooling necessary. SEC for hobbing decreased with increasing production volume. Milling and LBM process sequenced are constant with increasing production value. Embedded energy for milling remains constant due to tooling energy proportional to production unit at E1.1|milling = 115 MJ/part. Comparing the trends of the curves derived from data points of selected scenarios generated as a function of production volume, break even points of different scenarios could be deducted. It was observed that hobbing is not an energy efficient choice for small batches due to the need for extensive tooling. Milling offers the best energy-efficiency, that is more efficient than LBM for gear production. LBM is only competitive when lightweight design was produced as a functional unit. Milling and hobbing converged to a comparable SEC at high production volume. This is explained by a negligible influence of tooling with larger production volumes and comparable machine tool energy consumption with comparable machining process steps. The results show that LBM is competitive with hobbing regarding energy efficiency up to a production volume of 29 for high recycle and 55 for low powder recycle of the gear wheel produced. Compared to milling, LBM offers a similar embedded energy with lightweight design, which cannot be produced by milling or hobbing.

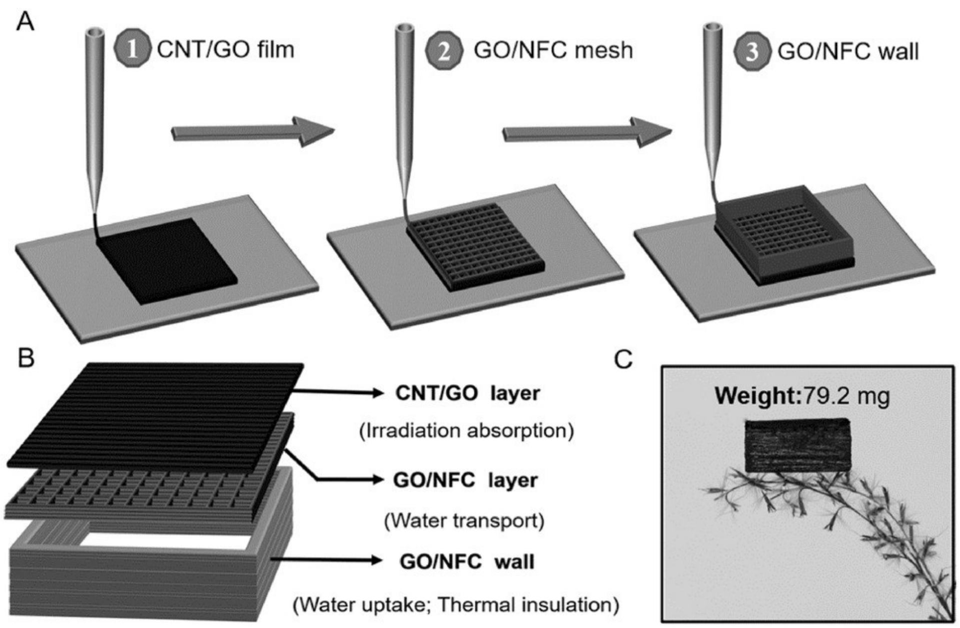


Figure 11. 3D printed efficient water evaporator [35]

Figure 11 illustrates construction of an integrated structure for high-efficiency solar steam generation by using layer-by-layer 3D printing fabrication. Li et al. [35] used Carbon Nano Tube (CNT), Graphene Oxide (GO), and Nano-Fibrillated Cellulose (NFC) as the building materials. The integrated structure consisted of a top layer of CNT/GO layer, (GO/NFC) layer, and GO/NFC supporting hydrophilic wall. The CNT/GO layer showed an efficient broadband solar absorption and excellent photothermal conversion. In addition, the thin and porous CNT/GO layer contributed to vapor escape and heat localization. The GO/NFC layer with porous mesh-like structure transported water inside its channels and wick water upward to the contiguous porous CNT/GO layer. The porous and hydrophilic GO/NFC wall, as a support, effectively drew water from the bottom by capillary effects without a pump. The air in porous GO/NFC wall served as an effective thermal barrier to reduce thermal losses to the bulk water, resulting in a high-efficiency solar steam generation. This 3D-printed evaporator (denoted as 3D-CG/GN) also demonstrated superlight construction, which made the overall support structure design easier. The energy conversion efficiency to generate steam was a maximum of 85.6% as compared to an average conventional solar collector's 26.6%. The cycling performance with one full sun radiation was also satisfactory with high stability making it a feasible candidate for solar-steam-generation applications.

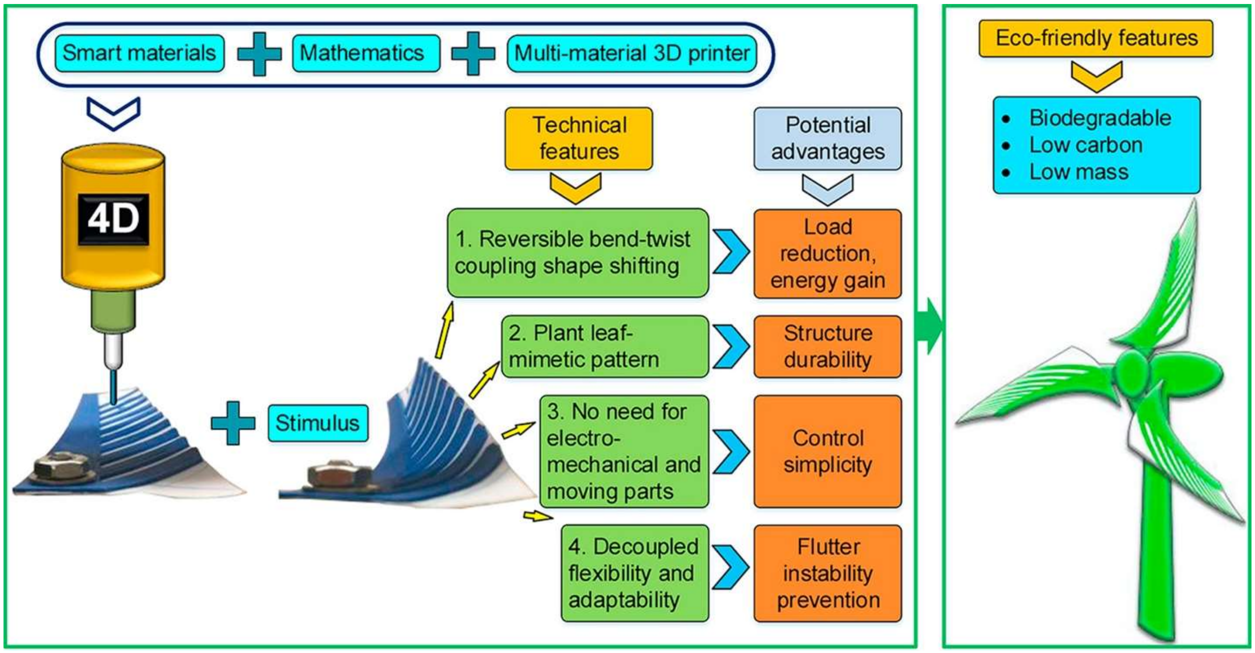


Figure 12. 3D printed wind turbine airfoil with plant leaf mimetic pattern. [36]

Lessons learnt from nature are being applied to develop large flexible turbine blades. Figure 12 shows conceptual use of plant leaf pattern in a wind turbine blade. Momeni et al. [36] argued that plant leaf veins grow into an optimized architecture not only to accomplish their biological and physiological functions but also to sustain the environmental loads. They found that the wind turbine blade mimicking nature's leaf architecture could have relatively lower stress and strain, and higher fatigue life compared to conventional blades. They showed a new technique for design and fabrication of wind blades with 4D printing process, where 4th dimension is a thermal treatment on the finished printed structure. The proposed blade having the plant leaf structure does not need sensors and actuators to determine proper deflection and changes its shape to reduce the flutter and noise observed in large installations. To reduce harmful CO_2 emissions, city-integrated renewable energy by wind turbines is a viable solution. Moreover, the city-integrated strategy can eliminate long-distance transmission systems required for the current wind turbines placed in remote regions. Locating the power generation system closer to the user, reduces the related transmission energy losses. These leaf-like silent airfoils will need AM to have the needed flexibility and functionality to integrate with digital "Smart City" infrastructure.

The eco-friendly attributes of the proposed blade are [36]:

1. Biodegradable materials: Polyactic Acid (PLA), which is biodegradable, can lead to eco-friendly wind turbines. PLA is a bio-based polymer generated from natural resources such as corn and is one of the cheapest biodegradable polymers to supersede petroleum-based plastics. It is used in rigid bottles for beverage, yogurt and other perishable food packaging, and has potential applications in many other industries such as automotive. PLA is usually degraded by hydrolysis and it could be produced with high molecular weights suitable for structural applications with enough lifetime and no rapid hydrolysis.

2. Low mass: The low mass improves performance, but thin blades need stiffeners and that is achieved by AM- either by printing specialized stiffening structures or by printing the mold on which the blade cast is made.

3. Low carbon emission: Ji and Chen [37] analyzed the overall carbon footprint by the full life cycle of a wind farm. They included construction, operation, and dismantling phases; and showed that the most carbon emission is in the construction that involved smelting and pressing of metals. Non-metallic airfoils with leaf-like stiffeners will reduce the carbon emission in their construction phase and most likely will be bio-degradable as suggested above.

6.1 Repair and remanufacturing of industrial hard to repair parts

Wind turbines are exposed to harsh weather and require periodic maintenance. Many of the parts are custom made and may not be available as aftermarket service parts. So, it may become necessary to repair the existing parts rather than replacing them; moreover, sometimes the size of the component makes it uneconomical to process at a distant location. Similarly, gas-turbine components have limited life and normally thermal damages are observed at local spots while the rest of the component may not have significant wear and tear. The laser engineered net shape (LENS) process has been evaluated for the repair of casting defects and improperly machined holes in gas turbine engine components [38]. Various repair geometries, including indentations, grooves, and through-holes, were used to simulate the actual repair of casting defects and holes in two materials: Alloy 718 and Waspaloy. The influence of LENS parameters, including laser energy density, laser scanning speed, and deposition pattern, on the repair of these defects and holes was studied. Laser induced surface re-melting of the substrate prior to repair was used to remove machining defects and prevent heat-affected zone (HAZ) liquation cracking, which happens in partially melted zones. Ultrasonic nondestructive evaluation techniques were used as a possible approach for detecting lack-of-fusion in repairs. This technique can be extended for on-site wind turbine repairs without dismantling the large structures.

6.2 New additive structures

Scientists have reported that plant leaf veins grow into an optimized architecture not only to accomplish their biological and physiological functions but also to sustain the environmental loads [36]. One design option is shown in Figure 12. Researchers showed that the wind blade mimicking the leaf architecture have relatively lower internal strain energy, better static strength and stiffness, smaller stress intensity, and higher fatigue life compared with the conventional blade structures. However, the plant leaf-mimetic wind blade has so far remained at the level of simulations.

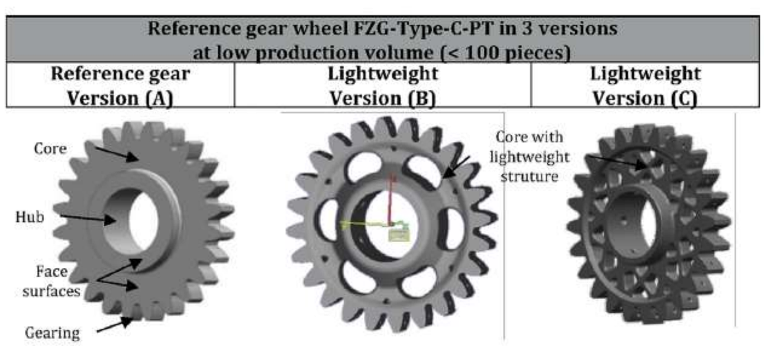


Figure 13. Design for AM showing reduction in weight of a classical gear. [34]

Figure 13 shows how the AM design is conceptually different from conventional shapes. It shows three different designs for the same component created by Kamps et al. [34]. Version A is the conventional gear. Version B and C are more AM friendly designs with less material, thus lower build time. The mating surfaces, that is the shaft mount and gear teeth are the same for all three. The load carrying capacity is also the same, yet version B and C show significant reduction in material used. These designs are being possible with the advancement of optimization routines and better availability of high-performance computers. Note that computer CPU processing speed has not increased much in recent years but the RAM memory capacity has increased significantly to handle these complex calculations.

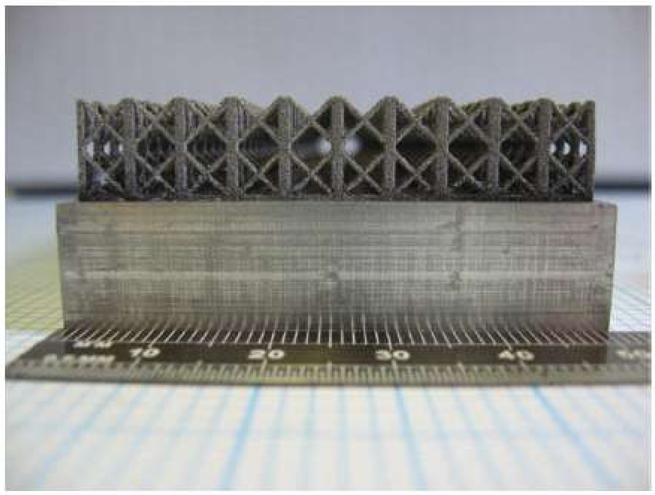


Figure 14. Complex lattice structure as fin made with AM. [39]

Figure 14 shows Lattice fin structure used by Wong et al. [39]. They demonstrated that increasing the heat transfer surface area does not necessarily bring about an improvement in heat transfer performance. The lattice structure did not perform as well as it was anticipated. There were two justifiable causes of Lattice’s poor performance. First, the low thermal conductivity material and thin sections caused that each strut within the lattice had a large temperature gradient across it resulting in a poor fin efficiency. Second, although the lattice was complex there were channels aligned with the flow for the length of the heat sink, thus allowing cooling air to travel through without much interaction with the structure. Moreover, the wakes behind the upstream rows of Lattice enveloped downstream struts and reduced heat transfer (not enough gap). When these two effects were combined, much of the heat transfer surface area became ineffective. There are clearly more optimization studies with conductive materials to be tested before a high performing lattice fin can be designed. This work showed that benefits from AM is not guaranteed and needed to be earned by expert analysis and intelligent design techniques.

7. AM for Gas, Steam and Combined Cycle Applications:

Gas turbine is a constant pressure combustion engine that burns gaseous or liquid fuel to deliver thrust energy. Common applications are aircraft engines and rotating machinery, which could deliver electricity or mechanical energy to drive compressors and propellers. Most of the jet aircrafts today use gas turbine engines. It is also the major technology used to convert fossil fuels to electricity. Current trend is to replace conventional gas and oil powered steam plants with combined-cycle power plants using gas turbines along with the steam turbines for the efficiency gains that they provide. Gas turbine research has direct implications for majority of energy industry be it power generation, aviation, transportation, or oil and gas. Figure 15 shows the proportion of different energy sources in the US. Power generation from nuclear and coal uses steam turbines, and natural gas uses gas-turbine. The combined cycle uses steam turbine at the bottoming cycle and gas-turbine on the top. It is clear from this data that any improvement in the efficiencies of the gas or steam turbines could impact 80% of the electricity generation sources in the country.

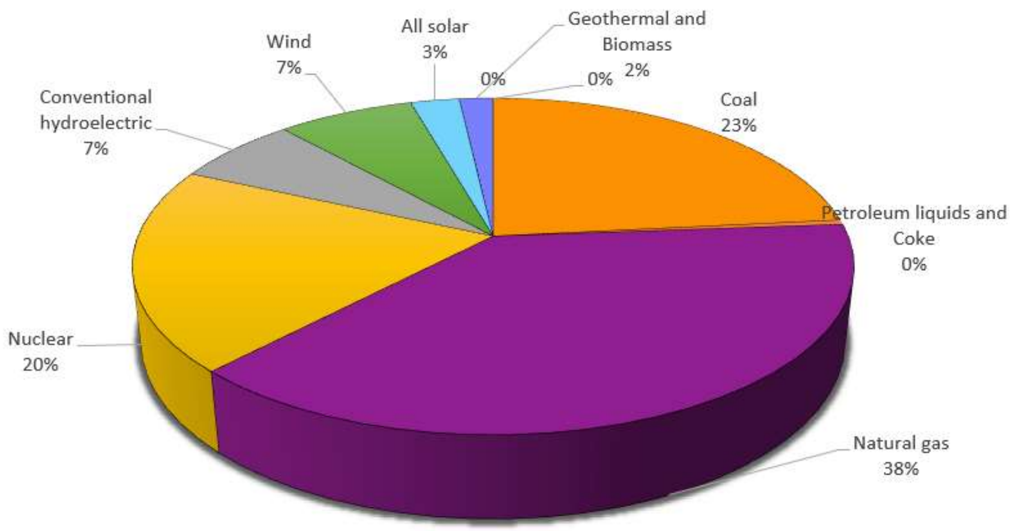


Figure 15. Net Electricity Generation in the United States by Source (2019)(data [40])

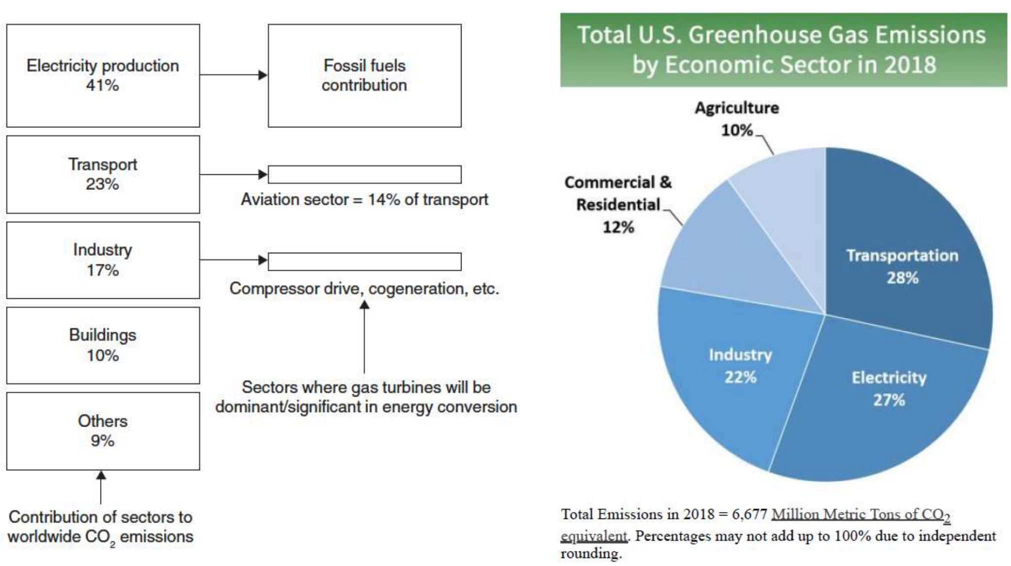


Figure 16. Sources of worldwide CO_2 emissions and potential of gas turbines (in 2010 and 2018) (data [41,42])

Overall, it can be seen from Figure 16 that gas turbines are important in multiple sectors and will be responsible for about 50% of the total worldwide CO_2 emissions. Gas-Turbine efficiency goes up as the inlet temperature to the turbine rises. The operating temperature is already above the melting or softening temperature of the turbine material. Therefore, to increase the turbine inlet temperature, also known as firing temperature, the cooling techniques of the hot gas-path components need to improve. The gas turbine efficiency improvements have resulted from a combination of technology efforts on various fronts; high temperature material, better cooling, improved thermal barrier coatings, lower aerodynamic losses, and reduced leakage flow. AM has brought in new ideas and components in all of these fronts.

Specifically, AM can be adapted to the gas turbine industry at the design and prototype stages and it helps by vastly reducing the design, prototype and testing cycle time of the gas turbines from few years to few months. AM can be used to directly manufacture production parts in the areas of the turbine with non-rotating parts and lower stresses or parts with lower rotational speeds and also to indirectly make parts by improving the casting process used for making the single crystal gas turbine blades. AM can also be used for the repair of these highly expensive turbine parts there by prolonging the life and impacting the sustainability. However, AM processes used for gas turbine applications are mostly metal processes and comes with its own set of challenges such as toxicity of metal powders, powder handling challenges, size limitations, higher cost, microstructure, surface roughness issues and post processing requirements to name a few. Kaplanskii et al.[43] presented a post print treatment to enhance the life of gas-turbine rotor blades. They observed that Laser Powder Bed Fusion (LPBF) printing followed by Hot Isostatic Pressing (HIP) reduced the metal porosity, improved microstructure of the printed material, and improved thermo-mechanical properties of the finished product. They experimented and found optimum printing and post-print treatment operating conditions for different materials and powder particle sizes.

Kirsch et al. [44] used AM to make micro-scale design optimizations for efficient heat removal. At the micro-scale, the surface finish plays a significant role in the heat transfer and pressure loss of any cooling design They observed that additively manufactured cooling channels have shown the surface roughness increases both heat transfer and pressure loss to similar levels as highly engineered turbine cooling schemes. Snyder et al. [45] further expanded on the work. They have investigated the opportunities exist to tailor additively manufactured surfaces through control of the process parameters to further enhance the desired heat transfer and pressure loss characteristics.

GE changed the commercial AM landscape for gas turbine applications by using 3D printed fuel nozzles in their LEAP jet engines. It is an important milestone for production scale additive manufactured parts. GE's 'MXL2 with Additive Manufactured Performance' (MXL2 AMP) upgrade utilizes metal AM to decrease the weight and incorporate advanced cooling channel in their heat shields to significantly elevate the output and efficiency of existing GT13E2 gas turbines. According to GE Power this upgrade could reduce the component cooling requirements by up to 25%, increasing turbine output by up to 21 MW in a combined-cycle configuration, achieving additional efficiency up to 1.6% in a combined-cycle configuration, and delivering maintenance intervals of up to 48,000 hours.

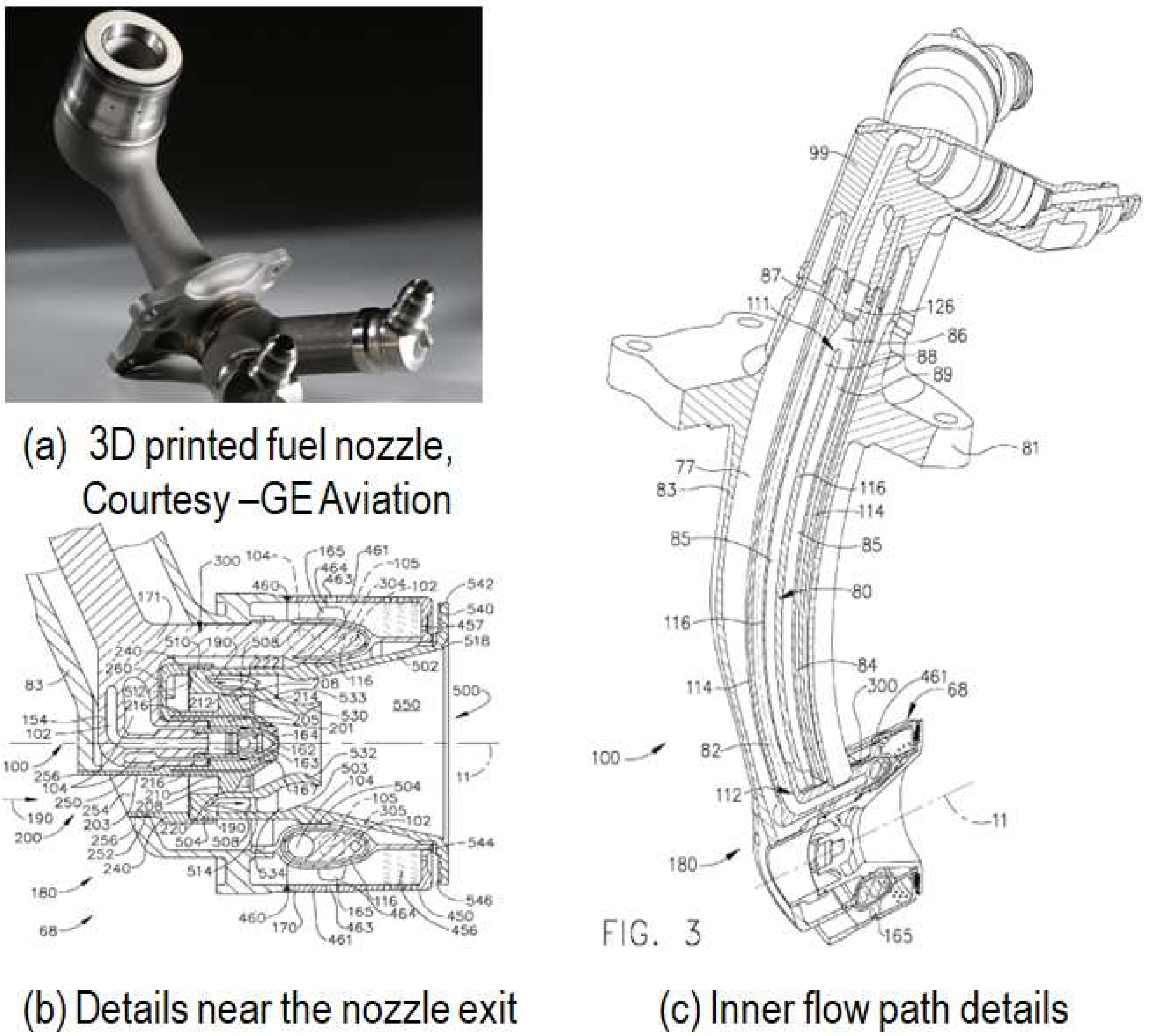


Figure 17. A successful implementation of AM in mass production is LEAP engine fuel nozzle (images [46,47])

GE aviation created a fuel nozzle for their LEAP engine. By 2018, they successfully printed 30,000 of them. This nozzle picture is widely circulated, but viewers usually marvel at the surface finish and external appearances of this palm sized part. The surface finish is not contributed by the 3D printing, but that was achieved by post-machining by conventional techniques. The 3D printing achieved the internal complex flow paths as shown in Figure 17. The actual design will perhaps not be published due to proprietary design, but some idea can be obtained from the patents published by the design group as shown. Figure 17 a and b shows the inner details and those are nearly impossible to produce economically by conventional manufacturing techniques. This component is one of the big success stories of commercial component development by AM. Since this has intricate invisible flow structures, proper design of flow testing rig is essential for successful implementation.

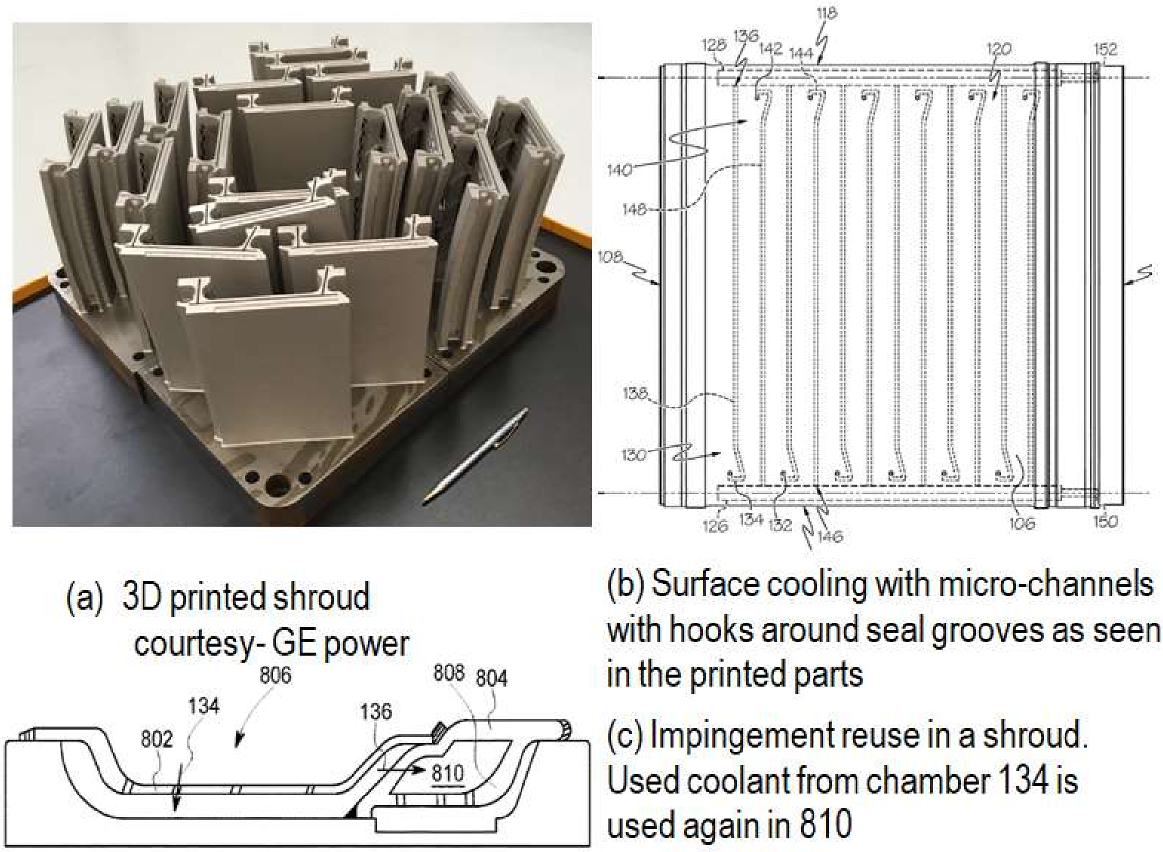


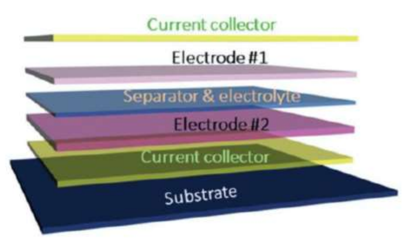
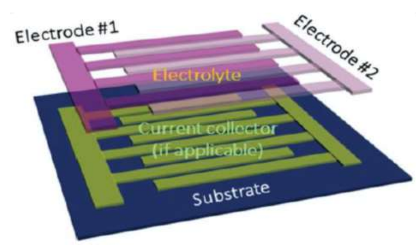
Figure 18. Advanced cooling technologies implemented in turbine heat shield[48,49]

Figure 18 shows the heat shield, also known as shroud, of a power generation turbine. These shrouds form the outer casing for the rotor blades. Like previous fuel-nozzle example, this component is suitable for AM not from external appearances but for inner intricate configurations. The details of the design are not publicly available, but two conceptual designs from that design group are added here. One is a micro-channel with complex bends around the seal groove and the other with reuse of impingement cooling air with complex backside compartmentalization. These micro channels are placed closer to the hot surface and are known as surface cooling technology. This surface cooling can also be applied on turbine airfoils. Note that the shroud has a slight curve and that is important and increases the manufacturability. It is very difficult to print perfectly flat surfaces due to thermal deformations during and after printing. The natural curvature of the surface helped with the printing process and this is another success story by AM in gas-turbine domain.

8. AM Applications for Energy storage and Solar:

Energy storage devices like battery and supercapacitors have tremendous development opportunities with AM. The small passage structures, proximity of reactants without touching each other, and need for high surface area per unit volume makes AM attractive over conventional manufacturing processes. Solar energy applications extend from photovoltaic to steam generation, which is seeing innovative channel designs with AM.

Table 2: Use of 3D printed technologies in Batteries and Supercapacitors [50]

		Sandwiched Design		**In-Plane Design**	
					
Type	**Tech**	**Materials**	**Performance**	**Materials**	**Performance**
Batteries	Inkjet printing [51,52]	Ag nanoparticles	5 mA h cm^{-2}	Reduced Graphene Oxide /Lithium Titanate /Lithium Nickel Cobalt Aluminum Oxide	0.35 mA h
	Fused deposition modelling [53]	Lithium Titanate /Lithium Manganese Oxide	3.91 mAh cm^{-3}	--	--
	Stereolithography [54,55]	Lithium Titanate / Lithium Iron Phosphate	500 µAh cm^{-2}	NiSn/ Lithium Manganese Oxide	2 µAh cm^{-2} μm^{-1}
Supercapacitors	Inkjet printing [56,57]	Polyaniline-Graphene paper	864 F g^{-1}	Reduced Graphene Oxide	0.1 mF cm^{-2}
	Direct ink writing [58]	--	--	Polyaniline / Graphene Oxide	1329 mF cm^{-2}
	Fused deposition modelling [59,60]	Polylactic acid /Graphene	485 µF g^{-1}	Acrylonitrile Butadiene Styrene /Carbon black	12 µF cm^{-2}
	Stereolithography [61,62]	Polymer/ NiP/ Reduced Graphene Oxide	250 mF cm^{-2}	Pyrolized	0.206 mF cm^{-2}

Besides the geometrical architecture of individual electrodes, 3D printed batteries and supercapacitors are mostly assembled using an in-plane or sandwiched design as shown in Table 2. Each configuration has its own advantages and disadvantages and affect the electrochemical performance of Electrical Energy Storage Devices (EESDs), and hence their application areas. For example, the sandwiched type EESDs are better suited for mass production. Whereas, in-plane designs allow minimum footprint with enhanced ionic transport, thus it is better for ultrathin film batteries or supercapacitors. Listed references in Table 2 explored potential of in-plane design and investigated the effect of electrode thickness by printing multiple layers of electrode material. They found that areal and volumetric capacitance of a supercapacitor showed a linear positive dependence with the number of printing layers. They also observed, shorter interspaces showed higher areal capacitance than the capacitors with longer interspaces. However, printing compact designs with shorter interspaces and thicker electrode layers was challenging due to the rheological properties of the conductive ink, which consisted of binders, solvents, additives and active materials. They also observed that in-plane designs were preferred when EESDs were fabricated using DIW and IJP, while sandwich designs were better for FDM and SLA-based 3D printing. They found that FDM and especially SLA based 3D printing could create form fitting devices in a single or multistep print. Whereas, IJP by comparison was essentially a bottom up planar printing process, and that limited the possible printed shapes. SLA technology could print polymer graphene based conductive substrates, which were then electro-phoretically coated to result in tri-layer sandwiched design with anode material (LTO), LiAlO2-PEO membrane and cathode material (LFP). Test results on these printed devices were very encouraging. Experimental cells cycled at 0.1C provided areal capacity of 400-500 μAh cm-2. The specific capacitance of the printed supercapacitor had 1329 mF cm−2 , which was the highest achieved to that date using DIW technique. The Graphene design exhibited high capacitance of more than 0.1 mF/cm^2 and a long life of over 1000 cycles.

Gulzar et al.[50] noted that whether its sandwiched or in-plane design, the nature of charge storage process was an important consideration before the selection of materials and method. Surface pseudocapacitive storage and electrochemical double layer capacitance benefitted from a higher surface to volume ratio, which was achieved by etching or selective decomposition of the composite printed thermoplastic or photocurable resin. This was attainable as long as the mechanical integrity of the printed object was not compromised by excessive degree of porosity, residual solvent, or overheating. Moreover, a high surface area material capable of capacitive charge storage could be built if the printed material was sufficiently electrically conductive. The 3D printing technique involved the knowledge of final device operation and material selection. This knowledge requirement was more important for a successful build when the internal volume fraction of additive material was both conductive and accessible to Li (or other) ions to maximize volumetric and gravimetric energy density or areal capacity.

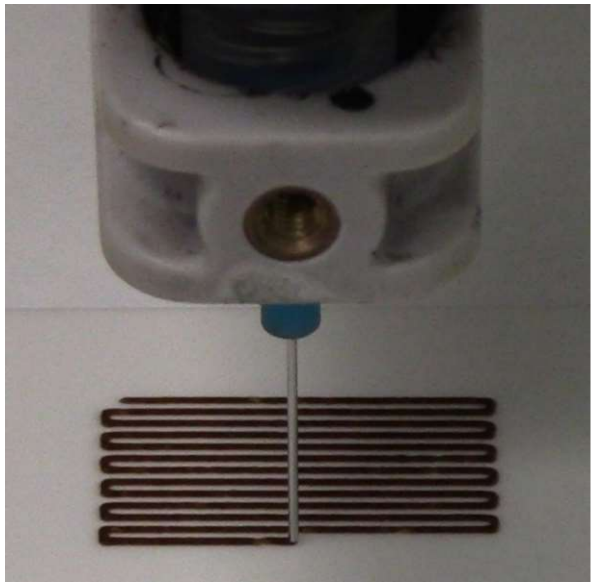


Figure 19. 3D printing with viscoelastic ink. [35]

Figure 19 shows the technique to build a high-efficiency solar steam generator. The composite inks were uniformly extruded to form microfilaments from a 305 μm diameter nozzle. 3D printing ink needs to flow well (thin) with reasonable pressure and retain the shape during printing (thick). So, there is a conflicting demand on the viscous effects and the ink rheological properties are important for material extrusion-based 3D printing fabrication. Experiments by Li et al. [35] indicated that rheological properties of their fabricated composite inks were comparable to printable inks suitable for 3D printing technique. They provided guidelines to obtain good inks for 3D printing.

Fieber et al.[63] discussed supercapacitors, especially Electro-chemical Double Layer Capacitors (EDLC); and identifies opportunities for AM in fabrication. They identified new geometric form factors, complex shaped electrodes on contoured substrates, shortened ion diffusion paths, feed material flexibility, decentralized fabrication, and on-chip printing of energy storage devices for electronic devices. There are many other applications that have already been developed or being developed but publication of those details is restricted due to the proprietary nature of the products and components. Knowledge gained through research is only meaningful if it can be successfully transferred to the next generation of young minds and that is truer than ever with everchanging technological landscape of AM. Most Engineering programs in universities now offer dedicated additive manufacturing courses, which introduce students to wide range of AM technologies. This allows students to not only be aware of existing technologies but allows them to witness the benefits and challenges of AM processes firsthand. These young engineers are already exposed to this new technical landscape; and it is expected that they will be able to adapt to this changing manufacturing protocol and will bring new economic prosperity.

9. AM applications for wind Turbines and Support Structures:

Following discussions are based on the Component development aspects related to Wind Turbines and other power-gen energy industry related products. Oak Ridge National Lab [64–66] is very active in the application of additive manufacturing in renewable energy technologies. Wind power is an inexhaustible form of energy that is being captured throughout the U.S. to power the engine of our economy. A robust, domestic wind industry promises to increase U.S. industry growth and competitiveness, strengthen U.S. energy security independence, and promote domestic manufacturing nationwide. As of 2016, about 82GW of wind capacity was installed, and wind power provided more than 5.5% of the nation's electricity and supported more than 100,000 domestic jobs, including 500 manufacturing facilities in 43 States. But those numbers were short of the targeted long-term goals. U.S. Department of Energy's (DOE's) 2015 Wind Vision study targets 35% of the nation's end-use demand to be satisfied with wind energy by 2050. To get there, significant advances are necessary in all areas of wind technologies and market development. An area that can greatly impact the cost and rate of innovation in wind technologies is the use of advanced manufacturing. AM can build complex blades customized to the wind patterns for a given location, can build towers at the installation site, and can build the heavy-duty machinery that goes inside the nacelle. Considering the tremendous promise offered by advanced manufacturing, this report identified the use of AM in the production and operation of wind energy systems. Interestingly, some applications developed with AM are not obvious, like Wang et al.[67] printed a carbon fiber mesh on the surface of a wind turbine blade. This was done to avoid lightning damage to the airfoils. This carbon fiber mesh was light weight and spread the striking current outward to the surface preventing the blade core from having major internal damages.

9.1 Manufacturing of tall structures at installation site

Gerdes [68] discussed that the enormity of the blades and tower segments make it difficult to transport the finished products on highways to the project site. A California startup, RCAM, thinks that there is a workaround to tackle this transportation problem. RCAM Technologies was recently awarded a $1.25 million grant from the California Energy Commission (CEC) to develop and test 3-D printing technology enabling the construction of concrete turbine towers at the project site. The average tower height for turbines installed in the United States is over 80 meters and getting taller. RCAM Technologies, founded by National Renewable Energy Laboratory (NREL) alumnus, will erect towers 140 meters tall or higher. The company expects that a 140-meter tower would increase electricity production by more than 20 percent for a similar sized turbine at a site with moderate wind availability. By enabling turbines to reach steadier, stronger winds, these ultra-tall towers would boost capacity factors and generate electricity at a lower cost.

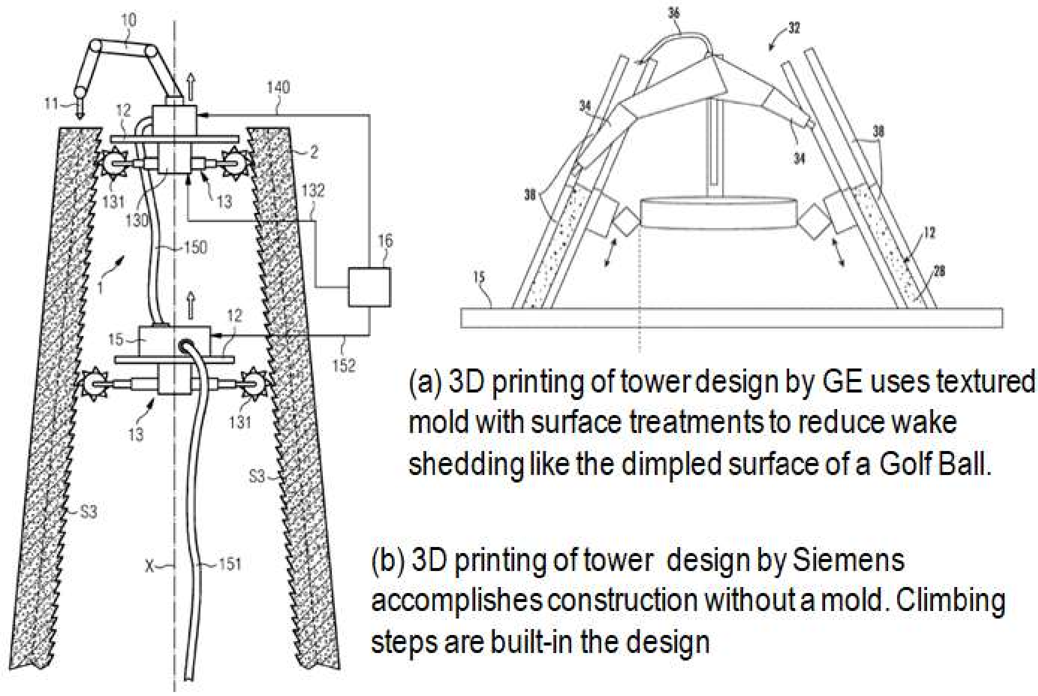


Figure 20. AM used for wind turbine column construction (images [69,70])

Figure 20 shows two different commercially viable techniques of 3d printing of the wind turbine tower. The self-climbing design builds steps so the printer and concrete supply mechanism can raise itself as it builds layer by layer. The other design uses removable molds to print a chunk at a time and can have special surface finish to create turbulent boundary layer with less wake shedding, thus reducing vibration and aerodynamic losses from the tower. IT service provider Accucode is partnering up with RCAM Technologies, a specialist in large-scale concrete additive manufacturing, to develop large-scale, 3D printed concrete structures supporting offshore wind turbines [71] The joint team will develop a 3D concrete printed wind turbine foundation that will reduce offshore deployment costs by up to $4M per foundation and $400M per wind plant.

9.2 Molds for large wind turbine airfoils

The Department of Energy's Oak Ridge National Laboratory (ORNL) worked with TPI Composites to use the BAAM (Big Area Additive Manufacturing) system to fabricate a wind turbine blade mold [72]. The fabricated wind turbine blade mold was produced in 16 additively manufactured sections, was 13 meters long, had heating channels integrated into the design, and was post fabrication mounted into a steel frame. This research effort served as a case study to examine the technological impacts of AM on wind turbine blade tooling and evaluate the efficacy of this approach in utility scale wind turbine manufacturing. ORNL has a wide campaign on promoting this technology and easily available with a literature search. There is not much to add in addition to their observations.

Goldman [73] mentioned that in production, rapid tooling with AM makes agile manufacturing feasible. Outfitting a production plant with jigs, fixtures, tools, and molds is now fast and has much less overhead which also means changing process, products, and designs has a much lower opportunity cost. AM is suitable for agile manufacturing primary because the same printer can be used for producing different parts and reconfiguring for a different part to be manufactured takes minutes instead of hours as in CNC environment (assuming the detailed drawing STL files are ready).

9.3 Components: Actual blades (mostly small scale), Heat Exchangers, Magnets

Wisconsin technology developer ADDere has demonstrated its large scale additive manufacturing capabilities with the production of a sample 5ft 11in stainless steel turbine blade produced in the course of one single 30 hour run, the blade's height maintains a tolerance within 0.5mm of its designed height, an outstanding achievement for the technology. Jackson[74] has more details on this. In addition to its 5ft 11in in height (61.32 in total) the demonstration blade produced by ADDere measured 20 in wide. This blade is hollow inside with 0.5mm wide side walls and the structure weighed 135lbs. Achieving the tight tolerances of the blade was made possible by closed loop in-situ monitoring of the process. ADDere WALS control software also handled heating, cooling and melt-flow parameters to prevent internal stresses.

With the appropriate design, wind turbines could be rapidly manufactured (printed) and assembled on-site at an as needed basis without additional tooling beyond a 3D printing machine and printing filament [75]. Authors examined the design considerations of such a wind turbine including material properties, reinforcement techniques, integration of non-printed components, printed component design and print optimization. A rapid manufacture-able design is presented of vertical axis configuration.

A miniature shrouded wind turbine aimed at energy harvesting for power delivery to wireless sensors in pipes and ducts is presented by Howey et al. [76]. The device has a rotor diameter of 2 cm, with an outer diameter of 3.2 cm, and generated electrical power by means of an axial flux permanent magnet machine built into the shroud (Fabrication was accomplished using a combination of traditional machining, rapid prototyping, and flexible printed circuit board technology for the generator stator, with jewel bearings providing low friction and start up speed.

AM is used in small devices as well. A portable micro wind turbine was made of 3D printed parts producing renewable and clean 5-volt USB power in need. By utilizing 3D printing technology, the most intricate parts of the turbine can be readily printed and accurately replicated, greatly reducing the time and cost associated with production. Print time for the necessary 3D printed parts is approximately 120 minutes. For those who live with electricity on a daily basis, this device may be indispensable when travelling to remote places. The micro turbine's 200 mm (8 inch) diameter carrying case is very portable and it can be setup in under 2 minutes. Designed to power USB devices in low wind speeds, this turbine begins making power at 2.5 m/s, reaching full 5-Watt charge at 5.5 m/s. Each micro wind turbine includes a battery pack with USB outlet for charging of cell phones, flashlights, tablets, GPS, cameras, etc. One can increase storage capacity by using personal inexpensive USB battery packs.

10. Patents in Additive Manufacturing for Energy Applications

Following items discuss the new development in product design with the availability of additive manufacturing. Three key industries are discussed, namely gas-turbine technologies, batteries, and fuel cells. Note that only publishable (not proprietary information) are discussed here as available in the public literature in the form of patent disclosures. There are many underlying reasons to come up with designs that cannot be fully disclosed without permission from the sponsoring companies.

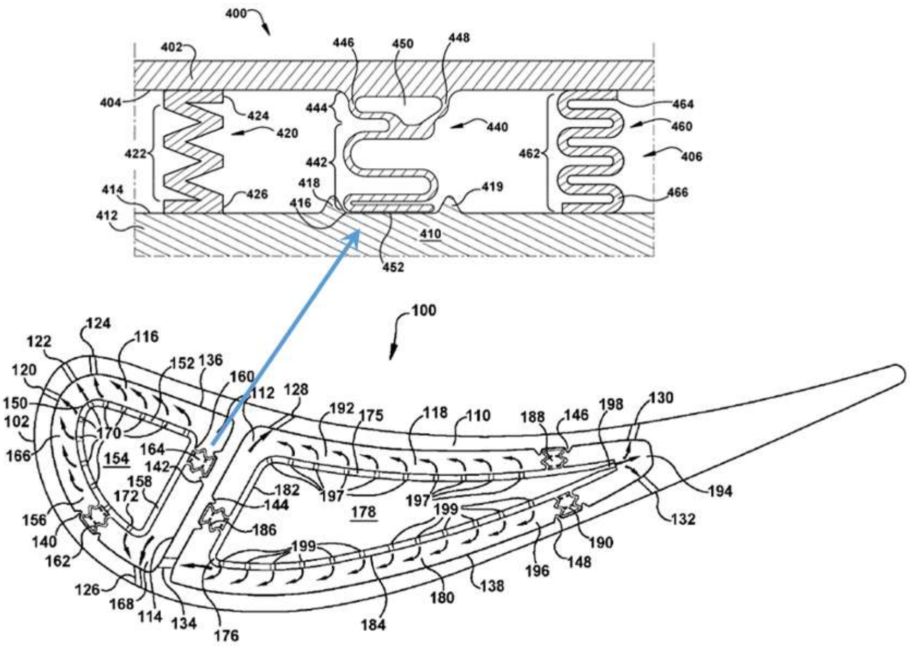


Figure 21. Compartmentalized impingement chambers in a gas-turbine. (images [77])

AM has initiated a new wave of thinking and a new design paradigm for cooling technologies. It is worth noting that the maximum possible efficiency of a gas-turbine is defined by Carnot Cycle, and that is entirely dependent on the high and cold temperature sources. The efficiency of a typical gas turbine engine increases with increasing the gas temperature entering the first stage rotor blades. It is also known as the firing temperature of a gas-turbine and obtained after the coolant mixes with the first stage stator components and thus less than the flame temperature. The AM has created opportunities to develop new cooling technologies that were not previously possible due to manufacturing restrictions or feasibility. Snider et al. [77] developed an adjustable seal as shown in Figure 21 for the impingement chamber, where the coolant are compartmentalized to provide specific cross flow direction to spent jets. Readers interested in crossflow effects are encouraged to explore heat transfer from jet arrays. These seals are formed with AM in the insert or as separate structures and were demonstrated to improve the insert positioning and controlling the flow direction and jet back pressure to provide consistent coolant distribution as designed during the entire life of the component.

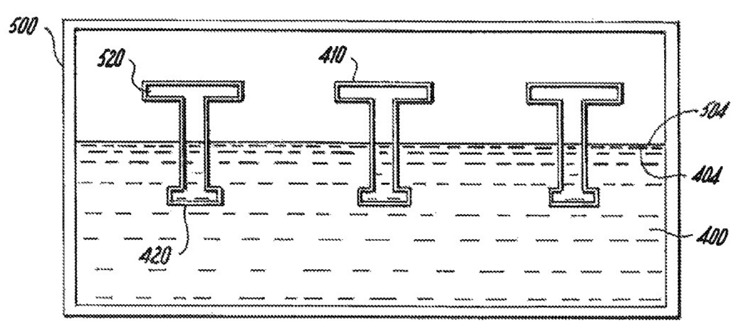


Figure 22. Innovative flow channels in fuel cells. [78]

Figure 22 shows complex flow channels in fuel cell. Brousseau [78] used design for AM to increase channel cross section area to make more reactive surface in fuel cell. The channel design cross section may not be fixed and need to adapt to mass flow changes as the mass transfer across the membrane varies with the volume flowrate of reactants. In addition, there is phase change in water causing significant volumetric and pressure effects. The figure shows one of the possible new channel cross-sections to optimize the fuel cell performance and is feasible to manufacture due to available AM technologies. We were expecting more fuel cell channel configurations available in the public literature, but most designs are protected with proprietary intellectual property rights and therefore not citable. Research done at hydrogen and fuel cell research center at the University of South Carolina [79] [80] discussed fluid flow and mass transfer in fuel cell channels. It was found that standard flow models did not work well in fuel cell channels due to several reasons. One reason was, there was mass transfer across the membrane; and the other main contributor to deviations from simple gas flow was condensation of moisture and formation of liquid water from electro-chemical reactions. Based on these flow physics, new flow channel configurations are being designed to provide optimum performance based on gas concentration and proper moisture content so that the fuel cell membrane does not dry in high current operations or does not get flooded in low current operations. It is a complex technology and interested readers are encouraged to follow citation chains based on the references provided in this paper.

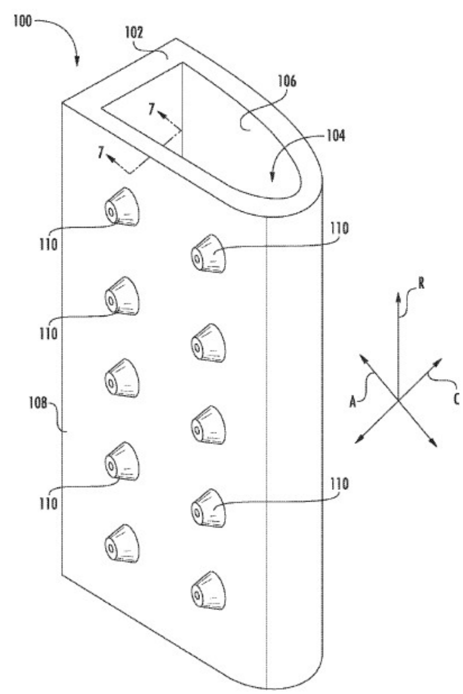


Figure 23. Special structures on the impingement insert to reduce cross flow diversion of the impingement jets [81]

Impingement inserts that develop the cooling jets inside a gas-turbine airfoil received significant attention due to ease of inclusion with AM. Any change in the main airfoil structure require an expensive casting change. But these inserts are retrofitted and can be fitted in already installed airfoils during major shutdowns and upgrades. Dutta and Hart [81] developed a technique to deliver the jet closer to the target and the jet was protected from the spent cross-flow with a structure (see Figure 23). The actual manufacturing of the horizontal holes in a vertical layer-by-layer metal printing was not easy and the patent discusses slant roof technology inside the impingement holes.

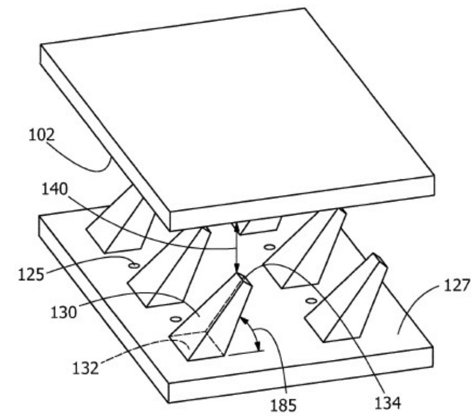


Figure 24. Heat transfer enhancing fins on the impingement inserts [82]

In another innovative design of impingement inserts, Dutta et al. [82] included fins on the insert surface. Earlier designs added these fins on the impingement target surface. This flipping of surface that contains the fins was possible only due to emerging AM techniques. Figure 24 shows that the fins were given an upward direction aligned to the build direction and successful prototypes were fabricated.

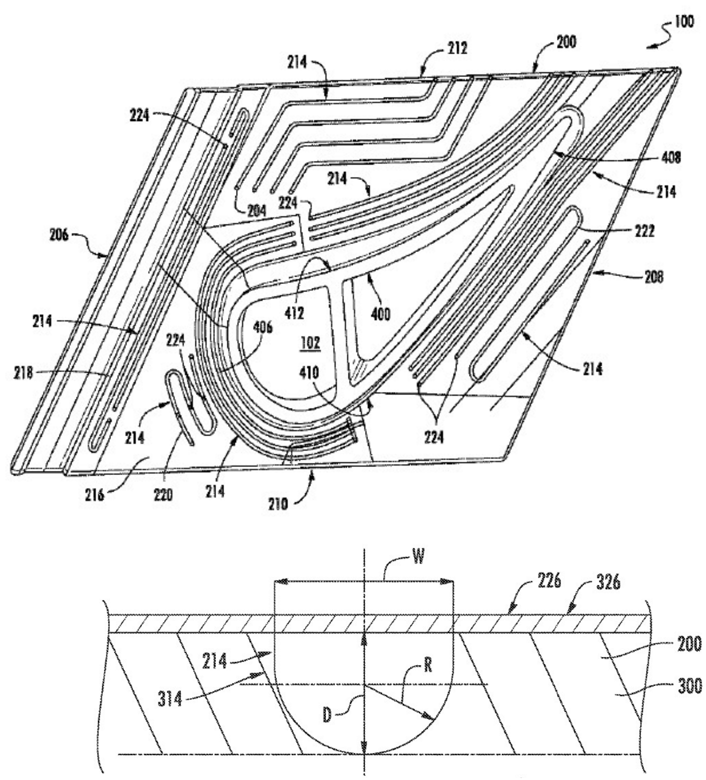


Figure 25. Innovative near surface cooling arrangement on airfoil platforms [83]

To enhance cooling of the surface locally instead of the whole component, Dutta et al. [83] developed a network of micro-channels on the heat transfer surface as shown in Figure 25. A cross-section of the cooling channel is shown. The cooling channels were flushed at the top and the channels could not be detected when the final product was built. These surface channels are suitable for AM and more difficult for the conventional machining processes. A similar surface cooling technology has been discussed for heat shields in a previous section of this paper.

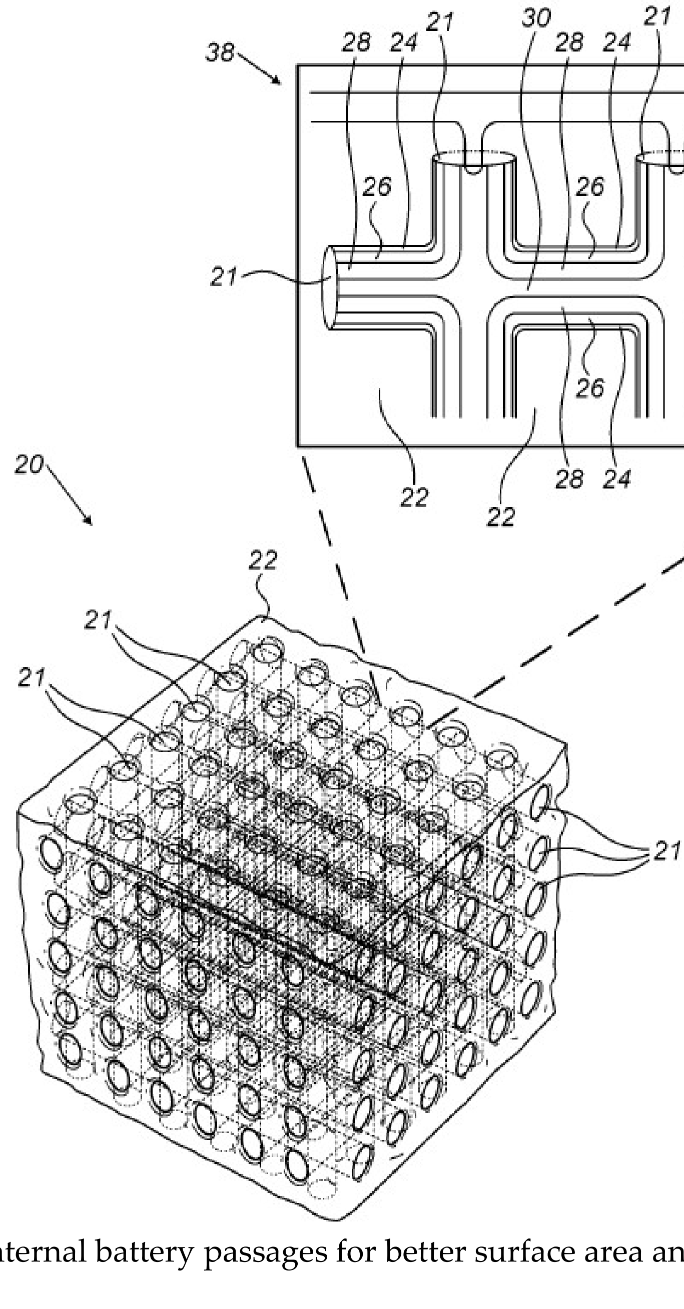


Figure 26. Internal battery passages for better surface area and temperature control. [84]

Higher surface area is crucial for efficient operation of an electro-chemical energy storage device. Golodnitsky et al. [84] developed an interesting structure with three dimensional energy storing battery that has intricate surfaces in-built to increase the surface area of electrochemical reactions. It can be seen from Figure 26 that the battery has internal cavities thus increasing surface area. Thin layers of cathode, anode, electrolyte, and current collectors are printed on the substrate with internal cavity structure. The energy density is significantly increased with increase in surface area. The connected cavities can be used for cooling fluids or it can be used for liquid batteries.

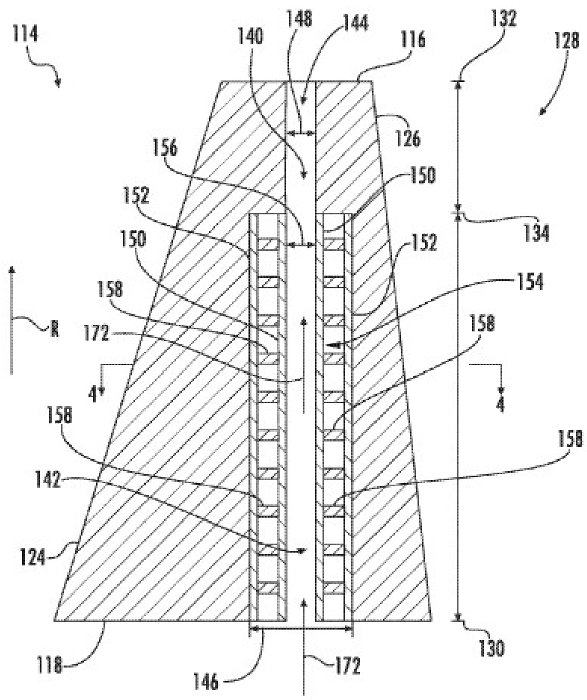


Figure 27. Thermal management of cooling channels in tall airfoils [85]

The new designs on cooling technologies that were discussed above were targeted to improve the heat transfer. There are situations where a designer wants to reduce the heat transfer. For example, Dutta and Weber [85] invented a double tube structure for long airfoils (Figure 27). If the cooling tube is long and thin, the coolant picks up heat near the entrance of the tube and locations far from the inlet cannot be cooled effectively. To cool a location at a distance, conventional designs over cools the upstream location and that is a waste of cooling power. The double tube AM structure provides an insulation from the hot airfoil base metal and thus coolant can retain its cooling effectiveness for a longer distance.

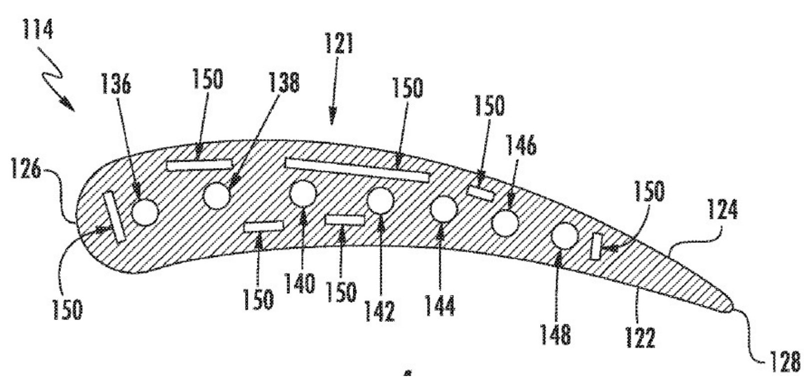


Figure 28. Heat load management to the cooling channels by adding hollow bubbles in the airfoil substrate [86]

In an attempt to preserve cooling power of coolant, Dutta and Itzel [86] developed a airfoil structure with strategically placed hollow bubbles in the metal as shown in Figure 28. The heat load is applied to the curved external airfoil surface and these bubbles disrupted the conductive path of heat from the round cooling tubes to the hot external surfaces.

11. Economic and Financial Aspects:

Following discussion focuses on the additive manufacturing from the perspective of the financial markets. Anyone with basic knowledge of NYSE knows that the industrial conglomerate General Electric Company (Ticker: GE) had a tough time recently and to survive, they dispersed several business units but invested in AM. GE is investing in additive manufacturing to prosper and grow in the future. GE 2019 Annual financial statement showed an additive reporting unit in their Aviation business segment. As of December 2019, the goodwill of that unit was $1.12 Billion. Siemens, another energy industry giant, has also identified additive as their focus in the 2019 fiscal year along with data analytics, artificial intelligence and automation. It can be concluded that additive manufacturing has become a part of the integrated industrial companies and it has reached a point of no return after significant investments.

The 3D printing technology stocks showed moderate growth in the recent past; however, the overall economy showed growth as well. The prominent 3D printing companies publish their earnings from different business segments and one can observe their yearly performances from those reports. To note a few major corporations, Protolabs (Ticker: PRLB) showed a 3D printing earnings growth to $53.3 Million in 2018 from $43.3 Million in 2017, and earnings grew further to $61.4 Million in 2019. 3D systems Corp (Ticker: DDD) indicated that a significant portion of their revenue were from outside the US activities indicating a global growth of AM business.

11.1 Growth and Sustainability

Major additive manufacturing businesses including 3D printing systems and Stratasys observed the following risks in their growth and sustainability:

- Changes in non-U.S. and US governmental policies, laws and regulations relating to business operations and investments;
- Changes in regulatory controls like data privacy, export controls, trade restrictions, tariffs and embargoes;
- Outbreaks and disruptions caused by political or civil matters, disease, terrorism;
- Variations in monetary exchange rates;
- Lack of enforcement on intellectual property;
- Different foreign work culture;
- corruption and fraud in some countries;
- Changes in tax rules;
- Changes in price or margin;
- Changes in product mix or service types;
- Disruption by new competition and technologies;
- Impairments of goodwill and intangible assets;
- Changes in the level of adoption of products and services from acquisitions and investments
- Changes in board of directors, key management;
- Changes in economic condition, liquidity, financing options;

It is hard to find a substantially big organization that has invested 100% in additive manufacturing. Most major contributors have additive in their business mix in addition to other conventional technologies. For example, Materialise (Ticker:MTLS), although a prominent AM based company, showed additive manufacturing as their one of three competencies. They observed that there exist significant risks from new competitors with possibly more efficient technologies. Sometimes, large corporations entered the competition by acquisition. They observed that the barrier to entry for software and medical markets are rapidly getting slim. Materialise's manufacturing sector revenue grew from 63.7 Million Euros in 2017 to $95 Million Euros in 2018. There was drop to 94.2 Million Euros in 2019, but the EBITDA improved from 11.4% in 2018 to 12.9% in 2019.

Even if there is risk and other concerns, there was a frenzy of activities in the past two years in AM technology improvement with the help of financial and governmental policies supporting this growth. Most of the Mechanical Engineering faculty job postings were interested in skills in AM.

Contract manufacturing company Stratasys (Ticker: SSYS) claims to have printed the following components for energy industries: Gas turbine nozzles, SSD sleeve, Sand control screens, Nozzles for downhole cleanout tool, Subsea chemical stick injection tool, Sealing accessories, Perforated pup joints, Liner hanger spikes, Drill bits, Investment casting patterns, Fluid/water flow analysis, Turbo machinery components, Jigs and fixtures, Rotor and Stator components, Mud motor modules, Flow meter parts, Pressure gauge pieces, Control-valve components, Pump manifolds, Spare parts. For the past three years, their earning from AM manufacturing and services averaged about $655 Million a year with a higher percentage coming from US operations in 2019 than that was observed in 2018 and 2017. In the annual report of 2019 (released in 2020) Stratasys pointed out that there is high demand of senior management and other key personnel related to additive manufacturing.

11.2 Recent Key Events

There has been rapid growth in AM in the past five years. Several major milestones driving additive manufacturing in the recent past are:[87,88]

- Desktop Metal entered metal 3D market with a claim of "world's fastest metal printer, delivering the lowest cost per part, is now officially in the field". It was powered by Single Pass Jetting technology; and the Production released version was more than 100x faster than quad-laser metal printers and 4x faster than similar binder jetting printer. It was also up to 20x lower cost-per-part than available metal 3D printing systems.
- SLM Solutions and British aerospace company Orbex revealed they had successfully 3D printed the largest single-piece rocket engine, which boasted 20% higher efficiency and 30% less weight than its traditionally manufactured counterpart.
- HP introduced new line of 3D Jet-Fusion printers named 5200 Series 3D printing solution. It had surplus powder reusability based and low carbon footprint per printed part for runs of 1500 or less when compared to injection molded parts. It provided up to 70% powder reusability ratio.
- Multi-material 3D printing from Inkbit with AI brought new levels of machine intelligence including closed feedback quality control to the AM process capable of delivering multi-material 3D printing. The smart vision system scanned each layer with micrometer resolution as the ink

was deposited. The smart system automatically compensated and corrected inconsistencies with the next layer.

- EOS developed Fine Detail Resolution (FDR) 3D printer Software that performed selective laser sintering (SLS) process with a CO laser with super fine detail.

- GE Additive, Oerlikon, Linde and the Technical University of Munich—formed a Bavaria based open AM cluster focused on R&D for additive technologies

- Markforged developed new AI software Blacksmith to connect manufacturing machines with a powerful Artificial Intelligence (AI) solution. Blacksmith automatically adjusted programming to ensure every part was produced as designed with a continuous feedback loop to make parts more accurate. Blacksmith learnt continually and adapted to variations in the process over the lifetime a manufacturing machine.

- nTopology introduced nTop Platform that unified design, simulation, and manufacturing data. The nTop Platform removed geometry bottlenecks in design by achieving more efficient workflows. It enabled users with lightweight parts with lattices, gyroid infill, and topology optimization.

- MSC's Apex Generative Design Software launched a new design optimization solution. It automated design processes and improved productivity by up to 80% compared to more traditional topology optimization tools.

- Jabil Materials Innovation Center provided services for developing, testing and manufacturing polymer powders and filaments for 3D printing. It had chemical reactors for polymer preparation; extrusion, precipitation and grinding for material production; and 3D printers from various builders for process development.

- Sandvik developed diamond composites for 3D printing. Mikael Schuisky, Head of R&D and Operations at Sandvik AM explained, "We now have the ability to create strong diamond composites in very complex shapes through additive manufacturing, which fundamentally will change the way industries will be able to use this material. As of now, the only limit to how this super-hard material can be shaped and used is down to the designer's imagination."

- Henkel joined SYMPA project to develop SLA materials, which would be a new photosensitive polymer with increased long-term thermal and mechanical properties. Moreover, a fiber reinforcement of the polymer and surface modification technologies suitable for automotive applications were proposed.

- IDAM is a research project that was initiated with the aim of transferring metal Additive Manufacturing technology into an industrialized and highly automated process, specifically for the automotive industry.

- AMFG partners with EOS to manage their entire additive manufacturing operations with AMFG's Manufacturing Execution System (MES)

- Stryker invests in 3D-printed implants to develop next-generation products and services across its medical surgical, orthopedics, neurotechnology, and spine units.

- Carbon raised substantial new growth funding to establish its first Advanced Development Facility (ADF) to expand in Europe and Asia. Additionally, Carbon will enhance development of recyclable and biocompatible materials. Carbon continues to work with high profile customers and recently brought to market its L1 3D printer with high volume capabilities, which has already been adopted by Adidas and Riddell.

- Sandvik got a stake in BeamIT to expand in metal components for industries such as automotive, energy and aerospace. With over 20 Powder Bed Fusion printers, the company produces parts through DMLS, EBM and SLS techniques. "The investment in Beam IT will complement our existing offer in Additive Manufacturing," said Lars Bergström, President of Sandvik Machining Solutions. "It is also in line with Sandvik's strategic ambition to become a leading solution provider for the wider component manufacturing industry."

- GKN bought Forecast 3D to offer full range of services from concept to series production.

- BASF acquired Sculpteo technologies to enhance 3D printing platform further into a global network.

- Metal Powder Industries Federation formed metal AM standards that can be applied to the characterization of powders used in metal additive manufacturing (AM) processes.

- The America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC) published the second version of its 'Standardization Roadmap for Additive Manufacturing'.

- SAE International released the first Additive Manufacturing (AM) Polymer specifications for the aerospace industry. AMS7100: Fuse Filament Fabrication Process and AMS7101: Material for Fused Filament Fabrication.

- Carbon, the Silicon Valley-based company that developed Digital Light Synthesis (DLS) 3D printing technology, installed their first 3D printed parts in production for Ford.

- Rocket Lab completed 100th 3D-Printed Rocket Engine that are built with 3D printed components using electron beam melting (EBM) technology.

- Volvo Trucks 3D prints more than 500 manufacturing tools and fixtures with Selective Laser Sintering (SLS).

- The Formlabs materials team collaborated with New Balance to develop a completely new material from the ground up for sole of sneakers.

While these were some of the most prominent milestones in 2019-2020, the AM industry continues to grow stronger and bigger; and more consolidated operations are in the drawing board. Despite of challenges and obstacles, the number of AM applications continue to grow, as more technological solutions emerge as better alternative to the previous generation components.

11.3 Energy Industry Research and Development from AM

Following are discussions by GlobalData Energy[89]. They are interesting and summarizes important activities in different energy sectors. We could not verify all the facts independently, but the overall discussion seemed reliable. 3D printing or additive manufacturing is the process of making objects from three-dimensional model data. In its current form, it is usually manufactured layer upon layer. In 2017 the 3D printing market was worth $7bn, which was up significantly from $3bn in 2013. Wohlers report estimates $15.8bn for 2020, which is more than double from 2017 valuation. Experts upped forecast of 2025 to $35bn globally from previous estimate of $20bn. AM is now used in both prototypes and in mainstream production. Following are the essence of the above referenced power-technology discussion. AM can produce complex geometries with ease with fewer raw-materials and with less or no waste. AM also usually have reduced specific energy consumption, and faster time-to-market. These advantages are beneficial to Manufacturers. AM has successfully serviced power industry and opened up new opportunities to get better at some of the previously established domains.

3D printing in the solar power industry has made significant progress. Even though technical feasibility of printed solar cells has been proven, the capacity factor (CF) is still low, which makes it difficult to attain economics of scale for large solar plants. This application is still under significant research and development. Namely, MIT researchers claimed that AM in solar panels could bring more efficiency and reduce manufacturing cost by half. 3D printed solar panels are thinner and lighter, thus helping with packaging, handling and transportation, The Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia printed rolls of solar cells with industrial 3D printers as large copy paper sized sheets. These thin and light solar panels can be mounted on the surfaces of windows and buildings and do not need elaborate mounting structures. Intensive research has produced special photovoltaic ink that are used on flexible plastic strips to build solar panels. Another example is, Australian Solar Thermal Research Initiative (ASTRI) and CSIRO developed a Concentrated Solar Plant (CSP), based on printed solar panels.

Wind energy sector is seeing increased share in the global energy supply and to sustain that it needs innovations in materials and manufacturing. Construction of large wind turbine systems at site is feasible with AM and it could address special needs for a given location. AM helps with spare parts of the discontinued wind turbine models. These parts are usually large, customized, and expensive and usually manufacturers do not maintain an inventory for repairs. Spare parts of obsolete components are a big market for additive manufacturing. Note that wind turbines are very large machines and usually are not mass produced in thousands. The US Department of Energy’s (DOE) Wind Program and Advanced Manufacturing Office has partnered with public and private organizations to innovate AM for the production of wind turbine blade molds. Conventional blade design makes full-size external skin representation of the final blade known as a plug, which is then used to make the mold. Creation of plug is one of the most time-consuming and repetitive labor-intensive processes in wind blade construction. 3D printing does a better job with fewer resources in these sophisticated CAD model reproductions of actual hardware. Another advantage is, a 3D printer could be taken on-site and "print" the blades from scratch thereby preventing damages during transportation and reduction of transportation cost.

Globally, research teams are working on 3D printing technologies to improve electro-chemical energy devices. The battery performance can be improved by changing the internal structures and optimization of electrode and electrolyte placements. Interestingly, the direction of print used in electrode manufacturing can play an important role on the performance of the device. Hamzah et al. [60] found that vertical print direction produced better electrodes than horizontal print direction. Recent advancements use ink-based writing technology to get electrodes printed on preformed surfaces. A team from Manchester Metropolitan University, UK – funded by the Engineering and Physical Sciences Research Council – is working on a project to develop an energy storage system (ESS) with conductive graphene ink. Their objective is to develop a desktop printer that can build ESS. Graphite is commonly used in Li-ion batteries; and Graphene, with better electrical and thermal conductivity, can replace graphite in these batteries to improve performance and service life. Another research team from Harvard University is using 3D printing to build a miniature version of Li-ion battery. These micro batteries were fabricated by accurately printing anode and cathode layers. This project could enable self-powered miniaturized electronics, robots, and medical implants. Researchers at the Ulsan Institute of Science and Technology in South Korea have developed a novel production technique of Lithium-Ion batteries that gets one step closer to direct electronics printing. A liquid battery that can produce energy and keep cool at the same time was developed by IBM and ETH Zurich. The team used 3D printing to produce an optimized system of micro-channels for supplying the battery with electrolytes. Optimization minimized the need for pumping power and eliminated internal high temperatures.

The US Department of Energy (DOE) financially supports and guides the development of 3D printing for energy applications. In July 2018, the DOE selected 15 R&D innovation projects related to fossil fuel power systems. One of the supported projects will explore computational support tools for optimization of heat exchangers based on micro-channel built with AM. These new heat exchangers will be used in supercritical CO_2 based power generation cycles. In another project, United Technologies Research Center will develop numerical models for the prediction of material behavior of additively manufactured nickel-based super-alloy parts in gas-turbine engines.

Large industrial companies are showing progress on adopting the AM. For example, in April 2018, Siemens produced the first 3D printed metal replacement parts for an industrial steam turbine. According to the company, this is a game-changer, as it can significantly reduce the lead time needed for procuring these low volume parts. Earlier in 2017, Siemens made and successfully tested gas-turbine AM blades in full-load engine. The company will expand additive manufacturing solutions to turbine vanes, burner nozzles, and radial impellers. Siemens acquired Materials Solutions in 2016 to expand in 3D printing. Another energy industrial behemoth, GE is also of the opinion that 3D printing is a disruptor for the energy industry in a positive way. The company has shipped more than 9,000 3D printed gas turbine components. GE will use 3D printing to further enhance their record-breaking power plant efficiencies with faster prototype fabrication and testing. An example of AM component developed by GE is the 3D printed fuel nozzles for the company's HA-class gas turbines. The nozzle helped the company push the efficiency of the turbines upwards, which is very difficult to do. GE acquired Arcam AB in 2016 to gain expertise in 3D printing.

There are several applications of 3D printing in the nuclear industry. In 2018 Rosatom, Russia's state-owned nuclear power utility, initiated the development of additive manufacturing technologies. It has already developed a pre-production prototype of a 3D printer. In 2017, Siemens successfully installed a 3D printed impeller in a fire protection pump at the Krško nuclear power plant located in Slovenia. AM can be used for producing obsolete parts that are no longer available, allowing old power plants to continue their operations with proper repairs. Westinghouse is also using AM in order to cut costs and shorten the lead times for parts that are difficult to obtain. 3D printing is gradually influencing both renewable and conventional power sectors, and battery storage devices. However, it is difficult to achieve high equipment standards required for power plants. Following items are excerpts from the investing news provided by Harwood[56].

Many startups are offering inexpensive 3D printers after the expiration of a key patent in 2009. There are several techniques, materials, build speed, and finish qualities in the broad concept of AM; and therefore, there are opportunities for specializing in different needs of AM. In 2013 retailer Staples (NASDAQ:SPLS) started selling 3D printers made by 3D Systems (NYSE:DDD) for the consumer market. This is a landmark event as it brought 3D printing into commercial market. 2016 saw large tech companies Hewlett Packard (NYSE:HPQ) and General Electric (NYSE:GE) enter the AM space. HP's Multi Jet Fusion technology is popular in 3D printing customer base. GE expanded by acquisitions namely two European companies specializing in 3D printing, Arcam AB and SLM Solutions. GE will use these resources and expertise to improve aviation components. In addition to creating parts, GE added a new opportunity in repairs with 3D printing processes. Often times, the engine components are slightly cracked or eroded, and a built-on patch can extend the life by a few thousand hours making it a viable and attractive option for the customer.

Investing News noted that a significant number of markets are adopting metal 3D printing. To name a few, Lomiko Metals (TSXV:LMR) will provide graphite to Graphene 3D Lab (TSXV:GGG). Graphene is used in 3D printing for better electrode performance. It is worth noting that Lomiko owns about ten percent of Graphene 3D Lab. Graphene is a nanomaterial and it is stronger than steel and more conductive than copper. An interesting development is extension to 4D printing, where the fourth dimension is not really time, but another manufacturing process applied on top of the 3D printing. It can be temperature, light, or vibration. Northrop Grumman's (NYSE:NOC) will develop a cross between a drone and a helicopter, known as TERN, or the Tactically Exploited Reconnaissance Node. It has a GE engine with many 3D printed components. TERN can fly both upwards and across and is being developed for the US Navy. It can convert any vessel to a drone carrier. To meet the demands of the "fast works" schedule imposed by DARPA, GE engine incorporated parts manufactured using the additive process, rather than castings that require a much longer timeframe to manufacture. These types of specialty components with low volume but expensive applications are most suitable for AM.

12. Conclusion

This paper discusses the latest development of AM in relation to the power and energy industries. Key contributions found are in wind, solar, electrochemical storage, and gas turbines. There are myriad of products developed in support of AM machines and techniques, but those were excluded here; instead we have discussed application of AM towards product development, feasibility of new designs, and change in thought process caused by this technology. The adoption of AM in energy based industries have different characteristics and incentives, and we have tried to portray them with a common theme; but note that AM technology differs significantly from one process to the other and hopefully we have been able to steer the reader in the right direction based on interests and affiliations. In wind energy, turbine components are physically big. AM helps to build them on site so that transportation logistics of extra-large components do not hinder a project or become cost prohibitive. On the other side of the size spectrum, Solar panels are small but can be built to be thinner and flexible with AM technologies, and that makes shipping to a customer and installation easier. Moreover, AM solar panels being easier to handle and with more sophisticated appearances; they are more attractive to the customer. There are many applications of AM in battery and fuel-cell technologies. AM can build the whole electrochemical package or inert structures on which these electrochemical devices can be built to have better performance with lighter weight. Gas-Turbines are one of the main drivers in the power-gen and aviation industries; and opportunities of AM based improvements are endless in this sector and perhaps essential for survival. Large industrial corporations are heavily investing in AM to improve gas-turbine technologies. Component designs in gas-turbines show that it is now possible to get ideal flow and mixing characteristics, that were not achievable merely five years ago. Engineers used to circumvent their dream designs to accommodate manufacturing limitations, which AM has eliminated to a great extent. This has rejuvenated the industry and younger generation is showing interest in joining and building a career in these professions. However, AM is also better suited for AI applications and therefore, professionals should keep that in mind as the market demand for engineers may shift quickly as software and AM machines mature with better integration and automated optimization routines. Unfortunately, we could not discuss AI in this paper due to length and scope limitations; but we plan to expand on AI in AM with more details in the near future.

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References:

1. Thompson, M.K.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R.I.; Gibson, I.; Bernard, A.; Schulz, J.; Graf, P.; Ahuja, B.; et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Ann.* **2016**, *65*, 737–760, doi:10.1016/j.cirp.2016.05.004.

2. Gibson, I.; Rosen, D.; Stucker, B. *Additive Manufacturing Technologies*; Springer, New York, NY, 2014; Vol. 17; ISBN 978-1-4939-2112-6.
3. Niaki, M. K.; Nonino, F.; Palombi, G.; Torabi, S.A. Economic sustainability of additive manufacturing: Contextual factors driving its performance in rapid prototyping. *J. Manuf. Technol. Manag.* **2019**, *30*, 353–365, doi:10.1108/JMTM-05-2018-0131.
4. Tosi, R. Enabling the uptake of large-scale additive manufacturing: Riccardo Tosi, senior research engineer at the MTC, identifies the barriers preventing future adoption of large-scale directed energy deposition in industry. *Laser Syst. Eur.* **2019**, 30–31.
5. Al-Meslemi, Y.; Anwer, N.; Mathieu, L. Environmental Performance and Key Characteristics in Additive Manufacturing: A Literature Review. *Procedia CIRP* **2018**, *69*, 148–153, doi:10.1016/j.procir.2017.11.141.
6. Yao, X.; Moon, S. K.; Bi, G. A hybrid machine learning approach for additive manufacturing design feature recommendation. *Rapid Prototyping Journal* **2017**, *23*, 983–997.
7. Baturynska, I.; Semeniuta, O.; Martinsen, K. Optimization of Process Parameters for Powder Bed Fusion Additive Manufacturing by Combination of Machine Learning and Finite Element Method: A Conceptual Framework. *11th CIRP ICME Conf.* **2017**.
8. Gu G.X., Chen C.T., Richmond D.J., Buehler M.J. (last); Chen, C.T.; Richmond, D. J.; Buehler, M. J. Bioinspired Hierarchical Composite Design Using Machine Learning: Simulation, Additive Manufacturing, and Experiment. *Materials Horizons Communication* **2018**.
9. Gobert, C.; Reutzel, E. W.; Petrich, J.; Nassar, A. R.; Phoha, S. Application of Supervised Machine Learning for Defect Detection During Metallic Powder Bed Fusion Additive Manufacturing Using High Resolution Imaging. *Additive Manufacturing* **2018**, *21*, 517–529.
10. Zhu, Z.; Anwer, N.; Huang, Q. Machine Learning in Tolerancing for Additive Manufacturing. *CIRP Annals - Manufacturing Technology* **2018**, *67*, 157–160.
11. Huang, S.H.; Liu, P.; Mokasdar, A.; Hou, L. Additive manufacturing and its societal impact: a literature review. *Int. J. Adv. Manuf. Technol.* **2013**, *67*, 1191–1203, doi:10.1007/s00170-012-4558-5.
12. Tata, K.; Fadel, G.; Bagchi, A.; Aziz, N. Efficient slicing for layered manufacturing. *Rapid Prototyp. J.* **1998**, *4*, 151–167, doi:10.1108/13552549810239003.
13. Adams, D.; Turner, C.J. An implicit slicing method for additive manufacturing processes. *Virtual Phys. Prototyp.* **2018**, *13*, 2–7, doi:10.1080/17452759.2017.1392684.
14. Verhoef, L.A.; Budde, B.W.; Chockalingam, C.; García Nodar, B.; van Wijk, A.J.M. The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach. *Energy Policy* **2018**, *112*, 349–360, doi:10.1016/j.enpol.2017.10.034.
15. Gaget, L. 3D printed solar panels: Meet the renewable energy revolution 2018.
16. Langnau, L. 5 opportunities for additive manufacturing in the Wind Energy Industry Available online: https://www.designworldonline.com/5-opportunities-for-additive-manufacturing-in-the-wind-energy-industry/.
17. Down, M.P.; Martínez-Periñán, E.; Foster, C.W.; Lorenzo, E.; Smith, G.C.; Banks, C.E. Next-Generation Additive Manufacturing of Complete Standalone Sodium-Ion Energy Storage Architectures. *Adv. Energy Mater.* **2019**, *9*, 1803019, doi:10.1002/aenm.201803019.
18. Singh, R.; Singh, H.; Farina, I.; Colangelo, F.; Fraternali, F. On the additive manufacturing of an energy storage device from recycled material. *Compos. Part B Eng.* **2019**, *156*, 259–265, doi:10.1016/j.compositesb.2018.08.080.
19. Zhakeyev, A.; Wang, P.; Zhang, L.; Shu, W.; Wang, H.; Xuan, J. Additive Manufacturing: Unlocking the Evolution of Energy Materials. *Adv. Sci.* **2017**, *4*, 1700187, doi:10.1002/advs.201700187.

20. Salonitis, K.; Jolly, M.; Pagone, E.; Papanikolaou, M. Life-Cycle and Energy Assessment of Automotive Component Manufacturing: The Dilemma Between Aluminum and Cast Iron. *Energies* **2019**, *12*, 2557, doi:10.3390/en12132557.
21. Keirstead, J.; Jennings, M.; Sivakumar, A. A review of urban energy system models: Approaches, challenges and opportunities. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3847–3866.
22. Shidid, D.; Leary, M.; Choong, P.; Brandt, M. Just-in-time Design and Additive Manufacture of Patient-specific Medical Implants. *Phys. Procedia* **2016**, *83*, 4–14, doi:10.1016/j.phpro.2016.08.002.
23. F42 Committee *Terminology for Additive Manufacturing - General Principles - Terminology*; ASTM International;
24. Khorram Niaki, M.; Nonino, F. *The Management of Additive Manufacturing - Enhancing Business Value*; 1st ed.; Springer International Publishing; ISBN 978-3-319-56308-4.
25. Moreau, C. *The state of 3D printing 2018.*; Sculpteo Annual Report; 2018;
26. Williams, H.; Butler-Jone, E. Additive Manufacturing Standards for Space Resource Utilization. *Additive Manufacturing* **2019**, *28*.
27. Carrillo, G.; Keck, D.; Martinez-Duarte, R. Mechanical Properties and Process Improvement of Tungsten Carbide Additively Manufactured with Renewable Biopolymers. *Procedia Manuf.* **2019**, *34*, 704–711, doi:10.1016/j.promfg.2019.06.226.
28. Hu, Y.; Fadel, G.M.; Blouin, V.Y.; White, D.R. Optimal design for additive manufacturing of heterogeneous objects using ultrasonic consolidation. *Virtual Phys. Prototyp.* **2006**, *1*, 53–62, doi:10.1080/17452750500271355.
29. Wohlers Associates Available online: https://wohlersassociates.com/2018report.htm (accessed on Mar 8, 2020).
30. Fu, K.; Wang, Y.; Yan, C.; Yao, Y.; Chen, Y.; Dai, J.; Lacey, S.; Wang, Y.; Wan, J.; Li, T.; et al. Graphene Oxide-Based Electrode Inks for 3D-Printed Lithium-Ion Batteries. *Adv. Mater.* **2016**, *28*, 2587–2594, doi:10.1002/adma.201505391.
31. Huang, Y.; Leu, M.C.; Mazumder, J.; Donmez, A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. *J. Manuf. Sci. Eng.* **2015**, *137*, doi:10.1115/1.4028725.
32. Al-Meslemi, Y.; Anwer, N.; Mathieu, L. Environmental Performance and Key Characteristics in Additive Manufacturing: A Literature Review. *Procedia CIRP* **2018**, *69*, 148–153, doi:10.1016/j.procir.2017.11.141.
33. Joshi, S.C.; Sheikh, A. A. 3D Printing in Aerospce and its Long-Term Sustainability. *Virtual and Physical Prototyping 10*, 175–185.
34. Kamps, T.; Lutter-Guenther, M.; Seidel, C.; Gutowski, T.; Reinhart, G. Cost- and energy-efficient manufacture of gears by laser beam melting. *CIRP J. Manuf. Sci. Technol.* **2018**, *21*, 47–60, doi:10.1016/j.cirpj.2018.01.002.
35. Li, Y.; Gao, T.; Yang, Z.; Chen, C.; Luo, W.; Song, J.; Hitz, E.; Jia, C.; Zhou, Y.; Liu, B.; et al. 3D-Printed, All-in-One Evaporator for High-Efficiency Solar Steam Generation under 1 Sun Illumination. *Adv. Mater.* **2017**, *29*, 1700981, doi:10.1002/adma.201700981.
36. Momeni, F.; Sabzpoushan, S.; Valizadeh, R.; Morad, M.R.; Liu, X.; Ni, J. Plant leaf-mimetic smart wind turbine blades by 4D printing. *Renew. Energy* **2019**, *130*, 329–351, doi:10.1016/j.renene.2018.05.095.
37. Ji, S.; Chen, B. Carbon footprint accounting of a typical wind farm in China. *Appl. Energy* **2016**, *180*, 416–423, doi:10.1016/j.apenergy.2016.07.114.
38. Liu, D.; Lippold, J.C.; Li, J.; Rohklin, S.R.; Vollbrecht, J.; Grylls, R. Laser Engineered Net Shape (LENS) Technology for the Repair of Ni-Base Superalloy Turbine Components. *Metall. Mater. Trans. A* **2014**, *45*, 4454–4469, doi:10.1007/s11661-014-2397-8.

39. Wong, M.; Owen, I.; Sutcliffe, C.J.; Puri, A. Convective heat transfer and pressure losses across novel heat sinks fabricated by Selective Laser Melting. *Int. J. Heat Mass Transf.* **2009**, *52*, 281–288, doi:10.1016/j.ijheatmasstransfer.2008.06.002.
40. US Energy Information Administration (UEI-Admin). *Net generation by energy source: Total (all sectors).*; 2019;
41. Modern Gas Turbine Systems - 1st Edition Available online: https://www.elsevier.com/books/modern-gas-turbine-systems/jansohn/978-1-84569-728-0.
42. US EPA Sources of Greenhouse Gas Emissions 2020.
43. Kaplanski, Y. Y.; Levashov, E.A.; KaKorotitskiy, A.V. Influence of Aging and HIP Treatment on the Structure and Properties of NiAl-based Turbine Blades Manufactured by Laser Powder Bed Fusion. *Additive Manufacturing* **2020**, *31*.
44. Kirsch, K.L.; Thole, K.A. Numerical Optimization, Characterization, and Experimental Investigation of Additively Manufactured Communicating Microchannels. *J. Turbomach.* **2018**, *140*, doi:10.1115/1.4041494.
45. Snyder, J.C.; Thole, K.A. Effect of Additive Manufacturing Process Parameters on Turbine Cooling.; American Society of Mechanical Engineers Digital Collection, 2019.
46. McMasters, M. A. et al. Fuel Nozzle 2014.
47. Benjamin, M.A. et al. Fuel Nozzle Structure for Air Assist Injection 2017.
48. Lacy, B.P. et al. Turbine Shroud Including Cooling Passages in Communication with Collection Plenums 2020.
49. Sezer, I. et al. System and Method for Shroud Cooling in a Gas Turbine Engine 2020.
50. Gulzar, U.; Glynn, C.; O'Dwyer, C. Additive manufacturing for energy storage: Methods, designs and materials selection for customizable 3D printed batteries and supercapacitors. *ArXiv191204755 Cond-Mat Physicsphysics* **2019**.
51. Saleh, M.S.; Li, J.; Park, J.; Panat, R. 3D printed hierarchically-porous microlattice electrode materials for exceptionally high specific capacity and areal capacity lithium ion batteries. *Addit. Manuf.* **2018**, *23*, 70–78, doi:10.1016/j.addma.2018.07.006.
52. Hahn, R.; Ferch, M.; Tribowski, K.; Kyeremateng, N.A.; Hoeppner, K.; Marquardt, K.; Lang, K.-D.; Bock, W. High-throughput battery materials testing based on test cell arrays and dispense/jet printed electrodes. *Microsyst. Technol.* **2019**, *25*, 1137–1149, doi:10.1007/s00542-019-04368-5.
53. Wei, T.-S.; Ahn, B.Y.; Grotto, J.; Lewis, J.A. 3D Printing of Customized Li-Ion Batteries with Thick Electrodes. *Adv. Mater.* **2018**, *30*, 1703027, doi:10.1002/adma.201703027.
54. Fu, K.; Wang, Y.; Yan, C.; Yao, Y.; Chen, Y.; Dai, J.; Lacey, S.; Wang, Y.; Wan, J.; Li, T.; et al. Graphene Oxide-Based Electrode Inks for 3D-Printed Lithium-Ion Batteries. *Adv. Mater.* **2016**, *28*, 2587–2594, doi:10.1002/adma.201505391.
55. Sun, K.; Wei, T.-S.; Ahn, B.Y.; Seo, J.Y.; Dillon, S.J.; Lewis, J.A. 3D Printing of Interdigitated Li-Ion Microbattery Architectures. *Adv. Mater.* **2013**, *25*, 4539–4543, doi:10.1002/adma.201301036.
56. Chi, K.; Zhang, Z.; Xi, J.; Huang, Y.; Xiao, F.; Wang, S.; Liu, Y. Freestanding Graphene Paper Supported Three-Dimensional Porous Graphene–Polyaniline Nanocomposite Synthesized by Inkjet Printing and in Flexible All-Solid-State Supercapacitor. *ACS Appl. Mater. Interfaces* **2014**, *6*, 16312–16319, doi:10.1021/am504539k.
57. Li, J.; Mishukova, V.; Östling, M. All-solid-state micro-supercapacitors based on inkjet printed graphene electrodes. *Appl. Phys. Lett.* **2016**, *109*, 123901, doi:10.1063/1.4962728.
58. Wang, Z.; Zhang, Q.; Long, S.; Luo, Y.; Yu, P.; Tan, Z.; Bai, J.; Qu, B.; Yang, Y.; Shi, J.; et al. Three-Dimensional Printing of Polyaniline/Reduced Graphene Oxide Composite for High-Performance Planar Supercapacitor. *ACS Appl. Mater. Interfaces* **2018**, *10*, 10437–10444, doi:10.1021/acsami.7b19635.

59. Foster, C.W.; Down, M.P.; Zhang, Y.; Ji, X.; Rowley-Neale, S.J.; Smith, G.C.; Kelly, P.J.; Banks, C.E. 3D Printed Graphene Based Energy Storage Devices. *Sci. Rep.* **2017**, *7*, 1–11, doi:10.1038/srep42233.
60. Bin Hamzah, H.H.; Keattch, O.; Covill, D.; Patel, B.A. The effects of printing orientation on the electrochemical behaviour of 3D printed acrylonitrile butadiene styrene (ABS)/carbon black electrodes. *Sci. Rep.* **2018**, *8*, 1–8, doi:10.1038/s41598-018-27188-5.
61. Xue, J.; Gao, L.; Hu, X.; Cao, K.; Zhou, W.; Wang, W.; Lu, Y. Stereolithographic 3D Printing-Based Hierarchically Cellular Lattices for High-Performance Quasi-Solid Supercapacitor. *Nano-Micro Lett.* **2019**, *11*, 46, doi:10.1007/s40820-019-0280-2.
62. Park, S.H.; Kaur, M.; Yun, D.; Kim, W.S. Hierarchically Designed Electron Paths in 3D Printed Energy Storage Devices. *Langmuir* **2018**, *34*, 10897–10904, doi:10.1021/acs.langmuir.8b02404.
63. Fieber, L.; Evans, J.D.; Huang, C.; Grant, P.S. Single-Operation, Multi-Phase Additive Manufacture of Electro-Chemical Double Layer Capacitor Devices. *Additive Manufacturing* **2019**, *28*.
64. National Laboratory, O.R. 3D printed tool for building aircraft achieves Guinness World Records title 2016.
65. Wootton, S. GE Additive and Oak Ridge National Laboratory Sign Cooperative Research and Development Agreement Available online: https://www.ge.com/additive/press-releases/ge-additive-and-oak-ridge-national-laboratory.
66. Mann, M.; Palmer, S.; Lee, D.; Kurup, P.; Remo, T.; Jenne, D.S.; Richardson, B.S.; Love, L.J.; Post, B.K. *The Current State of Additive Manufacturing in Wind Energy Systems*; Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), 2017;
67. Wang, B.; Ming, Y.; Zhu, Y.; Yao, X. Fabrication of Continuous Carbon Fiber Mesh for Lightning Protection of Large-Scale Wind-Turbine Blade by Electron Beam Cured Printing. *Additive Manufacturing* **2020**, *31*.
68. Gerdes, J. Is 3-D Printing the Solution for Ultra-Tall Wind Turbine Towers? Available online: https://www.greentechmedia.com/articles/read/is-3d-printing-the-solution-for-ultra-tall-wind-turbine-towers (accessed on Mar 8, 2020).
69. Keller, H. Method of Constructing a Tower 2017.
70. Cooper, G.E. Method for Manufacturing Wind Turbine Tower Structure for Preventing Vortex Shedding 2020.
71. 3D Printing for Offshore Wind Turbines Introduced Available online: https://www.oedigital.com/news/474179-3d-printing-for-offshore-wind-turbines-introduced (accessed on Mar 8, 2020).
72. Post, B.K.; Richardson, B.; Lind, R.; Love, L.J.; Lloyd, P.; Kunc, V.; Rhyne, B.J.; Roschli, A.; Hannan, J.; Nolet, S.; et al. *Big Area Additive Manufacturing Application in Wind Turbine Molds*; Austin, TX: University of Texas, 2017;
73. Goldman, J. Additive Manufacturing in Blade Production | Wind Systems Magazine.
74. Inside ADDere's 30 hour 3D printed turbine blade Available online: https://3dprintingindustry.com/news/inside-adderes-30-hour-3d-printed-turbine-blade-158040/.
75. Bassett, K.; Carriveau, R.; Ting, D.S.-K. 3D printed wind turbines part 1: Design considerations and rapid manufacture potential. *Sustain. Energy Technol. Assess.* **2015**, *11*, 186–193, doi:10.1016/j.seta.2015.01.002.
76. Howey, D.A.; Bansal, A.; Holmes, A.S. Design and performance of a centimetre-scale shrouded wind turbine for energy harvesting. *Smart Mater. Struct.* **2011**, *20*, 085021, doi:10.1088/0964-1726/20/8/085021.
77. Snider, Z.J.; Dutta, S.; Hart, K.M. Additive manufactured seal for insert compartmentalization 2018.
78. Brousseau, G.M. Additive manufacturing for fuel cell flow fields 2016.

79. Dutta, S.; Shimpalee, S.; Van Zee, J.W. Three-dimensional numerical simulation of straight channel PEM fuel cells. *J. Appl. Electrochem.* **2000**, *30*, 135–146, doi:10.1023/A:1003964201327.
80. Dutta, S.; Shimpalee, S.; Van Zee, J.W. Numerical prediction of mass-exchange between cathode and anode channels in a PEM fuel cell. *Int. J. Heat Mass Transf.* **2001**, *44*, 2029–2042, doi:10.1016/S0017-9310(00)00257-X.
81. Dutta, S.; Lacy, B.P.; Itzel, G.M.; Snider, Z.J. Impingement insert for a gas turbine engine 2018.
82. Dutta, S.; Weber, J.A.; Lacy, B.P. Impingement insert 2019.
83. Dutta, S.; Lacy, B.P.; Weber, J.A.; Stevens, P.G. Turbine nozzle with inner band and outer band cooling 2018.
84. Golodnitsky, D.; Kosa, G.; Kamir, Y.; Blanga, R.; Rosen, E.; Cohen, E. 3D Micro-Battery on 3D-Printed Substrate 2018.
85. Dutta, S.; Weber, J.A. Turbomachine rotor blade 2018.
86. Dutta, S.; Itzel, G.M. Turbomachine rotor blade pocket 2018.
87. 25 Key Milestones Driving Additive Manufacturing in 2019. *AMFG* 2019.
88. Major Milestones for Additive Manufacturing Companies | INN. *Invest. News Netw.* 2017.
89. GlobalData Energy 3D printing and the power industry: How technology is transforming the sector 2019.