Sustainability in Additive Manufacturing

Current status and roadmap to transparent AM

A fair comparison of AM vs. conventional manufacturing
BERNHARD LANGEFELD
SENIOR PARTNER, ROLAND BERGER

atomization of powders in particular consumes large amounts of energy before the material can be used in an AM machine. Metal ingots are melted and dispersed by a hot, high-speed inert gas stream to form spherical powders of a certain particle size. These particles then need to be sieved to retain an optimal particle size distribution – producing large amounts of scrap powder in the process. Moreover, additive manufacturing requires long processing times, normally in the range of a couple of hours for polymers, though metal powder bed fusion parts can take up to a week. Processing also presupposes an inert gas atmosphere, electricity to heat the build room and machine operation during printing. The process gases themselves are obtained via gas separation, which is itself very energy-intensive. In addition, AM fabrication is always followed by one or more post-processing steps that further enlarge the environmental footprint of the AM part.

All industries and technologies face a rising need to mitigate environmental impact and reduce CO₂ emissions. As an increasing number of companies across almost every sector commit to carbon neutrality or net-zero CO₂ emissions in the decade(s) ahead, additive manufacturing (AM) too must play its part in ensuring a more sustainable future. Sustainability is not only about reducing CO₂ emissions: recycling, renewable raw materials and waste mitigation are other important issues, along with all other aspects of the environmental, social and governance dimensions. Throughout this article, the reduction of CO₂ emissions therefore serves merely as an example to showcase AM’s contribution to the environment going forward and developing AM further as Next Generation Manufacturing technology.

At first glance, AM seems to be the perfect technology for responsible manufacturing, with a minimal impact on the environment. Building parts additively and therefore using only the material genuinely required for each part, with no waste, seems an ideal way to save resources. The reality, however, perhaps falls short of this lofty ambition. Almost all AM technologies require materials that have already undergone an additional processing step (see figure 1). The most relevant AM polymer material classes – polymer powders, filaments and resins – have previously been converted thermally or chemically, which requires energy and therefore adds a debit entry to their CO₂ emissions ledger. Similarly, metal AM materials such as metal powders and wires must first be atomized into particle-shaped powders or drawn into wires. The gas atomization of powders in particular consumes large amounts of energy before the material can be used in an AM machine. Metal ingots are melted and dispersed by a hot, high-speed inert gas stream to form spherical powders of a certain particle size. These particles then need to be sieved to retain an optimal particle size distribution – producing large amounts of scrap powder in the process. Moreover, additive manufacturing requires long processing times, normally in the range of a couple of hours for polymers, though metal powder bed fusion parts can take up to a week. Processing also presupposes an inert gas atmosphere, electricity to heat the build room and machine operation during printing. The process gases themselves are obtained via gas separation, which is itself very energy-intensive. In addition, AM fabrication is always followed by one or more post-processing steps that further enlarge the environmental footprint of the AM part.

Everyone thinks that additive manufacturing (AM) avoids waste and is kind to the environment. But what about the waste incurred when preparing powders, filaments and resins for use in AM processes? Not to mention the energy consumed and the further (in)efficiencies in the process? A new Roland Berger report scratches below the surface and shows that, for all its ability to go where conventional manufacturing has never gone before, additive manufacturing has the potential to get greener – and a lot more transparent. AM part production often has a larger carbon dioxide footprint than conventionally manufactured processes, though this unbalance can be richly offset during the downstream use phase – even more so if AM further improves its green credentials. All this, however, must be communicated to (potential) users, so the industry must first take the trouble to produce accurate life cycle analyses. Only then can customers know how climate-friendly AM really is and what value it genuinely adds. And only then will doors open to new areas of application that currently remain firmly closed. Roland Berger’s four-step roadmap shows the way.

How sustainable is AM today?

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How green is Additive Manufacturing?

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AM vs. conventional

Life cycle analysis

“While most AM manufacturing techniques require additional energy during the material and production phase, the significant benefits of AM in the use phase result in improved overall energy consumption.”

TIM FEMMER
PROJECT MANAGER, ROLAND BERGER

"Given this situation, a part produced using AM starts its life – i.e. before entering the usage and recycling phases – with a larger environmental footprint than a part manufactured conventionally on a per-kilogram and per-process-step basis. To date, the AM industry has seldom published entire life cycle analyses (LCAs) for AM parts or compared them with the conventional manufacturing route (see figure 2). Yet a fair LCA is vital to prove whether AM genuinely has a lower environmental impact than a conventional part. There is a problem, however: how do you compare the two manufacturing trajectories when AM can create parts that are impossible to produce with conventional techniques? Indeed, these “impossible” areas are where AM is making the fastest advances. Processing AM parts yields an energy disadvantage when comparing 1 kg of material in each process step of the production chain (see figures 1 and 2). However, the ratio changes for the example of a titanium aerospace bracket. This part showcases the fact that, thanks to the intelligent use of AM capabilities, parts that are impossible to produce with conventional processes can decrease a part’s environmental footprint not just in the early life cycle phases, but also during the downstream product use phase. Additive manufacturing is expected to deliver similar energy reduction effects in areas such as advanced cooling for vanes in gas turbines, which makes the gas turbines more effective and therefore again saves fuel. It is this “going beyond” the realms of the conventional that also justifies the additional cost that AM usually incurs compared with conventionally manufactured parts (see figure 4). Many industries are already benefiting from AM fabrication features and capabilities of the technology. To this end, Roland Berger has developed a four-step roadmap for AM as a sustainable manufacturing technology."

The four steps are:

1. Make the environmental footprint of AM materials, machines and processes more transparent;
2. Develop an LCA database especially for the usage and recycling phases;
3. Predict environmental impact before printing;
4. Take action to reduce the environmental footprint of AM (see figure 5).
Our roadmap toward greener AM

1. Make the environmental footprint of materials and processes more transparent

Existing AM users receive no information about how large the environmental footprint of their AM part could eventually be. Little information is provided about the AM materials that are printed. We investigated and found that only one supplier disclosed the CO₂ intensity for polyamide 12, whose fabrication generates approximately 7.8 kg of CO₂ per kilogram of AM powder. But apart from this, little detailed analysis is available about the environmental impact of the AM process – in particular about the post-processing chain (heat treatment, build platform separation, support removal, hot isostatic pressing, surface modification treatment, etc.). To increase the level of transparency, AM material manufacturers should estimate the amount of CO₂ emitted during AM material production and include it as one of the technical parameters in their product datasheets. AM machine manufacturers should follow suit, indicating the hourly environmental cost of operating their equipment for predefined process parameters. Additionally, stakeholders in the AM value chain should jointly develop a standard method to report the energy and CO₂ intensity of each link in the production and post-processing chains. This will give AM users visibility about the environmental implications of choosing different AM materials and items of equipment. It will also give them basic data with which to estimate the energy and CO₂ footprint of their AM part. Complementary information about possible recycling and zero-waste options would further enhance a sustainable customer experience.

2. Develop a suitable life cycle analysis database

Whether it is manufactured conventionally or using AM, the material production phase is the main driver of the CO₂ emissions of any part. On the other hand, it is the end-of-life phase – and especially the product use phase – that determine whether an AM part can reduce its overall CO₂ emissions compared with a conventional part. The requisite LCAs are published only sporadically, however, because of the level of detail that must be compared and the time and resources needed to produce them. In the future, comprehensive LCA databases should be available to verify energy consumption and CO₂ emissions throughout a product’s life cycle. Fair comparisons of the value added by AM are also needed. While there is a direct correlation between weight reduction in AM parts and fuel savings for moving parts (in the air or on the ground), it is less clear whether a similar relationship exists between the value added by AM and the LCA benefits. This notional correlation must be fleshed out on a case-by-case basis.

3. Predict environmental impact before printing

AM can produce parts that cannot. This must be accounted for in any comparison.

MAX SCHAUKELLIS
SENIOR CONSULTANT, ROLAND BERGER

AM saves energy for an aerospace bracket

Benefits of AM: less material needed and weight reduction

<table>
<thead>
<tr>
<th>Parts weight [kg]</th>
<th>Buy-to-fly ratio [kg/kg]</th>
<th>Raw materials production</th>
<th>AM materials manufacturing</th>
<th>Product manufacturing</th>
<th>Product use</th>
<th>End of life (inventory or recycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original shape conventional part</td>
<td>Original shape conventional machined part</td>
<td>Higher energy consumption of conventional part</td>
<td>1,500</td>
<td>Δ analysis</td>
<td>-10</td>
<td>-100</td>
</tr>
<tr>
<td>Original shape AM part</td>
<td>Optimized shape AM part</td>
<td>Less energy consumption of AM part</td>
<td>24,000</td>
<td>Δ analysis</td>
<td>-3</td>
<td>-20</td>
</tr>
</tbody>
</table>


Image Credits: Courtesy of GE Additive
**AM use cases for sustainability**

**figure 4**

<table>
<thead>
<tr>
<th>Description</th>
<th>AM technology</th>
<th>Addressed LCA step</th>
<th>Benefits of AM vs. conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace bracket</td>
<td>L-PBF</td>
<td>Product use</td>
<td>Weight and material</td>
</tr>
<tr>
<td>Conventional design (upper) and AM lightweight designed bracket for commercial aircraft from titanium</td>
<td>Metal</td>
<td>Product manufacturing</td>
<td>AM parts reduced buy-to-fly ratio of about 10:1 to 1:1</td>
</tr>
<tr>
<td>Recycled material AM</td>
<td>SLS</td>
<td>End of life</td>
<td>Material efficiency</td>
</tr>
<tr>
<td>Parts printed with 100% recycled PA12 polymer powder, recycling source is the unsintered AM powder</td>
<td>Polymer</td>
<td></td>
<td>With all subtractive manufacturing techniques in general there is more excess material needed compared with additive technologies</td>
</tr>
<tr>
<td>Custom eyewear</td>
<td>SLS</td>
<td>AM mat. manuf.</td>
<td>Material waste</td>
</tr>
<tr>
<td>Frames produced additively via powder SLS from PA and subsequent coloring customized to user</td>
<td>Slurry SLS</td>
<td>Product use</td>
<td>AM eyewear shows up to 58% lower CO2</td>
</tr>
<tr>
<td>Gas turbine parts</td>
<td>L-PBF</td>
<td>Product use</td>
<td>Fuel efficiency</td>
</tr>
<tr>
<td>Gas turbine blade made from nickel chrome superalloys with internal cooling channels</td>
<td>Metal</td>
<td>Product use</td>
<td>Vanes and fuel burner tips can be optimized via AM</td>
</tr>
<tr>
<td>Reactor autoclave</td>
<td>L-PBF</td>
<td>AM mat. manuf.</td>
<td>Fewer reactants needed</td>
</tr>
<tr>
<td>High-pressure reactor for autoclaving made from 316L stainless steel for applications up to 225 bar</td>
<td>Metal</td>
<td>Product use</td>
<td>Freedom of design enables better chemical reaction control leading to fewer reactants</td>
</tr>
<tr>
<td>Door shaft</td>
<td>L-PBF</td>
<td>Product use</td>
<td>Parts integration</td>
</tr>
<tr>
<td>Latch shaft made from titanium via L-PBF for door of A350 XWB commercial aircraft</td>
<td>Metal</td>
<td>AM mat. manuf.</td>
<td>10 conventionally made parts could be integrated in 1 single AM part</td>
</tr>
<tr>
<td>Bus spare parts</td>
<td>SLS</td>
<td>Product use</td>
<td>On-demand production</td>
</tr>
<tr>
<td>Visible polymer PA parts for premium buses stored digitally and produced based on demand</td>
<td>Polymer</td>
<td>End of life</td>
<td>Digital spare parts warehouses in combination with decentralized on-demand production decrease transport/warehouse needs significantly</td>
</tr>
</tbody>
</table>

Source: Roland Berger

**Seven AM use cases showing the added value of AM for an LCA**

**I** Weight reduction

**II** Material recycling

**III** Over-production

**IV** Fuel efficiency

**V** Reactor efficiency

**VI** Parts integration

**VII** Digital inventory/localized product
Once transparency has been established,

Additive manufacturing was not initially conceived of as a “green” technology. When the first AM machine was commercialized in 1986, the intent was to build parts and geometries that were impossible with subtractive techniques, not a manufacturing solution to reduce CO2 emissions. And in the three and a half decades that followed, AM has seen rapid development and progress. Emissions have not been optimized, of course, but initial steps toward this goal can be prioritized even without in-depth LCAs. The AM-specific energy and emission contributors are AM material production and AM part production, while the benefits of AM are seen in the product use phase.

The producers of AM materials – powders, filaments, resins and wires, for example – need to identify and address their main sources of emissions. One immediate step would be to replace the fossil fuel energy inputs in their processes with renewable alternatives, as this would cut emissions directly. Another would be to implement measures to increase energy efficiency in the process (such as by recovering heat wherever possible). Another long-term initiative would involve R&D around AM materials derived from alternative raw materials (e.g. plant-based fibers as reinforcements instead of glass and carbon fiber) and/or around chemical methods that generate less pollution.

To reduce emissions during the production of AM parts, AM machine manufacturers can achieve a lot by optimizing the rate of powder recycling, reducing inert gas consumption and optimizing the build-job preparation software that, together with other parameters, defines the necessary support structures. Furthermore, more-stable AM processes would diminish the need for testing and inspection. Upgrades such as in-process, layer-by-layer monitoring could prove the absence of porosity and – using X-rays and CT scans, for example – avoid extensive and expensive non-destructive testing, which also comes with its own environmental cost. Finer build jobs that result in nearer net-shape parts can also shorten post-processing steps if the overall AM process time is not extended. In this way, post-processing steps such as chemical surface modification and machining could be reduced, leading to lower costs and emissions.

"AM parts must be designed and engineered with a specific 3D-printing value-add in mind so that their energy consumption and embodied CO2 are minimized and their business case is optimized."

MIGUEL LÓPEZ
CONSULTANT, ROLAND BERGER

Reduce AM’s environmental footprint

4

"When the business case improves, the emissions will likely improve as well."

TIM FEMMER
PROJECT MANAGER, ROLAND BERGER

Why is sustainability in Additive Manufacturing so important?

Bernhard Langefeld: Sustainability is a top priority for companies today with focus on (total) CO2 emissions, with regard to bio-compatibility but as well recycling and zero waste. We see more and more companies from the consumer goods industry addressing these questions systematically when selecting a production technology and associated supply chain. Sustainability is therefore also a critical part of our Next Generation Manufacturing framework. Additive Manufacturing can have a huge impact on Scope 1 emissions (material usage) and Scope 3 (use phase) as explained in this study.

How can Additive Manufacturing improve the ESG rating of a company?

Bernhard Langefeld: Every time a manufacturing technology is chosen to produce a part and Additive Manufacturing is on the list of possible choices, the overall emissions should be taken into account. Here a fair life cycle analysis of the part made with conventional technologies or Additive Manufacturing reveals the impact to especially the E of the ESG rating. Critical here is to look at the entire part’s life from raw material to recycling. As well 3D printing often is a key enabler for local production, addressing short transport ways and fast delivery, which positively impacts transport emissions.

Additive Manufacturing is still expensive, will sustainability make it even more costly compared with conventional techniques?

Tim Femmer: Our research shows that this is very unlikely. Two aspects are critical here, first of all, if less raw material from AM directly reduces material costs and emissions are reduced simultaneously. Second, during the use phase of the part, the advantages of Additive Manufacturing usually make the difference. When the AM part performs better than a conventional one, it is most likely also better from an emissions point of view, especially when it is a moving component in the air or on land. The drivers for the AM business case and the AM emissions case follow the same logic.

"The real work begins"

Sustainable Additive Manufacturing

Roland Berger
The roadmap toward AM as a sustainable manufacturing technology

A four-step approach

1. **Gain Transparency of Materials and Processes**
   - Understand energy demands end-to-end, from raw materials to final produced part, incl. recycling
   - Indicate specifics for different materials, AM production processes and post-processing techniques used

2. **Develop a Suitable Life Cycle Analysis Database**
   - Develop fair benchmark of AM (incl. added value) vs. conventional manufacturing routes
   - Based on (1), further consider parts/products use, recycling and disposal
   - Also analyze further dimensions of environmental, social and governance impacts

3. **Predict Environmental Impact Before Printing**
   - Based on (1) and (2), develop a predictive tool to estimate environmental impact of AM part/product before production, incl. estimated product use phase and end-of-life phase for carbon dioxide emissions and other environmental impacts

4. **After Gaining Transparency, the Real Work Starts – Mitigate AM Harm to the Environment**
   - Address main drivers on carbon dioxide sources in the AM process value chain
   - Further improve key AM aspects to realize AM benefits in product use phase
   - Intensify the effort in recycling techniques for AM, both in-process (powder, inert gases) and at end of life

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**Save money and carbon dioxide**

- **Analogy between AM part business case and carbon dioxide emission**

<table>
<thead>
<tr>
<th>AM parts business case</th>
<th>AM parts carbon dioxide emission</th>
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</thead>
<tbody>
<tr>
<td>Lower material cost</td>
<td>Process CO₂ reduction Less energy consumed in AM material production</td>
</tr>
<tr>
<td>Saved costs for, e.g., powder atomization, AM material production</td>
<td></td>
</tr>
<tr>
<td>Less material purchased</td>
<td>Lower CO₂ for material production Less energy and waste during production</td>
</tr>
<tr>
<td>Less material needed</td>
<td>Process and usage CO₂ reduction Fewer assembly steps</td>
</tr>
<tr>
<td>Lower manufacturing cost</td>
<td>Lower manufacturing cost Fewer manufacturing and assembly steps</td>
</tr>
<tr>
<td>Increased productivity and material efficiency</td>
<td></td>
</tr>
</tbody>
</table>

- **AM materials manufacturing**
  - AM material processing efficiency incl. powder recycling
  - High conversion rate from raw material to final part (e.g., buy-to-fly ratio)
  - Parts integration, batch flexibility and mass customization
  - AM printing process improvements (e.g., faster build-speed, fewer supports/less inert gas)

- **AM printing process**
  - Weight reduction of parts
  - AM parts geometry optimization (integrated cooling channels, etc.)
  - AM-enabled new part functionalities (e.g., parts integration, chemical reaction enhancement)

- **End of life (disposal)**
  - Prevention of overproduction (e.g., digital warehousing, mass customization, etc.)

- **Increased revenue**
  - Topology optimization as functional benefit
  - Higher parts efficiency and sales price Better parts performance with added value
  - Increased revenue Broad application, improved performance, lower material costs

- **Part and usage CO₂ reduction**
  - Lighter parts save, e.g., energy, fuel
  - Usage CO₂ reduction (e.g., higher efficiency)

- **AM materials recycling**
  - Lower warehousing/waste removal cost Lower inventory levels, waste levels
  - Less wasted CO₂ in products/processes Less waste, less storage/movement

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Sources: Roland Berger
Globalization was yesterday; it’s time to localize production. Make supply chains broader, for regional cost differences and existing capacity restraints. Consequently, increased use of local production will replace expert know-how, and data is replacing local-for-local production. However, there will still be limitations due to crisis. As companies consider sourcing decisions, there will be renewed emphasis on prioritizing local-for-local production. There are two major trends that will be crucial to mitigating the risks highlighted by the pandemic. The first is the trend toward regionalization and digitalization. The second is the shift toward sustainability-driven innovation: How sustainability will change manufacturing, and who will pay? (Photo FIT Additive Manufacturing Group)

Open up your operations
Integration platforms and bidding platforms offer new ways of working together. Value chains are being deconstructed and production franchised.

Perfect your value chain
Aim for simplicity and maximize resilience. Shorten your value chains to localize production. Make your value chains broader, for shared operations and for better load balancing across ecosystems.

Embrace digital
We are entering an age of “mirror worlds” — representations of the real world in digital form. Virtual Reality 4.0 has arrived. You can now not only test products virtually, you can even simulate their future fields of application.

Reorchestrate value generation
Globalization was yesterday; it’s time to make supply chains again. Resources are scarce and you must adapt your use of them to their availability. Consumers have increasingly local requirements.

Accelerate the learning game
It’s all about data: data-driven learning is replacing expert know-how, and data is forming the basis of your decisions.

Further readings

Next Generation Manufacturing
Next Generation Manufacturing gets ready to roll
After a long, slow ride, manufacturing is about to get exciting again

Additive Manufacturing
New business models and comprehensive product innovation
Polymer additive manufacturing
De-risking your supply chains
Taking metal 3D printing to the next level
Beyond powder bed — AM on the brink of industrialization

Sustainability
Climate Action
A new competitiveness paradigm
Sustainarama
How sustainability will change the world in 2050
Innovate and industrialize
Offshore wind energy
Hydrogen
Transporting the fuel of the future
Green steel
The race is on
Roland Berger, founded in 1967, is the only leading global consultancy of German heritage and European origin. With 2,400 employees working from 35 countries, we have successful operations in all major international markets. Our 52 offices are located in the key global business hubs. The consultancy is an independent partnership owned exclusively by 250 Partners.

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