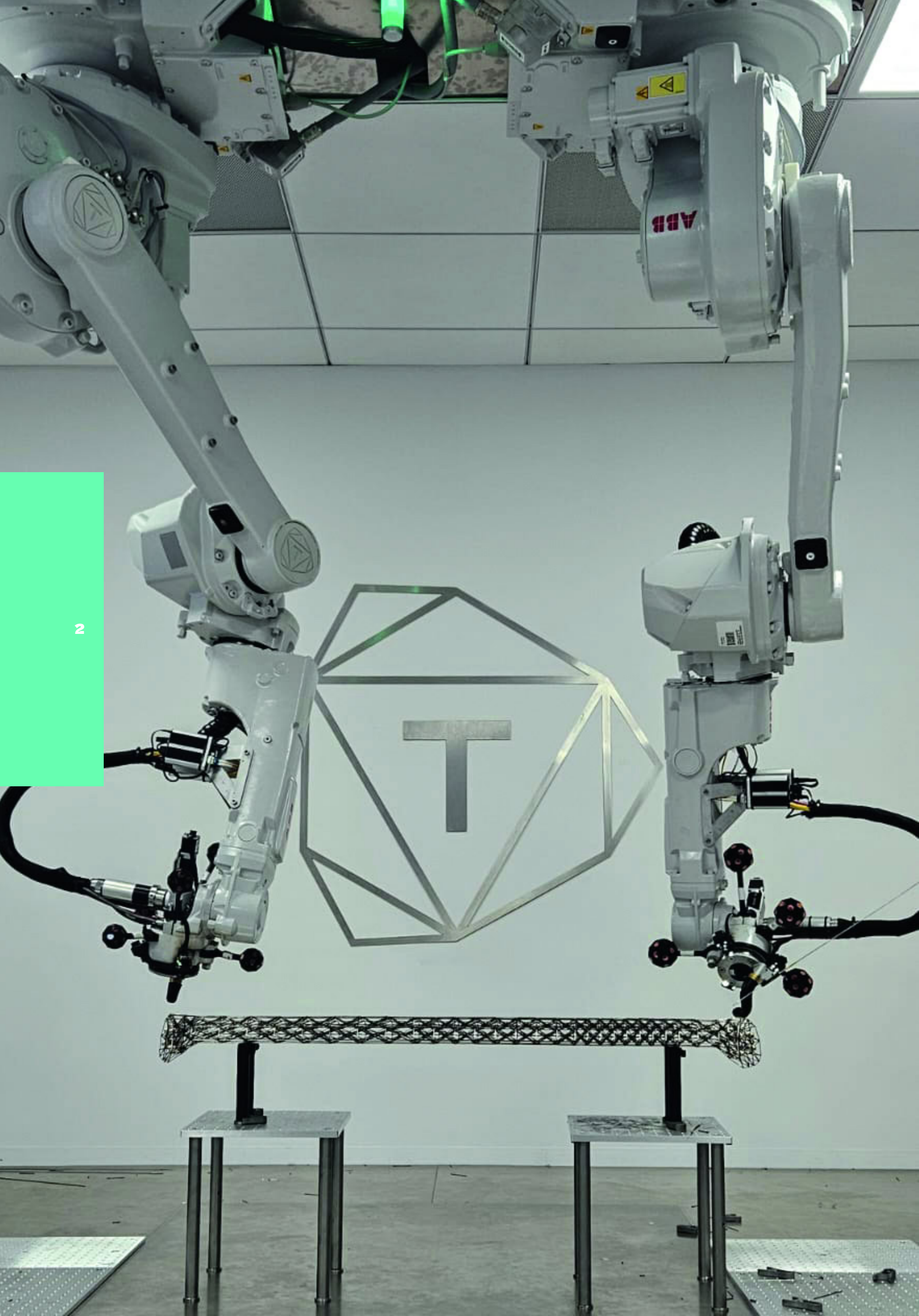
Study Report
January 2025

Energy consumption in Adaptive Space Lattice Manufacturing

TETMET



introduction

Adaptive Space Lattice Manufacturing (ASLM) is a recent development in non-printing metallic-based additive manufacturing processes, exploring alternative venues for the fabrication of non-standard, highly performing components. Instead of melting and layering materials, it assembles solid rods in any direction using laser spot welding, as shown on Figure 1. The robot places the rod at a predetermined location, the laser beam welds it at one end and cuts it at the other end. The cut is obtained by melting the cross-section of the rod at the cut point with the laser and pulling on it with a robot motion before it solidifies. ASLM appears as a promising metallic-based AM process given the preservation of material integrity it enables, and the material savings allowed by the truss geometries fabricated. Furthermore, as the energy consumption of the process is condensed in short spikes as the laser welds rods, it is assumed to be much lower than any other metallic-based AM process.

The present report provides a comprehensive study of the energy consumption of Adaptive Space Lattice Manufacturing (ASLM), confirming the insights on energy savings that existing use cases have hinted to. Associated energy costs are evaluated and compared with other metallic-based AM processes - machining, casting, powder-based AM and wire-based AM. Starting with measures of the energy consumption on site, a comprehensive study is performed across different units of measure (kWh/kg, kWh/rod, kWh/m3, kWh/I-beam). An energy breakdown is provided, including a material-process balance assessment through the integration of material embodied energy. Finally, the impact of design opportunities offered by ASLM is studied, evaluating various unit-cells lattice geometries across a sensitivity study.

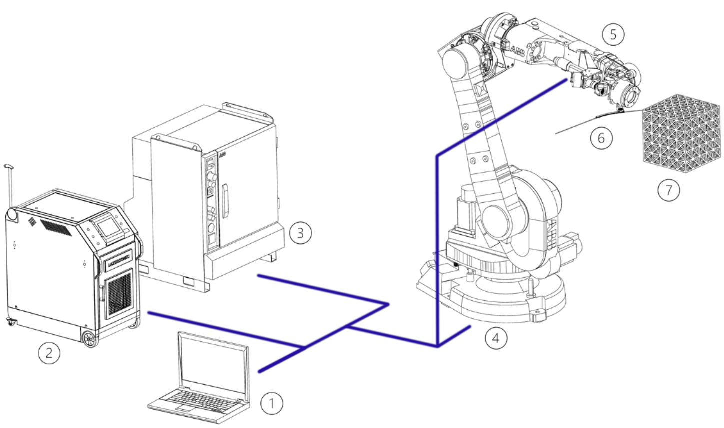
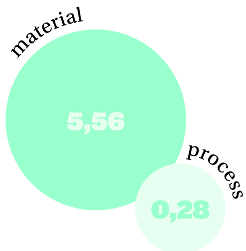


Figure 1. Schematics of the ASLM process: 1. system control, 2. laser source, 3. robot controller, 4. 6-axis robot, 5. laser beam steering, 6. wire holder, 7. ASLM-produced structure.

40%
save on material

90%
save on energy

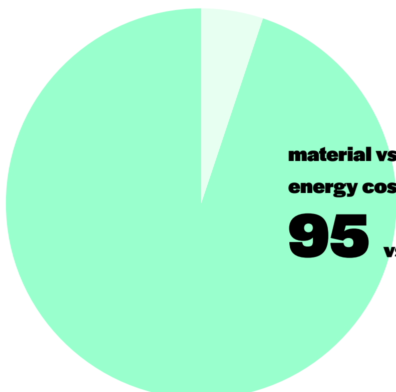
96%
save on time



energy footprint

5,84 kWh / kg

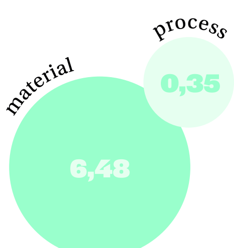
the ASLM process uses up to 99,7% less energy than other AM processes



material vs process energy costs

95 vs **5** %

the ASLM rods have a 3x lower embodied energy than metallic AM powders



carbon footprint

6,83 kg CO_2 eq. / kg

1:10
energy saving potential with lattice unit-cell design optimization.

summary of results

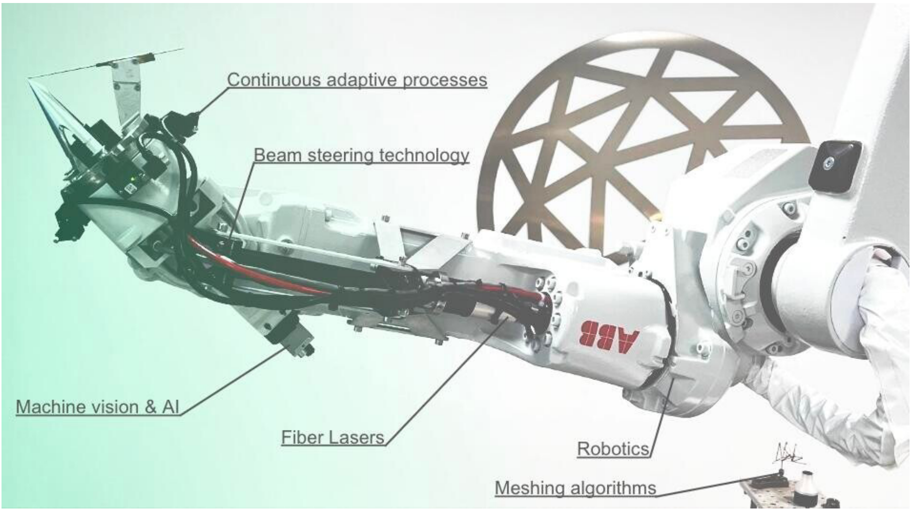


Figure 2. (previous page) Overview of results

Figure 3. (above) Overview of the Tetmet ASLM process

Results show the very significant reduction of energy consumption in the ASLM process compared to other metal forming processes, from 67,5% to 99,7% of reduction depending on the technology it is compared with, and from 88,6% to 99,7% of reduction compared to other steel AM technologies.

As part of these energy savings, ASLM allows for the use of more environmentally affordable resources: the embodied energy of steel rods is three times inferior to the steel powder used in other AM processes. Energy savings are also associated with significant time gains, as the detailed comparison with L-PBF demonstrates ASLM to be 96,4% faster.

The ASLM process is able to produce a large range of various truss configurations, based on different lattice cells and with differentiated scales made possible. The study of impacts associated with different lattice configurations highlights 1:10 energy consumption differences.

contents

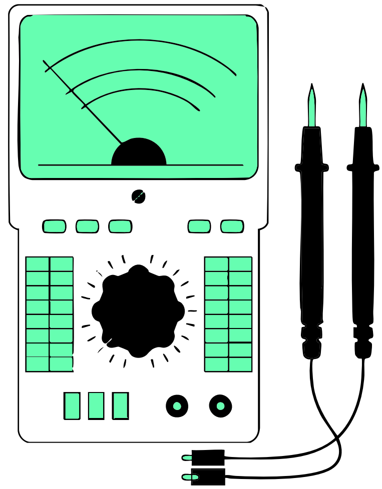
methods

key references

Bekker, A.C. M., & Verlinden, J.C. (2018). **Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel**. Journal of Cleaner Production, 177, 438-447. Faludi, J., Baumers, M., Maskery, I. and Hague, R. (2017), **Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate?**. Journal of Industrial Ecology, 21: S144-S156. Galjaard, S., Hofman, S., Perry, N., Ren, S. (2015). **Optimizing structural building elements in metal by using additive manufacturing**. In Proceedings of IASS Annual Symposia (Vol. 2015, No. 2, pp. 1-12). International Association for Shell and Spatial Structures (IASS). International Organization for Standardization: ISO 14040-14044.

Investigations into metallic-based additive manufacturing (AM) have been increasingly successful over the past decade in developing processes and applications for vairous industries. However, research has also shown the significant impact of such manufacturing processes on the environment, particularly their high energy consumption. While conventional manufacturing techniques for metals are already energy-demanding, digital fabrication processes increase the demand even further. Moreover, in AM processes the power can represent up to 80% of the impacts, in comparison to the materials and machine, making this aspect instrumental. Despite enabling a customization of parts that can play a key role in optimizing components, the high energy demand requested by metallic AM processes questions their potential in industrial applications. As such, the energy demand is an already well-studied aspect for other AM processes than ASLM, and existing studies provide a methodological framewok upon which the assessment presented in this report relies.

The research considers energy costs assessed over A1-A3 phases according to the ISO 14040-14044 framework. Preliminary results are also presented regarding greenhouse gas emissions associated to electricity use and to raw material production. The latter is achieved by relying on data found in prior literature. Key references mobilized are presented in each section.



On-site energy measure

As the focus of the research is to understand the energy footprint of ASLM, notably to compare it to other metal forming processes available on the market, a key aspect in methods selections is to enable the obtention of data usable in such comparison. Therefore, aligning with methods of measure adopted in other research regarding the energy footprint of metal forming processes and digital metal forming processes is the chosen starting point. A large part of the literature on the evaluation of energy consumption in an environmental perspective relies on on-site measures with a wattmeter. In particular, existing studies have chosen this method to evaluate the energy footprint of wire-arc additive manufacturing, a major process to compare ASLM to. Furthermore, on-site wattmeter measures allow to examine the breakdown of the energy footprint between different parts of the system as well as the energetic cost of idle time periods. This precision in understanding the repartition of energy costs is instrumental in bettering the environmental impacts of the process and in leveraging environmental assessments to achieve energy savings.

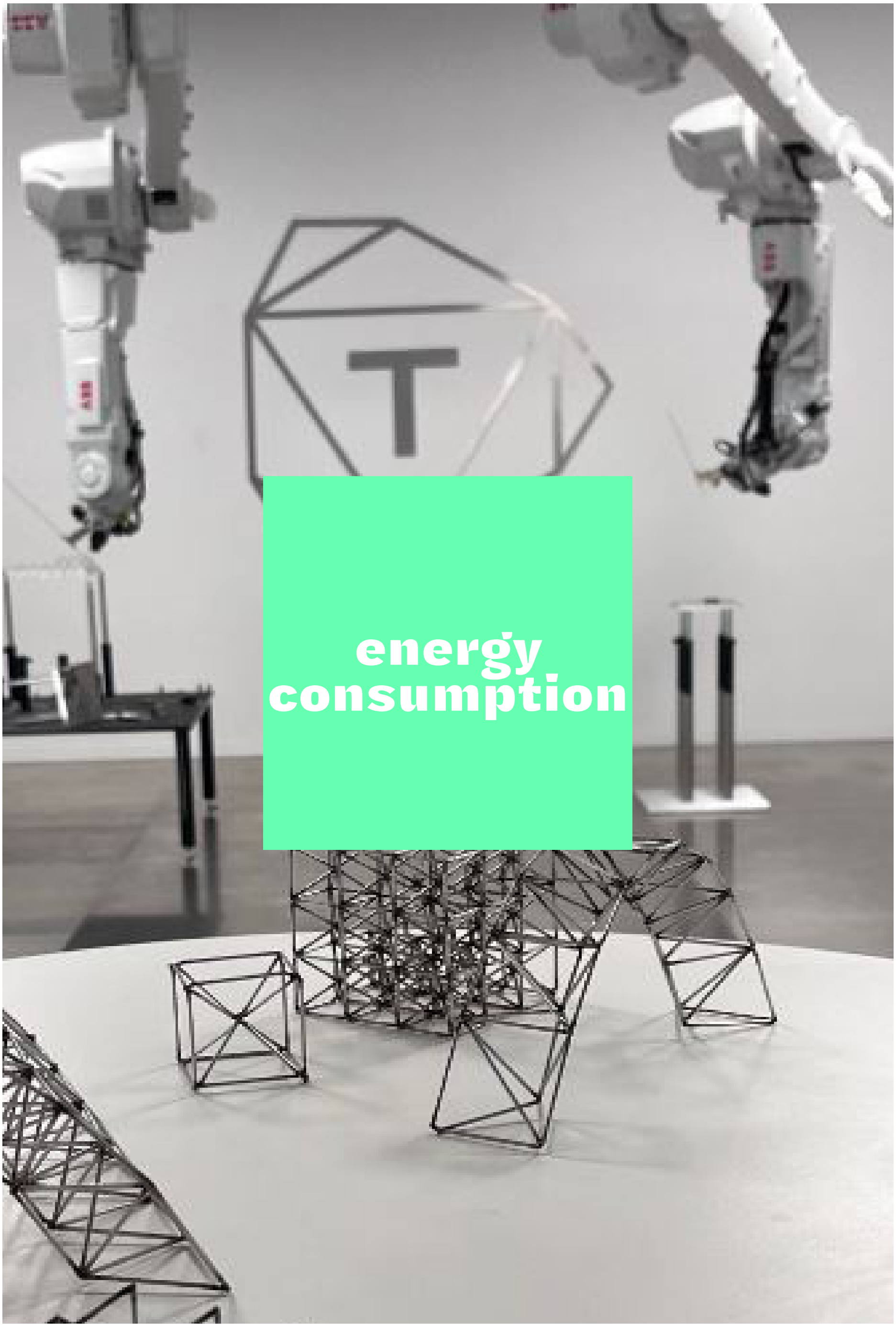
Assessed units

Several units have been evaluated to be used in the assessment. Existing literature on the topic commonly performs assessments per kg of matter processed, including beyond assessments specific to metal forming or to digital fabrication techniques. Therefore, to align with the state of the art and obtain comparable data, evaluating impacts per kg of matter processed is considered as first unit in this report.

However, it is also common to perform the assessment for volumes of matter (m^3). Given the nature of the ASLM process and the material scarcity it leverages, evaluating impacts per m^3 of matter not only allows for comparisons with existing data in the literature, it also is a more relevant unit to understand the process itself. It is therefore the second unit considered in the report.

Finally, while measuring impacts per rod of matter used is unusual in the literature and does not allow to establish direct comparisons with other processes assessed, it is the basic unit of ASLM. This makes it a relevant unit to examine, not for comparison to other forming processes, but to understand how to guide design principles based on environmental impacts within ASLM. Also because of this particularity of ASLM, some results are presented detailing the specific type of unit-cell considered in the lattice, as well as the number of rods and density that the use of such unit-cell entails. Given the high changeability of this parameter, a sensitivity study for the various type of unit-cells available is also performed in the last part of the report to examine its impact in greater detail.

energy consumption



1kg

5,88

Energy footprint (kwh/kg)

1m^3

29,6

Energy footprint (kwh/kg)

1 rod

0,0007

Energy footprint (kwh/kg)

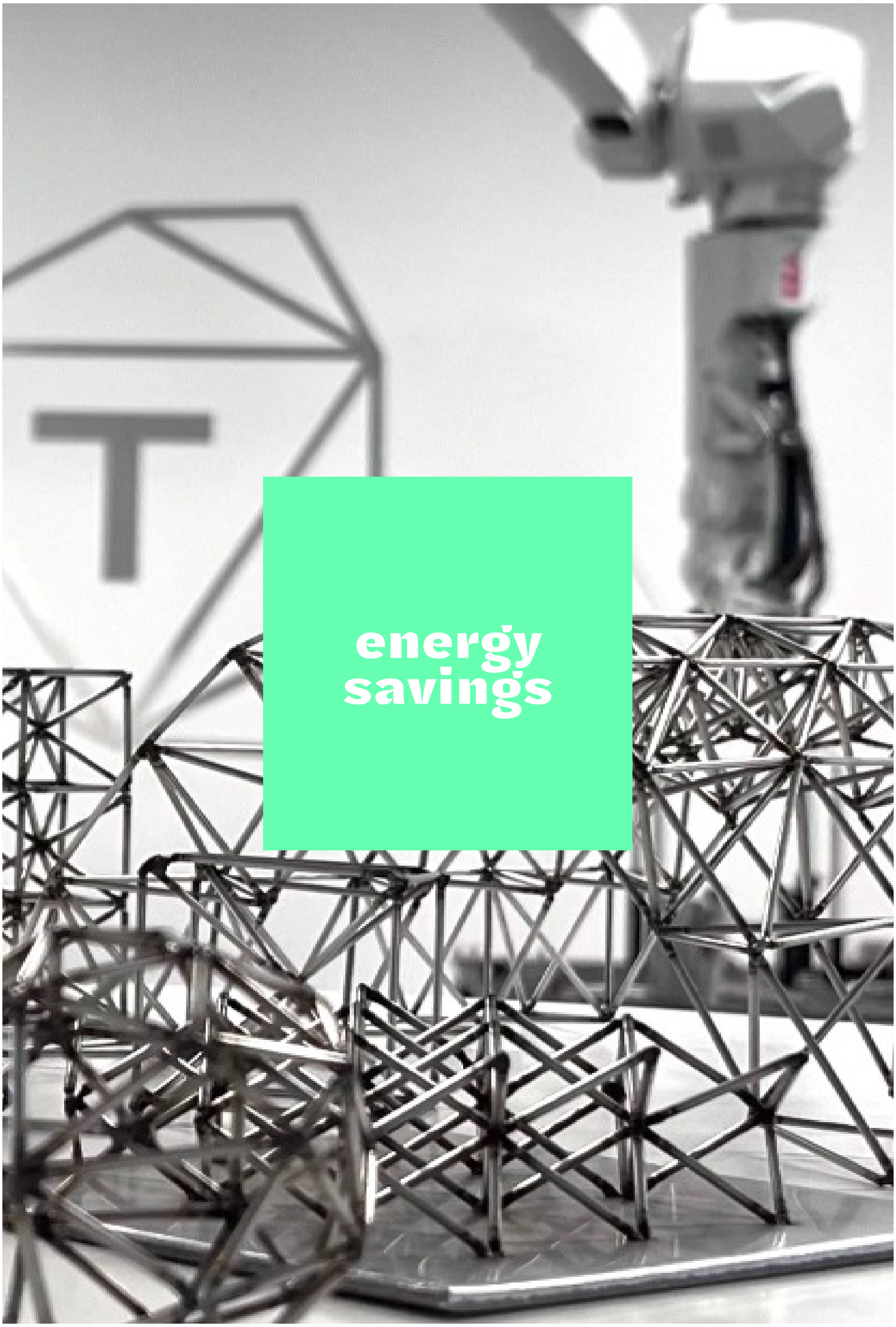
	Embedded energy (kWh/unit)	Process energy (kWh/unit)	Total energy cost (kWh/unit)
1 kg	5,60E+00	2,80E-01	**5,88E+00**
1 m^3	2,82E+01	1,41E+00	**2,96E+01**
1 rod	4,82E-04	2,32E-04	**7,14E-04**

Table 1. Energy footprint per unit assessed

	Material GHG emissions (kg CO_2 eq./unit)	Process GHG emissions (kg CO_2 eq./unit)	Total GHG emissions (kg CO_2 eq./unit)
1 kg	6,15E+00	3,50E-01	**6,50E+00**
1 m^3	3,10E+01	1,76E+00	**3,28E+01**
1 rod	5,29E-03	1,39E-05	**5,31E-03**

Table 2. Carbon footprint per unit assessed

Table 1 presents the energy footprint per unit assessed, calculated based on the on-site measurements performed at the Tetmet facility. Table 2 presents the carbon footprint per unit assessed, calculated considering 6,00E-02 kg CO2 eq. / kWh for the French energy mix (based on data by Carbone 4).



energy savings

	Energy footprint for 1 kg (kWh)	Energy saved (%)
ASLM	0,28	-
Wire Arc Additive Manufacturing	2,46	88,6
Laser Directed Energy Deposition	82	99,7
Casting	2,96	90,5
Fine Machining	0,86	75,9
Selective Laser Sintering	14,5	98,1

Table 3. Energy footprint comparison with other metal forming processes

Table 3 presents a general comparison between adaptive space lattice manufacturing and other metal forming processes. The data presented in the first column relies on a direct comparison of the energy footprint by considering kWh consumed per kg of material processes published in the literature. Discrepancies might exist in the system boundaries for each of the assessments relied on depending on the methodological specificities of energy consumption measure in each publication. This section therefore requests further evaluation to confirm preliminary results. The second column presents energy savings performed by ASLM in comparison to each of the other assessed processes.

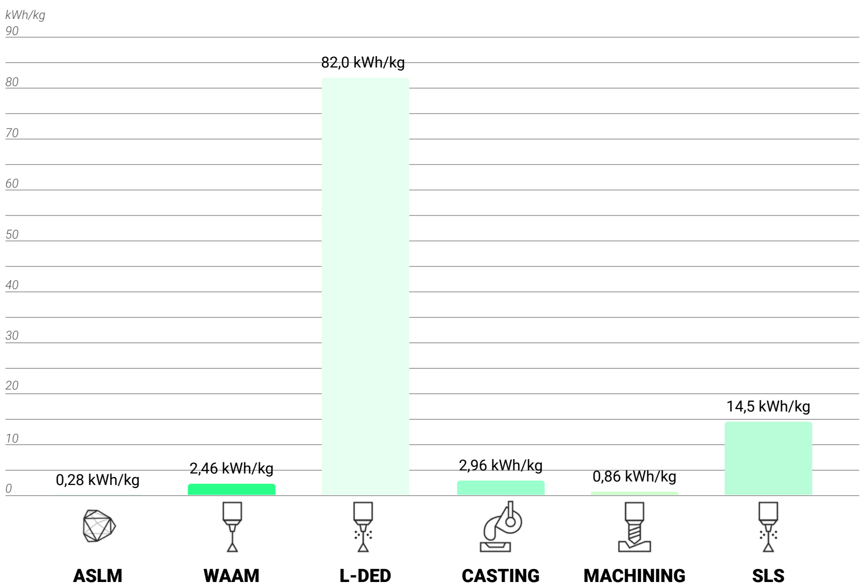
key references

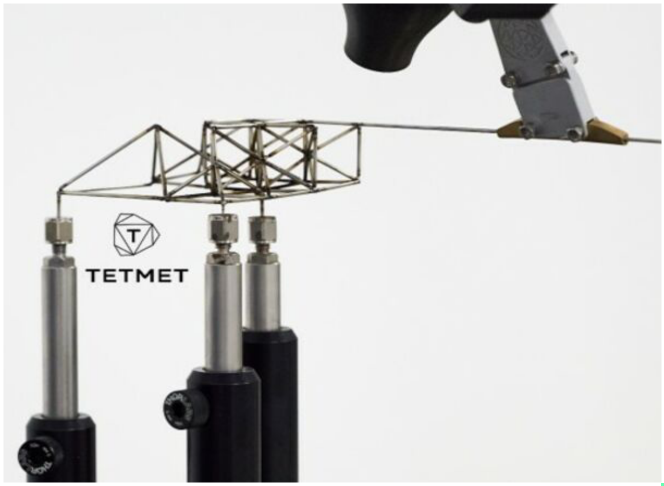
Duflou, J.R., Kellens, K., Renaldi, Guo, Y., Dewulf, W. (2012). **Critical comparison of methods to determine the energy input for discrete manufacturing processes**, CIRP Annals, 61, 1, 63-66. Le, V.T., Huu, M.N., Ha, Q.T., Nguyen, V.A. (2024). **Environmental Performance Comparison Between Wire-Arc and Powder-Laser-Based DED Processes**. In: Long, B.T., et al. Proceedings of the 3rd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2022). MMMS 2022. Lecture Notes in Mechanical Engineering. Springer, Cham. Shah, I.H., Hadjipantelis, N., Walter, L., Myers, R.J., Gardner, L. (2023). **Environmental life cycle assessment of wire arc additively manufactured steel structural components**, Journal of Cleaner Production, 389, 136071. Teubler, J., Weber, S., Suski, P., Peschke, I., Liedtke, C. (2019). **Critical evaluation of the material characteristics and environmental potential of laser beam melting processes for the additive manufacturing of metallic components**. Journal of Cleaner Production, 237, 117775.

ASLM / LPB-F comparison

Figure 4 (below) presents the comparison accross all metal forming processes examined. Table 4 (next page) presents the numerical premises and results of a more detailed comparison between ASLM and laser powder-based fusion (LPB-F). For ASLM, a 316L SS diamond lattice unit-cell (5856 rods or 5.04 kg) with rods ø 1.6 x 55mm and 3.6 s per rod cycle is considered. For laser powder-based fusion, 50µm powders and build speed 0.5g/min is considered. While laser powder-based fusion is currently widely used for complex components manufacturing in aeronautics, ASLM offers a 98% energy footprint reduction and a faster production process for identically complex components.

Figure 4. Energy consumption for 1 kg of material processed

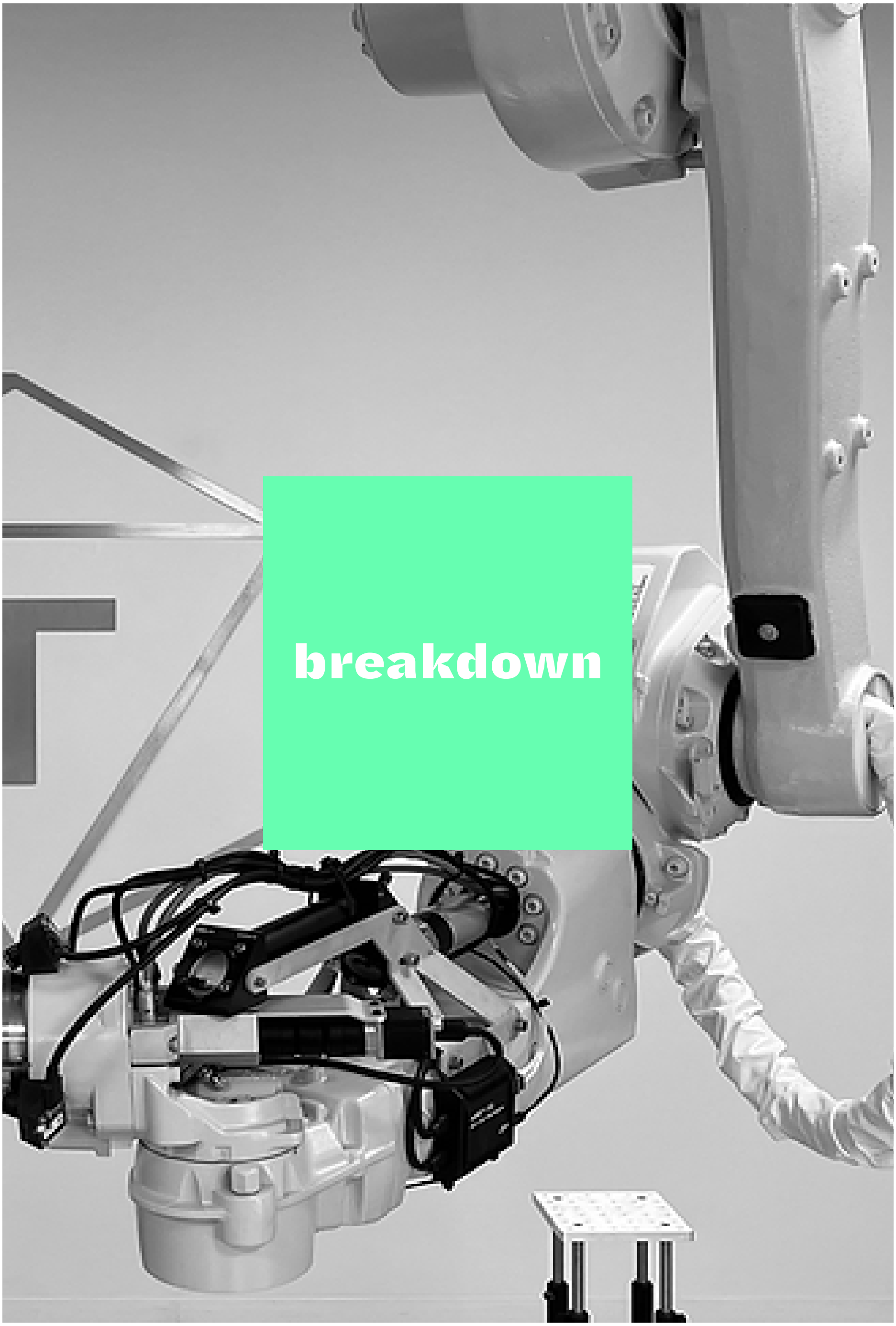




	Material embodied energy (kWh/kg)	Manufacturing time for 1kg (h)	Manufacturing time for 1m3 (h)	Process energy for 1kg (kWh)	Process energy for 1m3 (kWh)	Total energy footprint for 1m3 (kWh)
ASLM	5,6	1,20	6	0,28	1,42	29,6
L-PBF	23	33,00	166	276	1390	1506

Table 4. ASLM and L-PBF comparison data

breakdown



	Energy consumption (J)
Laser	205
Robot	69
Computer	60
Base power	500
Total	**834**

Table 5. Energy footprint breakdown per part of the system

On-site measurements allow for a precise breakdown of the consumption per equipment part. Table 5 presents numerical results relative to the energy footprint of each part of the system. Results correspond to the measured energy consumption during the fabrication process, for the assembly of one rod into the lattice. This assembly has an average duration of 3,6 seconds (0.6 s of laser, 2 s of robot moving, 1s idle). Furthermore, the average laser consumption if considering only power peaks is 534J per rod. Tables 6 and 7 present the distribution of energy and carbon costs across material and process.

Embedded energy - Rod (kWh/kg)	5,56E+00
Energy consumption - Process (kWh/kg)	2,80E-01
Total (kWh/kg)	**5,84E+00**

Table 6. Energy consumption breakdown per material and system

Global Warming Potential - Rod (kg CO_2 eq / kg)	6,48E+00
Global Warming Potential - Process (kg CO_2 eq / kg)	3,50E-01
Total (kg CO_2 eq / kg)	**6,83E+00**

Table 7. Carbon footprint breakdown per material and system

key references

Joly, A., Rouault, B., De Montmarin, S., Margo, M., Grillet, C., Arduin, I. (2023). **Le vrai du faux sur l'énergie, les gaz à effet de serre et la population**. https://www.carbone4.com/analyse-faq-energie-ges-population accessed 9th of January 2025.

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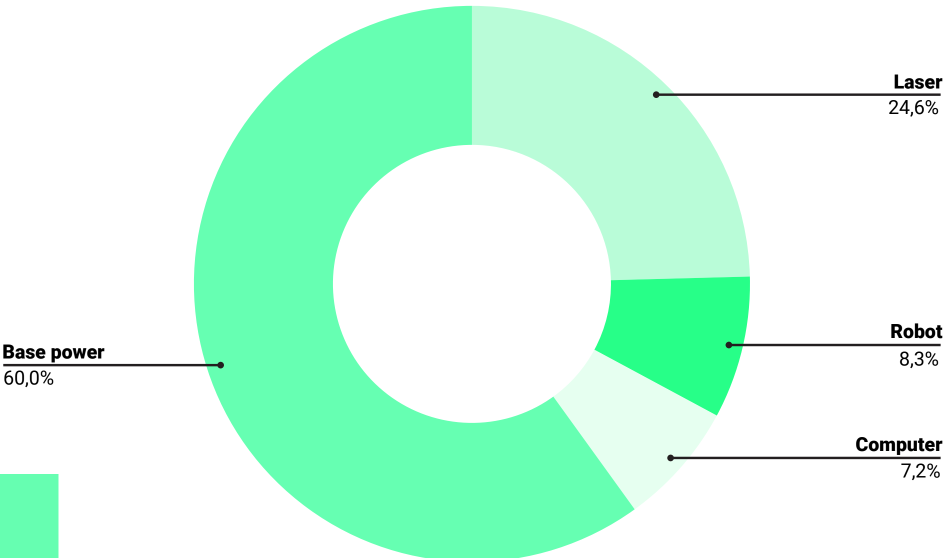


Figure 5. Energy breakdown per part of the system for ASLM

parts of the system

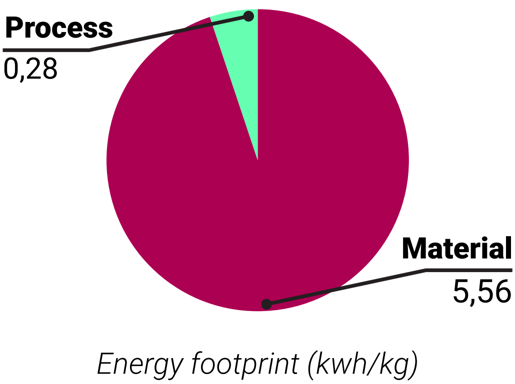
- ABB I1660ID
- ABB IRC5 compact (single phase)
- MAXphotonics 1kW fiber laser
- 2 PI E-617 piezo amplifiers
- 4 Basler Dart cameras

energy consumption breakdown

Figure 5 displays the total energy consumption broken down into the use per each part of equipment. It is noteworthy that the base power composes the largest part of this consumption: energy peaks for the displacement of the robot and the laser firing are much smaller. This indicates that further studies on the consumption of the system while idle would provide venues of energy consumption optimization.

from energy to carbon footprint

Figure 7 presents the relationship between the measured process energy footprint and the embedded energy of the material itself. It shows the very low energy footprint of the process, as 95% of the energy costs in ASLM originates in the material itself. A similar relation between material and system costs exists in the partial carbon footprint assessment performed, with 95% of the impact originating in the material. This is only a partial assessment, as it only evaluates carbon emissions caused by the energy consumption itself. However, it allows a further understanding of the low costs of the ASLM process in comparison to other manufacturing processes at large.



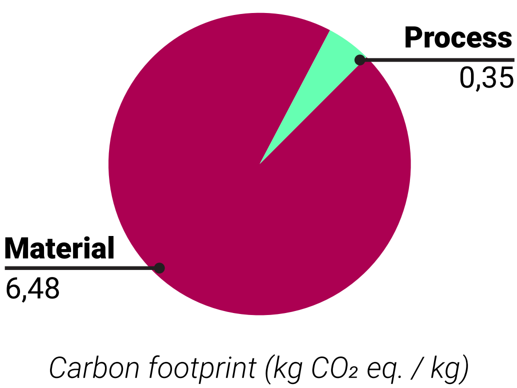
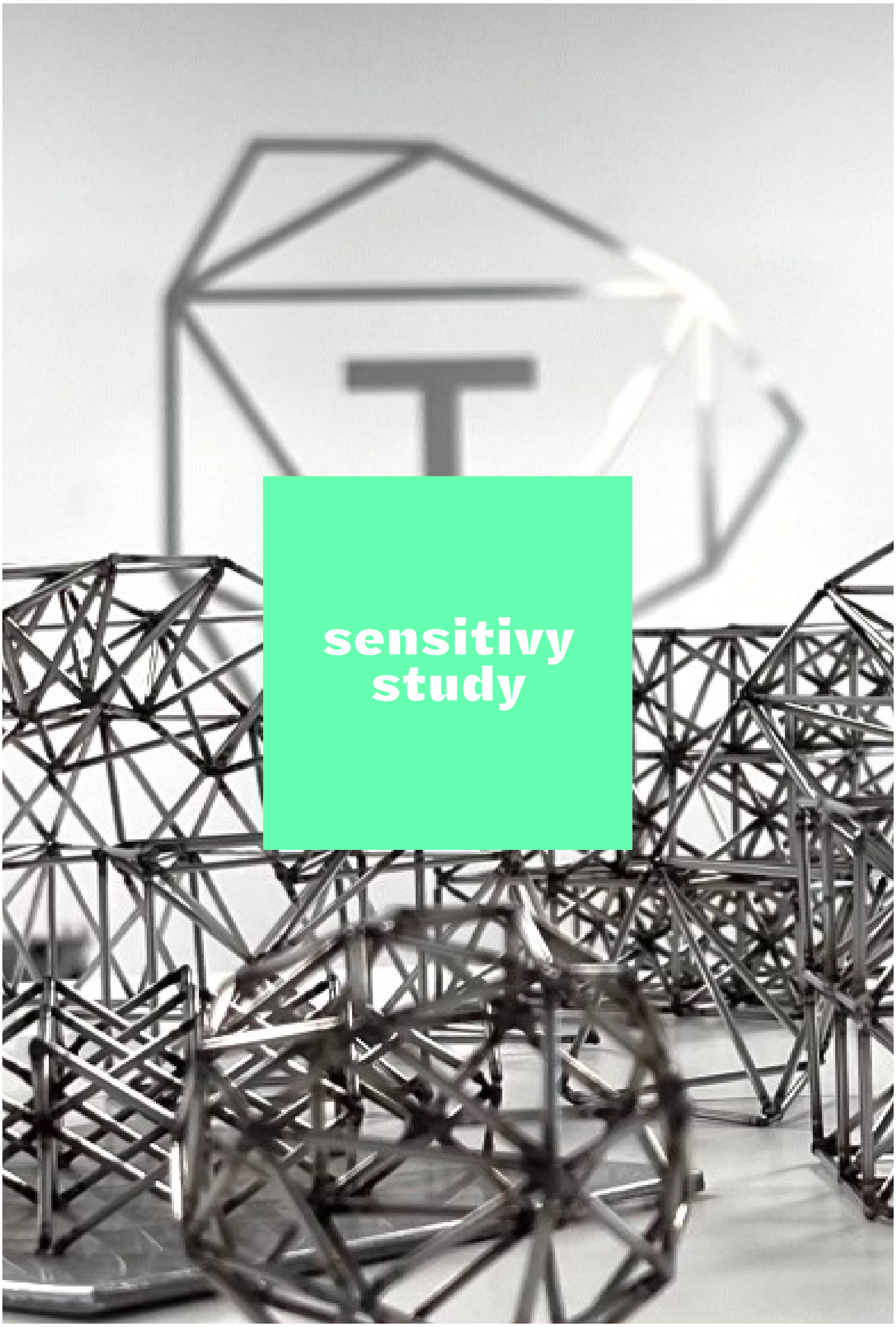


Figure 7. Breakdown per material and system


sensitivy
study

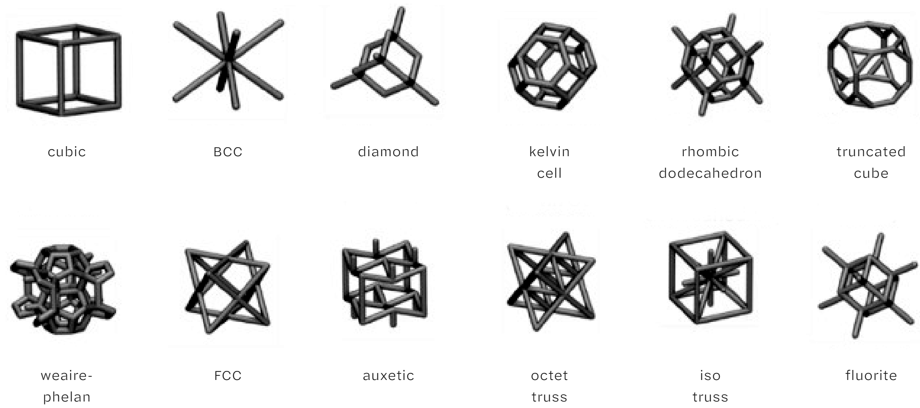


Figure 8. Examples of unit-cells for the ASLM lattices

ASLM manufacturing allows for great flexibility in the type of lattice implemented. Figure 8 displays some of the geometries achievable with the process and the variability of unit-cells on which the lattices can be based. Various types of unit-cells have different densities which affects the energy consumption per m3 of the process, making their specific footprint a relevant parameter to assess. In order to understand the role played in the global ASLM energy footprint by the type of lattice selected to be manufactured, a sensitivity study has been performed. Sensitivity studies are complementary evaluations to the obtention of primary data on the environmental impacts of a given process. By varying a key parameter in the system evaluated and observing the changes in the environmental impacts resulting from this variation, the weight of the parameter is evaluated. This gives the ability to reduce environmental impacts efficiently, by identifiying the most potent parameters within any given system. The following section presents the sensitivity study performed to evaluate the difference in impact of different unit-cell types. Results shows that the type of unit-cell indeed has a strong weight in the system as impacts can vary tenfold.

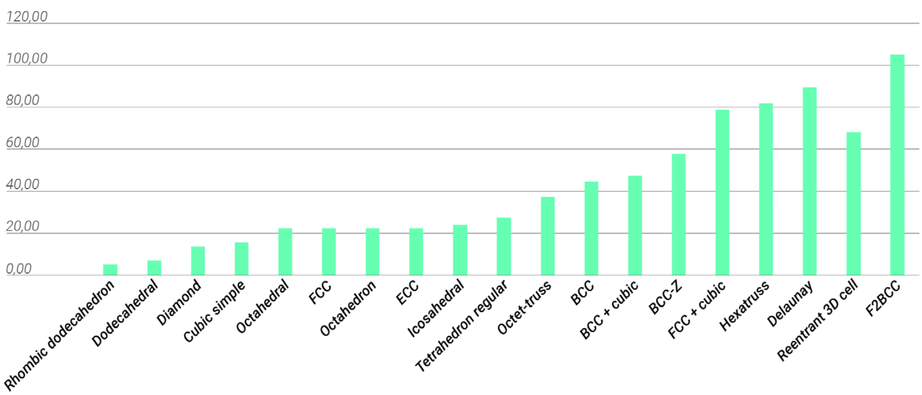
	Energy density (J/cm³)	Global Warming Potential (Kg CO_2 eq./cm³)
Diamond	5,12	1,11E-06
Dodecahedral	6,86	1,48E-06
Rhombic dodecahedron	13,65	2,95E-06
Cubic simple	15,76	3,40E-06
Octahedral	22,29	4,81E-06
FCC	22,29	4,81E-06
ECC	22,29	4,81E-06
Octahedron	22,29	4,81E-06
Icosahedral	24,08	5,20E-06
BCC	27,30	5,90E-06
Octet-truss	37,15	8,02E-06
Tetrahedron regular	44,57	9,63E-06
BCC-Z	47,28	1,02E-05
BCC + cubic	57,79	1,25E-05
FCC + cubic	78,80	1,70E-05
Hexatruss	81,89	1,77E-05
Delaunay	89,30	1,93E-05
F2BCC	68,24	1,47E-05
Reentrant 3D cell	105,6	2,27E-05

unit-cells as performance design drivers for ASLM

Figure 9 presents the sensitivity study performed to evaluate the impact of different unit-cell types on energy consumption, considering rods ø 0,8mm and length 55mm. Table 8 presents the detailed results of this energy density evaluation per unit-cell type, as well as the greenhouse gas emissions associated to each unit-cell type. It considers both the emissions associated with the material and the emissions associated with the process energy. As the energy efficiency of the unit-cells correlates with these emissions, the best performing unit-cells are the same as in Figure 9: the diamond and dodecahedral cells feature less than 1.5E-05 Kg CO2 eq./cm3 greenhous gas emissions, while the five last configurations feature over ten times bigger emissions. This shows that the type of unit-cell has a strong weight in the system, and can be a powerful driver for further optimization through design.

Table 8. (previous page) Energy and carbon footprint per unit-cell type

Figure 9. (below) Sensitivity study for energy density per unit-cell type (J/cm3)



conclusion

The present report places the ASLM process within recent steel AM developments from an energy perspective, demonstrating the drastic reduction of consumption associated with the process and confirming the potential of ASLM for many industries. ASLM allows up to 99,7% of energy savings compared to other steel AM technologies and, as part of these energy savings, allows for the use of more environmentally affordable resources, with a lower embodied energy.

Part of the present assessment however relies on a comparison considering kWh consumed per kg of material processes published in the literature. Therefore, discrepancies might exist in the system boundaries for each of the assessments relied on, which would request further evaluation to confirm results. Limits to this study also include the restriction to energy consumption. To assess impact transfers that are potentially at play in digital manufacturing processes, a complete LCA of ASLM remains necessary.

Finally, not only is the ASLM process is able to produce a large range of various truss configurations for components, based on different lattice cells and with differentiated scales made possible, but the sensitivity study also shows that the type of unit-cell has a strong weight in the system as impacts can vary tenfold. This can be leveraged directly in design work with ASLM, transforming analytic LCA into a performative design tool. The lattice configurations enable further optimization of the energetic footprint of components, as their differentiated consumption entails the possibility of strategic use of different configurations.

credits

The **on-site measures** have been conducted by Justin Dirrenberger and the Tetmet team.

The **assessment** has been conducted by Justin Dirrenberger and Nadja Gaudillière-Jami.

The **writing, data visualizations and graphic design** have been carried out by Nadja Gaudillère-Jami.

The **photographs** are Tetmet copyrights.

bibliography

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