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Energy Consumption and Scope 2 Emissions for Fused Deposition Modelling

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Abstract

Additive Manufacturing (AM) is a layer-by-layer manufacturing process and gaining importance for applications in digital manufacturing, repair and remanufacturing. Although there are many studies on life cycle assessment in AM, the existing studies do not focus on quantifying Scope 1 and Scope 2 emissions which are required for reporting to support net-zero pathway. It is timely to model and optimise additive manufacturing processes for the net-zero carbon agenda. This study discusses energy state monitoring and energy studies to quantify and understand the energy consumption and Scope 2 carbon emissions for fused deposition modelling (FDM) based on the evaluation of the energy states of the FDM machine and energy consumption when printing an exemplar product. The proposed approach can assist manufacturers in identifying key modules of the machine design and process responsible for significant energy consumption, quantifying energy consumption of fused deposition and its contribution to Scope 2 emissions.

Keywords: Additive manufacturing; scope 2; low carbon manufacturing; fused deposition modelling

1. Introduction

Climate change has become a huge global challenge. Global warming is disrupting the weather and ecosystem's equilibrium. By 2050, essential industries such as manufacturing must attain Net-Zero Emissions by focusing on industrial process CO_2 emissions based on Scope 1 and Scope 2 emissions [1].

The Greenhouse Gas (GHG) Protocol provides a framework for businesses, governments, and other entities to measure and report their greenhouse gas emissions in ways that support their established mission and goals according to three operational groups for emissions [2]. Scope 1 emissions are direct GHG emissions that arise from sources that are owned or controlled by the company. Examples are emissions from combustion in owned or controlled boilers, furnaces, vehicles and on-site process emissions. Meanwhile, the indirect GHG emissions from the generation of purchased electricity consumed by the company are classified as Scope 2. Other indirect emissions from sources not owned or controlled by the company, for example related to production, recycling and disposal are covered by Scope 3. Scope 3 is an optional reporting category that allows for treating all other indirect emissions. Most organisations are pursuing or contemplating a net-zero transition based on Scope 1 and 2 emissions only. While organisations report aggregate emissions at the company level, it is important to understand what is contributing to these emissions, especially at the production and machine level and how this interacts with productivity.

BS EN ISO 14040, BS EN ISO 14044, PAS 2050 are to guide the evaluation of the carbon footprint and life cycle GHG emission of goods and services [3-5]. The assessment of GHG emissions can be done using Life Cycle Assessment (LCA) [6]. LCA includes four steps, according to BS EN ISO 14040 and BS EN ISO 14044: Goal and Scope, Life Cycle Inventory, Life Cycle Impact Assessment, and Life Cycle Interpretation. The scope of LCA can normally cover Cradle-to-Grave, Cradle-to-Gate or Gate-to-Gate analysis. While this is comprehensive, it does not perfectly align with Scope 1, 2 and 3 emissions reporting. Scope 1 and 2's system boundary can be considered closest to Gate-to-Gate analysis of manufacturing, but focused on procured energy and on-site emissions inventory.

Kellens et al. published a well-defined methodology for the generation of uniform, complete and robust unit process life cycle inventory (UPLCI) based on screening and an in-depth approach [7]. While the screening is based on available data and modelling, the in-depth approach includes a time study, a power consumption study, a consumables study, and an emissions study. All relevant processes in- and outputs are measured and analysed in detail. While their approach was in the context of informing LCA, this paper is with the motivation for energy effectiveness and reporting Scope 2 emissions.

Therefore, companies need a simple tool for evaluating energy patterns and emissions linked to manufacturing variables. This would give latitude to optimise both energy/emissions and manufacturing objectives. Key technology for digital manufacturing is 3D printing, and it is important to understand the associated emissions according to the GHG protocol. Hence, this paper focused on Scope 2, carbon emissions for fused deposition modelling, a popular 3D printing technology.

1.1. Fused Deposition Modelling Machine

Additive manufacturing (AM) by fused deposition modelling (FDM) consists of a heated build bed, a polymer-based material deposited through an extrusion nozzle to a build platform. The extrusion nozzle deposits plastic-based material based on the contour of the current layer. Electric heating partially melts the material, extruded through a nozzle that determines the diameter. While the material is added to the top portion of the partially finished part, the build platform is adjusted in the z-direction to determine the layer thickness.

Gutowski et al. investigated and modelled the electricity requirements for manufacturing processes according to equation (1) [8]:

$$P = P_0 + k\dot{v} \tag{1}$$

where P and P_0 represent total power and idle state power respectively in W, k is a constant, with units of J/cm^3 and v is the rate of material processing in cm^3/s.

Balogun et al. [9] modelled the direct energy requirement in FDM machines as shown in equation (2):

$$E = P_b t_b + e_m V_R t_{va} \tag{2}$$

where E is the direct energy requirement in J, P_b is the basic power in W for non-value adding activities, t_b is the basic energy state duration in seconds, e_m is the specific material printing energy as determined by the material and process mechanism in Ws/mm^3, V_R is the volumetric manufacturing rate in mm^3/s and t_{va} is the actual build time in seconds.

1.2. Research Aim

The research aim is to understand and characterise the energy operating states, energy consumption and associated carbon emissions of fused deposition modelling. The system boundary is the entire FDM printing process, consistent with Gate-to-Gate analysis and Scope 2 emissions at the process level. The functional unit is defined as 3D printing of a defined component. BS EN ISO 14955-1:2017 [10] on machine tools and environmental evaluation of machine tools is used to create the new framework for evaluating the energy operating states.

2. Power Monitoring in Fused Deposition Modelling Machine

2.1. The new framework of energy consumption for Fused Deposition Modelling Machine

In order to investigate the power profile for a Stacker S4 FDM machine, the machine operating states are defined following the framework from ISO 14955-1:2017 standard operating state of machine tools. The major components contributing to energy usage are control unit, heating elements, cooling elements, and stepper motors. These components are illustrated in Fig. 1 and defined as follows:

- *Control unit and always ON fans*: The main device for controlling all the sub-devices when the machine is turned ON.
- *Heating:* Consisted of heating elements for the build bed and extruder nozzle.
- *Cooling elements*: Consisted of two cooling fans and one blower fan. One fan is attached on the filament extruder's stepper motor, and another one is attached to the heat sink on the nozzle. The blower fan is used to cool the filament as it exits the nozzle.
- *Stepper motors*: The devices for the movement in x, y, z-axis and feeding the filament into the extruder.

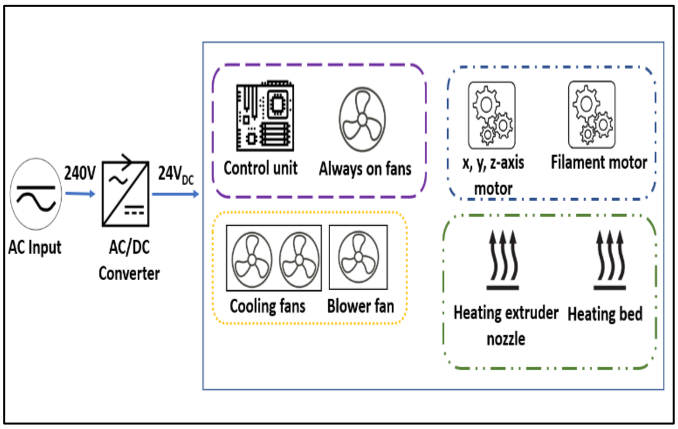

Fig. 1. Main energy consuming components in Stacker S4 FDM machine

The energy operating states for the FDM machine can be partitioned into four primary operating states: standby state, warm-up state, printing state, cool-down state, as listed in Table 1 and explained below.

- *Standby state*: This state begins after the machine is switched ON and after cool-down state. The main controller and always-ON fans are turned ON.
- *Warm-up state*: The heating elements of FDM machine are heated up from initial temperature to the desired

temperature i.e. 70°C for the build bed and 230°C for the extruder nozzle for the Stacker S4.

- *Printing state*: The printing process starts after reaching the desired temperature, while the temperature of the heating elements is continuously controlled within the desired temperature.
- *Cool-down state*: All the printing and heating elements for the build bed and nozzle are turned OFF during the cool-down stage.

Table 1. Operating states for FDM machine

Operating State	Control Unit & Always ON Fans	Heating Elements	Fans and Blower Fan	Stepper Motors (Filament Drive, x,y,z- Axis)
Standby	ON	OFF	OFF	OFF
Warm-up	ON	ON	ON	OFF
Printing	ON	ON	ON	ON
Cool-down	ON	OFF	ON	OFF

Based on the design of FDM machine and operating states, the energy requirements in the FDM machine can further be derived as in equation (3):

$$E = P_i t_i + P_b t_b + P_{bn} t_{bn} + P_{pp} t_{pp} + P_c t_c \quad (3)$$

where P_i, P_b, P_{bn}, P_{pp} and P_c are the basic power in W for standby state, heating build bed, heating bed and nozzle, processing, and cool-down state, respectively.

Investigations are done on the Stacker S4 machine to characterise the machine's energy and time requirements for the entire printing process. The electrical power demand is measured using a Fluke 434 Power Quality and Energy Analyser, and Fluke i30s AC/DC Current Clamp with a tolerance of ± 1% [11]. The investigations are extended to two more FDM machine models i.e. Ultimaker S3 and Prusa i3 MK3 for comparison.

3. Results and Discussions

3.1. Energy consumption according to the operating states

Fig. 2 presents the power profile during the warm-up process of the build bed, while Fig. 3 shows the power profile for the warm-up process of the extruder nozzle from initial temperature. Their average power usages for the build bed and extruder nozzle are 233.30 W and 49.91 W, respectively. The Stacker S4 uses a PID controller to continuously adjust the power for the heating of the nozzle and build bed, in order to maintain the consistent temperatures during printing state [12].

The functional unit and printed part used for all the measurements of the FDM machines is a landing gear attachment model for a DJI F450 Drone, as shown in Fig. 4. This model has an overall dimensions of 201 mm x 35.4 mm x 8.8 mm. The workpiece material used is Polylactic Acid (PLA) and the parameters setting for the FDM machines are listed in Table 2.

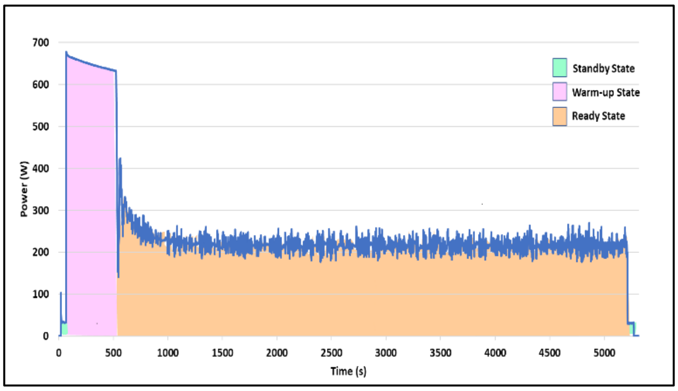

Fig. 2. Power profile during warm-up the build bed for Stacker S4

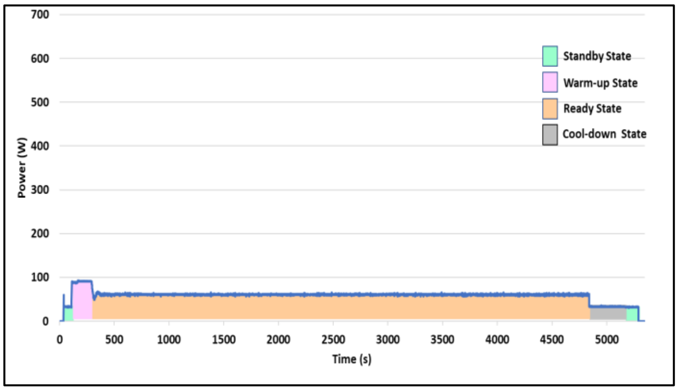

Fig. 3. Power profile during warm-up the nozzle for Stacker S4

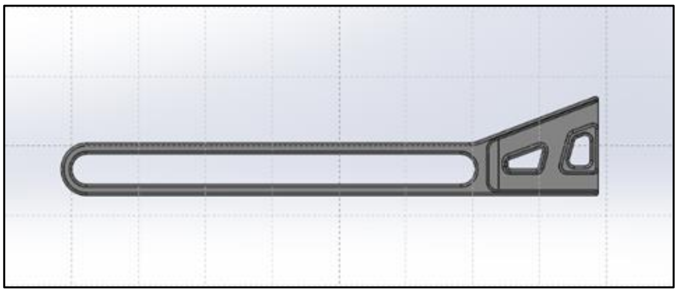

Fig. 4. Landing gear attachment model

Table 2. Parameters for printing landing gear

Parameter	Setting value
Diameter of the filament	1.75 mm
Nozzle size	0.40 mm
Build Bed Temperature	70 °C
Nozzle Temperature	230 °C
Printing Speed	60 mm/s
Infill Density	50 %

Fig. 5 illustrates the power profile of Stacker S4 for the entire printing process. The warm-up process requires 621 s to reach the desired temperature for the build bed and extruder nozzle before printing. This process occurs only once, unless the build bed and extruder nozzle temperatures decrease to room temperature.

The total area under the curve is the direct energy consumed by the Stacker S4 corresponding to the operating states. The average power and energy in printing the landing gear are summarised in Table 3. Clearly, the average power used during the warm-up stage is the highest. Even though the average power usage of the printing process is lower than the warm-up state, it can be seen in Fig. 6 that the energy consumption is larger than the latter. The printing state contributed 77% of the energy requirements. The warm-up state is second highest, contributing about 21% of the energy requirements. This is expected since the entire duration of the printing state is significantly longer (refer to Fig. 5).

During the cool-down state, fans for the stepper motor and nozzle are turned ON. The fans turned OFF automatically when the temperature of the nozzle drops below 100°C.

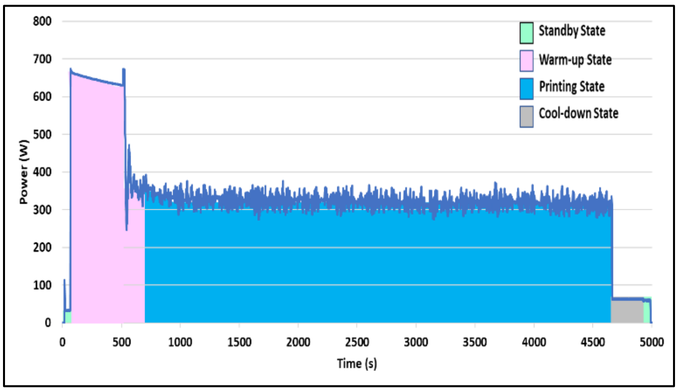

Fig. 5. Power profile during entire printing process for Stacker S4

Table 3. Average power and energy consumed by the Stacker S4

Operating state	Standby	Warm-up	Printing process	Cool-down
Duration (s)	108	621	3970	266
Average Power (W)	50.06	572.27	323.37	62.20
Energy (Whr)	1.55	98.88	356.70	4.61

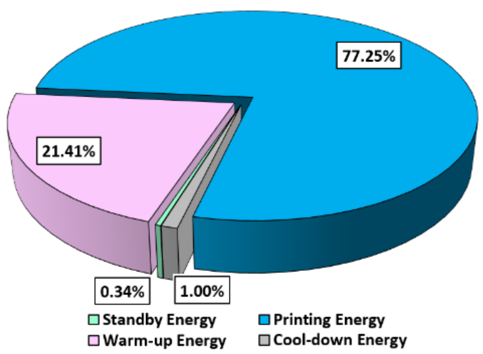

Fig. 6. Energy demand according to the operating state

3.2. Benchmarking of three (3) different FDM Machines

The energy consumption of three different FDM machine models are compared i.e Stacker 4S, Ultimaker S3 and Prusa i3 MK3 by printing the same part as shown in Fig. 4 and using the same parameters setting in Table 2. Even though Ultimaker S3 features an integrated support material nozzle, this was turned OFF during the printing process to ensure all settings are the same. Table 4 shows the specifications of the FDM machine models.

Table 4. Specification of FDM machine models [13-15]

	Stacker S4	Ultimaker S3	Prusa i3 MK3
Power supply	230 V_{AC}	230 V_{AC}	230 V_{AC}
Build volume (cm)	36.5 x 51 x 65.5	23 x 19 x 20	25 x 21 x 21
Number of nozzles	4	Dual-extrusion	1
Print surface	Aluminium bed with Flex-Plate and BuildTak	Heated glass build plate	Magnetic heat bed with removable PEI spring steel sheets

Fig. 7 and Fig. 8 show the power profile of the entire printing process for the Ultimaker S3 and Prusa i3 MK3, respectively. It can be seen that the power profile for all FDM machine models during the warm-up state is similar (refer Figs. 5, 7, and 8) as high-power usage is needed to achieve the desired temperature in a short period.

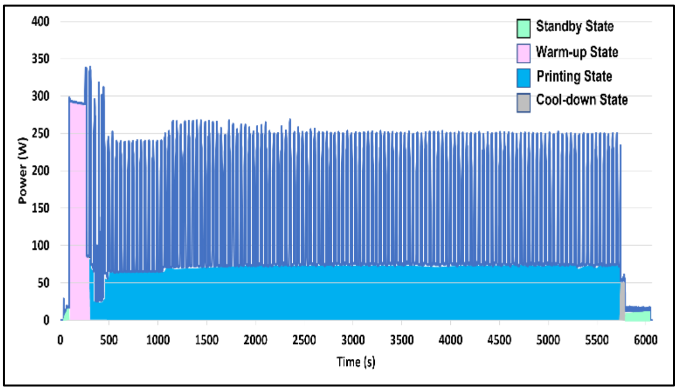

Fig. 7. Power profile for Ultimaker S3

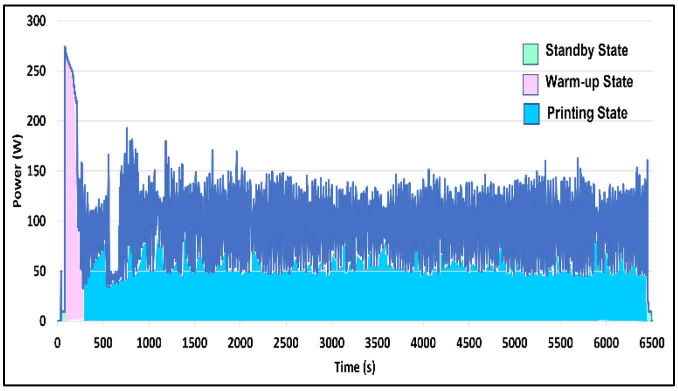

Fig. 8. Power profile for Prusa i3 MK3

The average power and energy consumption of Ultimaker S3 and Prusa i3 MK3 are tabulated in Table 5 and Table 6, respectively. Table 7 summarises the energy consumption for the three FDM machine models in various operational modes. The total energy is calculated using equation (3). It needs to be noted that the size of the Stacker S4's build bed is larger than Ultimaker S3 and Prusa i3 MK3. It is expected that the Stacker S4 used more energy to heat up the bed than Ultimaker S3 and Prusa i3 MK3. In addition, Prusa i3 MK3 has no significant energy demanding cool-down state as fans are immediately turned OFF after the printing state is finished.

Table 5. Average power and energy in Ultimaker S3

Operating state	Standby	Warm-up	Printing process	Cool-down
Duration (s)	282	226	5425	47
Average Power (W)	16.18	273.96	133.93	54.29
Energy (Whr)	1.27	17.20	201.82	0.71

Table 6. Average power and energy in Prusa i3 MK3

Operating state	Standby	Warm-up	Printing process
Duration (s)	78	211	6166
Average Power (W)	9.63	192.16	95.32
Energy (Whr)	0.21	11.26	163.27

Table 7. Energy consumption in FDM machine models

	Stacker S4	Ultimaker S3	Prusa i3 MK3
Standby Energy (Whr)	1.55	1.27	0.21
Heating Energy (Whr)	98.88	17.20	11.26
Printing Energy (Whr)	356.70	201.82	163.27
Cooling Energy (Whr)	4.61	0.71	-
Total Energy (Whr)	461.74	221.00	174.74

Fig. 9 illustrates the energy consumption by the Stacker S4, Ultimaker S3 and Prusa i3 MK3 compared to other manufacturing processes as published by Gutowski et al. [16]. It can be seen that the energy per build volume for those FDM machines falls within the cluster of other previously studied FDM machines (circled in red). However, it is interesting to see that the energy per build volume for FDM machine can be further minimised by implementing multiple nozzles in the printing process as achieved by the Stacker S4 (Batch of 2 and 3). This nesting method took advantage of the size of the Stacker S4's build bed and reduced the energy demand per build rate initially from 8.324E+07 J/kg at 0.019 kg/hr to 3.472E+07 J/kg at 0.058 kg/hr (Batch of 3).

3.3. Scope 2 carbon emissions

The Scope 2 carbon emission can be calculated from the direct energy consumed during the manufacturing process, as shown in equation (4).

$$Carbon\ Emission = E \times e_{co_2} \quad (4)$$

Carbon Emission is in $kgCO_2$, E is the direct energy consumed in manufacturing which is in kWh and e_{co2} is the carbon intensity factor in $kgCO_2/kWh$. According to Alswat and Mativenga, the carbon intensities factor of electricity generation in 2018 for the United Kingdom, China and the United States are 0.25, 0.69 and 0.41 $kgCO_2/kWh$ correspondingly [17].

Fig. 10 illustrates Scope 2 carbon emission for each operating state as stated in Table 7 of the studied FDM machine models corresponding to United Kingdom carbon intensity factor. Fig. 11 shows the overall Scope 2 carbon emission for FDM machine models based on the carbon intensity of electricity used in each country. It can be seen that Scope 2

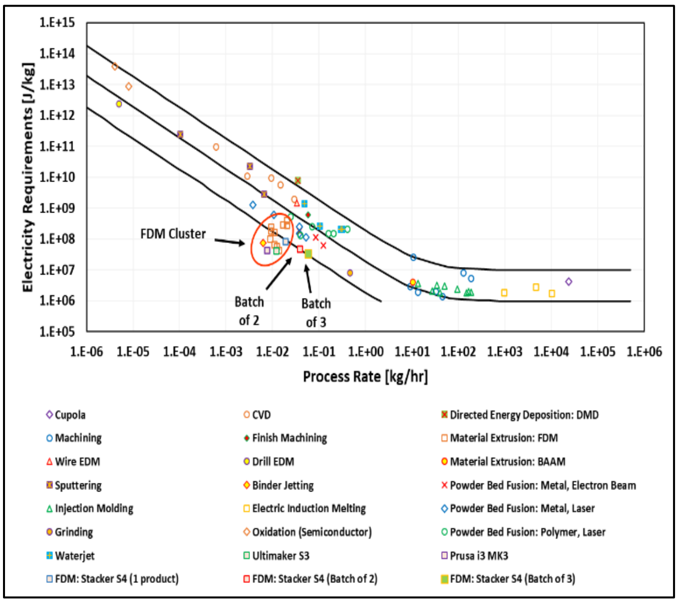

Fig. 9. Energy requirement per build volume

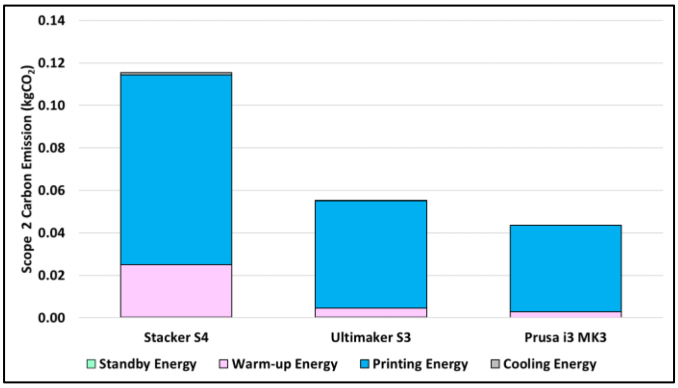

Fig. 10. Scope 2 carbon emission FDM machines in the United Kingdom

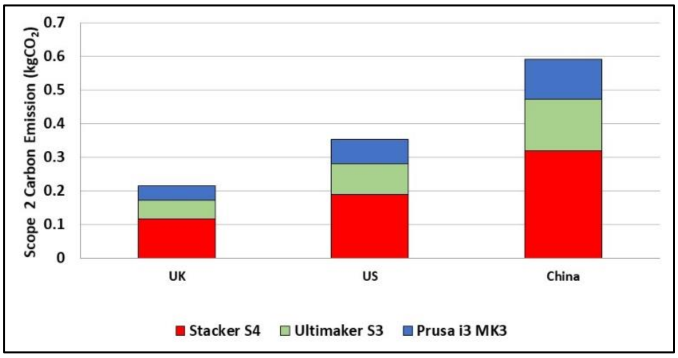

Fig. 11. Scope 2 carbon emission FDM machines according to countries

carbon emission of the countries varies due to international differences in the primary energy resource inputs for electrical energy generation and carbon intensity.

These results show that the energy requirements of FDM vary significantly for the same part, as influenced by the FDM machine design. This means that, there is significant unrealised potential in reducing the energy requirements of some FDM machines or in selecting FDM machines for reduced energy consumption. For lowering the associated emissions, both the design of energy-efficient FDM machines and choosing low carbon intensity electrical energy can help significantly reduce emissions. The key areas for improvement relate to bed heating and enabling rapid printing.

Conclusions

This research investigates the energy requirements of fused deposition modelling (FDM) machines and associated process level Scope 2 carbon emissions. The following conclusions are reached:

- The additive manufacturing process energy requirements and Scope 2 emissions can be modelled as other manufacturing systems based on BS EN ISO 14955-1:2017 energy states framework. Breaking the overall energy demand down into different operational states enables the identification of areas for improvement.
- The warm-up state dominates the maximum power demand for all three FDM machine models in this study. Innovative design of bed and nozzle heating systems needs to be considered, in order to reduce the peak power during warm-up and the associated energy for heating the printer bed.
- The printing state consumes a significant amount of energy compared to other operating states due to a high cycle time. The FDM printing state also includes regulation of the temperature of the build bed and extruder nozzle.
- Different FDM machine models consume different amounts of energy due to their design configurations and operating states. The three printers are compared by building the same model under the same settings. The obtained energy demand and Scope 2 emissions are more than doubled when comparing FDM machines. This shows that there is significant scope for reducing the energy requirements and Scope 2 emissions of FDM by considering the design and operating states of the machine. The reduction is from 55% to 64% when comparing the choice of FDM machine models in this study.

Data Statement

The data for this study is reported in the paper and supported by cited in the references.

CRediT Authorship Contribution Statement

Sakinah Zakaria: Conceptualisation, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualisation. **Paul Mativenga:** Conceptualisation, Writing – review & editing, Supervision, Project administration. **Akos Cseke:** Writing – Review & Editing.

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References

[1] Net Zero by 2050, A Roadmap for the Global Energy Sector, International Energy Agency (IEA), (accessed 27 June 2021).
[2] The Greenhouse Gas Protocol, A Corporate Accounting and Reporting Standard, revised edition, World Business Council for Sustainable Development/World Resources Institute. Available online: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf
[3] PAS 2050:2011, Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
[4] ISO 14040. 2006, Environmental Management – Life Cycle Assessment – Principles and Framework, International Organization for Standardisation..
[5] ISO 14044. 2006, Environmental Management – Life Cycle Assessment – Requirements and Guidelines, International Organization for Standardisation.
[6] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M. & Kellens, K. (2012). 'Towards energy and resource efficient manufacturing: A processes and systems approach', CIRP Annals, 61(2), pp. 587-609.
[7] Kellens K, Dewulf W, Overcash M, Hauschild M Z, Duflou J R. (2012). Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) —CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. International Journal of Life Cycle Assessment, 17:69–78. DOI 10.1007/s11367-011-0340-4
[8] Gutowski T., Dahmus, J., Thiriez, A.. Electrical energy requirements for manufacturing processes, 13th CIRP International Conference on Life Cycle Engineering 2006; Leuven, Belgium.
[9] Vincent A. Balogun, Neil D. Kirkwood, Paul T. Mativenga, Direct Electrical Energy Demand in Fused Deposition Modelling, Procedia CIRP, Volume 15, 2014, pp. 38-43.
[10] ISO 14955-1:2017, Machine tools — Environmental evaluation of machine tools — Part 1: Design methodology for energy-efficient machine tools.
[11] Fluke i30s AC/DC Current Clamp, Technical Data. Available online : https://dam-assets.fluke.com/s3fs-public/2747115_6001_ENG_B_W.PDF
[12] Stacker S4 User Guide Part II. Available online: https://www.stacker3d.com/pdf/STACKERS4S2UserGuide_PARTII.pdf.
[13] Stacker S4 User Guide Part I. Available online: https://www.stacker3d.com/pdf/S2-S4-UserGuide-Part-I.pdf.
[14] Ultimaker S3 and Ultimaker S5, Installation and user manual. Available online: https://support.ultimaker.com/hc/en-us/articles/360012089319-Ultimaker-S3-user-manual.
[15] 3D Printing Handbook, User Manual For 3d Printers: Original Prusa i3 MK3S+ Kit. Available online: https://www.prusa3d.com/downloads/manual/prusa3d_manual_mk3s_en.pdf.
[16] Gutowski T, Jiang S, Cooper D, Corman G, Hausmann M, Manson J et al. Note on the Rate and Energy Efficiency Limits for Additive Manufacturing. Journal of Industrial Ecology. 2017;21(S1):S69-S79.
[17] Haitham M. Alswat, Paul Mativenga, The International Dimension of Electrical Energy Derived Emissions for Machine Tools, Procedia CIRP, Volume 98, 2021, pp. 696-701.