Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

The recycling of E-Waste ABS plastics by melt extrusion and 3D printing using solar powered devices as a transformative tool for humanitarian aid

Mazher Iqbal Mohammed, Daniel Wilson, Eli Gomez-Kervin, Callum Vidler, Lucas Rosson and Johannes Long

Deakin University, School of Engineering, 75 Pigdons Road, Waurn Ponds, Geelong, VIC 3216, Australia

Abstract

This study demonstrates the EcoPrinting principal, which makes use of renewable energy to realise a low carbon footprint means of recycling waste plastics into feedstock for Fused Filament Fabrication (FFF) 3D printing. We present our work to date to encapsulate this principal in a singular device, which comprises a nanogrid solar/battery storage unit, a custom made filament extrusion device and modified FFF 3D printer system. We demonstrate that our system is capable of reforming ABS plastics found in electronic waste and converting these into functional items through a melt extrusion and additive manufacturing process. We successfully demonstrate the efficacy of the system to operate using solar derived energy and using the resulting filament to 3D print functional pipe connector components. We conclude Ecoprinting holds considerable potential as a sustainable means of converting waste plastics into functional components. Finally, the portable and self-sufficient nature of the system, Ecoprinting could feasibly could be applied as a cost effective aid solution for vulnerable communities in low socio-economic environments.

Keywords: 3D Printing, FFF, Polymer, Solar, E-Waste, Humanitarian Aid

Corresponding Author: mazher.mohammed@deakin.edu.au

1 Introduction

Thermoplastics are a prevalent manufacturing material which, have desirable material properties and can be fabricated using a vast array of manufacturing processes, such as Injection moulding [1], laser engraving [2] and 3D printing [3]. Equally, due to its desirability as an engineering material, production of plastics has escalated annual and is projected to increase to close to one billion tons in the year 2050 [4]. The sheer volume of production, in addition to the historical remnants of previous year's production is leading to unprecedented challenges with respect to the management and reuse of this resource. This problem is fuelled by us now living in a more disposable society, where many products are short lived and can be discarded in less than a year [5]. Solutions to this growing problem would require a more robust management process of this resource, which takes a holistic view, enabling recycling from the product design phase right through to waste processing to prevent plastics unnecessarily being destined for landfill or littering our environment [6].

Additive Manufacturing (AM) has emerged as a highly disruptive manufacturing process, with applications across several major industry sectors, from aerospace [7, 8], medical [7, 9, 10] and custom product development [7]. There are several distinct additive manufacturing processes by which to process a wide variety of material, from metals [11, 12] to living cells [13], exemplifying the maturity of this field. However, of all the available technologies one of the most widely utilised and accessible AM technologies is Fused Filament Fabrication (FFF), which now sees extensive use spanning both the education to home user sectors. FFF technology primarily utilised plastics as the feedstock material with the most widely used comprising PLA and ABS plastics. When considering the context of waste plastics, of these two plastics ABS is found in abundance in a variety of consumer products, such as electronic casings, toys, musical instruments and car parts, to name a few potential sources. Therefore, it would be considered reasonable that following the discarding of such products, that perhaps the waste ABS plastic may be reclaimed and repurposed for use in a standard FFF 3D printer.

We have previously proven the potential to use recycled ABS plastics for FFF characterising the decline in material properties when compared to virgin material [14, 15] . Our findings concluded that degradation of the mechanical properties can be as low as 13% when compared to virgin material, implying that there is considerable potential for recycled material to be used in functional applications where mechanical integrity is required. With respect to sustainable manufacturing, the use of renewable energy to power 3D printing systems has also been demonstrated in the studies performed by the Pearse Research Group [16]. When combined with recycled 3D printing, it would seem feasible that a sustainable manufacturing paradigm could be realised which leverages both technologies to enhance material reuse, and to do so with a minimised carbon footprint.

In this study we demonstrated a process which we term as EcoPrinting, which involves the recycling of waste plastics found in consumer waste into 3D printer filaments for manufacturing use, while generating all power for the instrumentation using renewable energy. As a demonstration of the potential of this process we document the progress made in developing a complete prototype system which could have potential for use in a humanitarian aid based scenario in a developing nation. We aim to optimise the system for potential operation in the remote jungle setting on the Solomon Islands to manufacture fittings to remedy leaking pipes. In this scenario, we anticipate the lack of any stable electrical infrastructure and assume ample waste plastics in the environment, which has been confirmed to us by project partners Plan International, who are currently engage in aid programs in this area. To test the efficacy of the prototype system, in this study we demonstrate that we can take ABS found in electronic waste, granulate it down using a hand operated grinder, before using this in a melt extrusion process to generate 3D printer filament. We then demonstrate that this filament can used to create 3D printable items, including a functional pipe connector part using energy generated from a bespoke solar energy generation system (nanogrid). Our preliminary tests confirm the functional operation of our system and its potential to revolutionise the current paradigm of aid delivery, though a more versatile approach that not only works sustainably, but leverages the advantages of product customisation offered by AM.

2 Methodology

There were several subsystems that comprised the entire EcoPrinting system to achieve the goal of converting e-waste ABS polymers to printed parts. An overview of the subsystems can be seen in Figure 1.

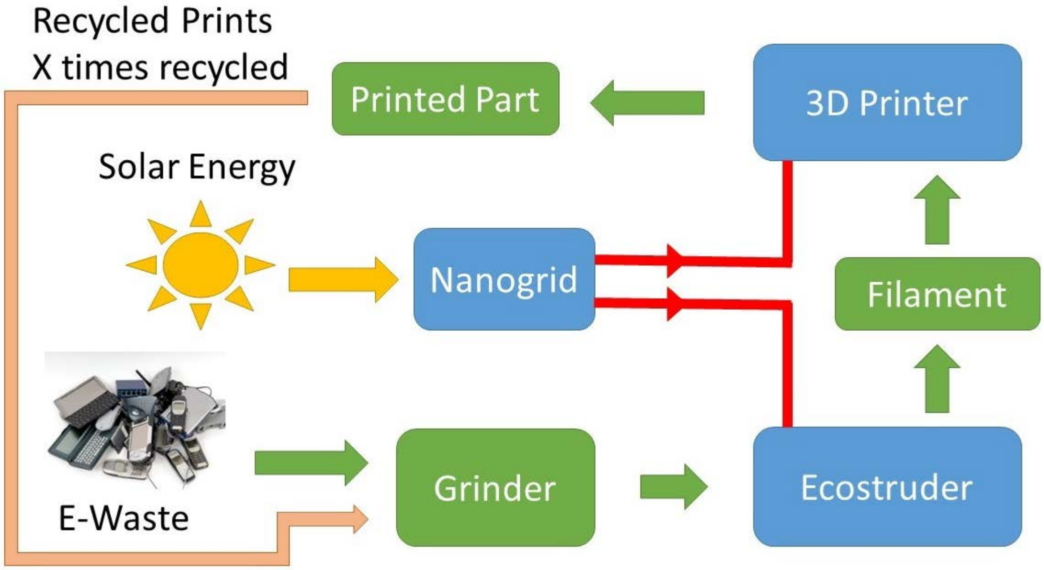


Figure 1: A flow diagram of the entire EcoPrinting system

2.1 Consumer waste reclaiming and granulation

In this study we reclaimed waste ABS plastics from discarded electronics within Deakin University's School of Engineering to be used as our test material. This waste would have otherwise been discarded by dispatch to local recycling centres for dismantling and sorting. In this instance, we manually dismantled the outer casing from items such as old computers, laptop docking stations and desktop telephones, which we sorted for granulation. It was believed that directly using post-consumer waste would be more reflective of what would be experienced should the devised system be used in a real world context out in the field.

Generally, most plastic were relatively free of contamination, but if required a light clean with a damp cloth was performed to remove any major dust and dirt accumulations. Once clean the plastic components were broken down into fragments, approximately no larger than 150x150mm, and fed into a hand operated granulation device. The device comprised a series of geared, interlocking teeth which could be rotated using a lever arm. The granulation process required that a piece of plastic underwent several phases of repeated grinding to reduce the granule size. Following this the plastic was place through a sieve with a mesh size of approximately 5mm, resulting in the end product that could be used in the filament extrusion device.

2.2 Filament Extrusion Device

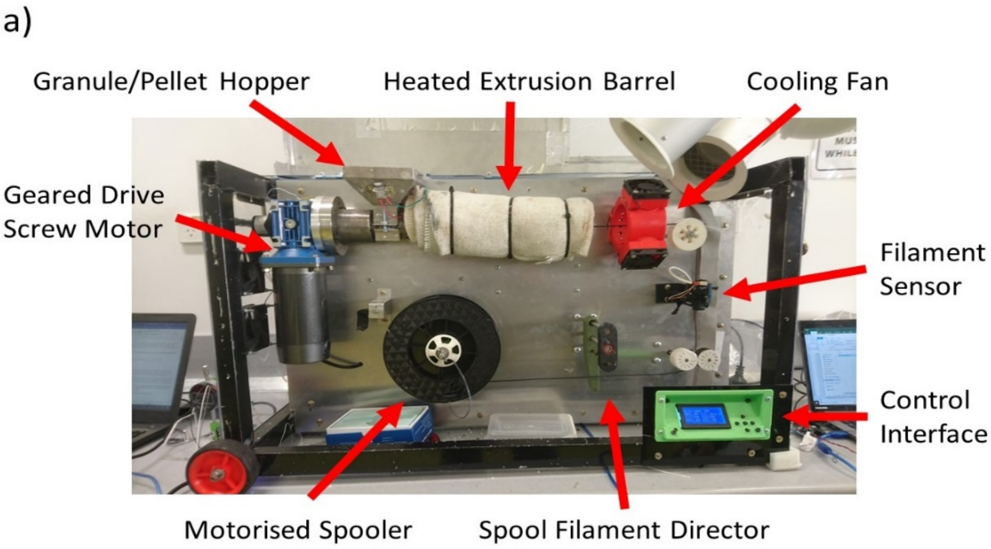
To convert the waste plastics into 3D printer filament we created our own bespoke melt extrusion device, which we have named as the Ecostruder system, and is the core element of the recycling system. The system is based on key elements from commercial melt extrusion systems utilising a single screw system [17, 18] and is powered by a 24V, 100W, internally geared DC motor. It is worth noting that a 300W, 240VAC to 24VDC power supply unit was incorporated into the Ecostruder to allow for use using mains electricity as found in a typical Australian electrical supply system. However, a secondary mode of operation through the nanogrid was also achieved and outlined in the section 2.4. To ensure that the screw operates at a constant RPM, an encoder is used to measure the rotational velocity, and which is feedback into a PID controller. The screw is also coupled directly to the geared motor, which provides a simple and robust interface where auxiliary chains are not required. Three individually controlled 50W band heaters provide the ability vary the temperature distribution along the barrel, which in turn allows for control of how the fed waste plastic transitions from solid to the liquid phases. The system also utilises a custom fabricated drive screw, which is tapered to become wider at the extremity of the barrel. This configuration is widely used in commercial extrusion system and where the screw geometry is optimised for the use of a particular family of polymers. The tapering geometry of the screw causes a compression of the material and builds pressure to force the molten material out of the barrel through a fixed size nozzle. During operation, the motor will rotate the screw, forcing the processed material along the barrel and out through the nozzle. The nozzle diameter, heater temperatures and material feed rate will dictate the final cross-sectional geometry of the exiting filament, but this can be further adjusted by tensioning of the filament prior to complete solidification of the polymer. Following extrusion, the Ecostruder system contains a cooling fan to enhance thermal relaxation, before the resulting filament is fed through an optical sensor. The sensor is linked to PID controller and allows for adjustment of the rotational speed of the motor, which in turn automates adjustment to increase or decrease the feed rate to achieve a desired filament diameter. In our current set-up, a 3mm nozzle is used and the extruded plastic and the sensor is set to achieve the desired set diameter. To examine the performance of the extruder, filaments were generated with 100% recycled consumer waste ABS and pelletised virgin ABS for performance comparison. A picture of the Ecostruder system can be seen in Figure 2a).

2.3 3D printing

All 3D printer testing and modifications were performed to a commercially available FFF machine (Lulzbot Mini, Aleph Objects Inc, USA). This format was selected due to the open source nature of the printer, both with respect to software and hardware, which allowed for modifications to be made with relative ease. The printer was also selected as it was found to be a good compromise of 3D printing size (152x152x158mm) to power consumption, as assessed from in-house testing (results not shown). The build size of the platform fundamentally allowed for the construction of all standardised sized of pipe connectors were likely to encounter should the system be implemented as intended in the Solomon Islands for water infrastructure maintenance.

For use in this study modifications were made to the printer to both allow for usability using our nanogrid system and also using recycled plastics. Modification were initially made to include a three stage switch to allow for the machine to move from a state of being switched off, use of the Australian standard 240VAC to 24VDC power supply unit, or to switch to the nanogrid system of operation which directly operates at 24VDC.

When performing test prints a nozzle temperature of 235^{o}C, print bed temperature of 100^{o}C and print speed of 50mm/s were employed, which were considered optimal for the use of ABS plastic. These settings were held constant across all variant of ABS plastics examined unless issues were observed in the printing process and then each of these parameters, starting with the print speed were adjusted stepwise to obtain optimal manufacturing. For all designs examined, prints were performed using 100% infill to ensure the fabrication of the most mechanically robust pipe connector parts possible.



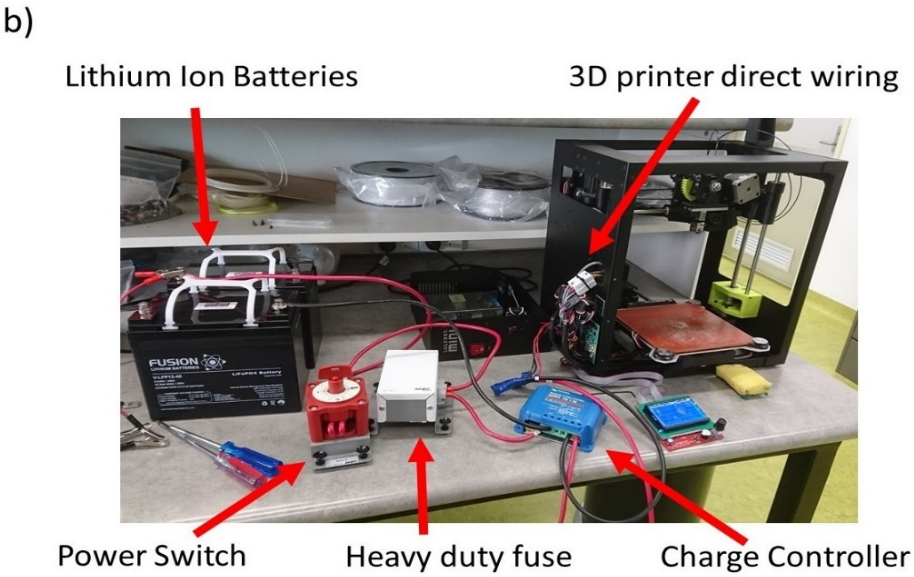


Figure 2: a) An annotated picture of the Ecostruder system and b) A photograph of the nanogrid battery and charge controller system being used with the 3D printer

2.4 Nano Grid system

An important feature of the Ecoprinting process is the generation of electricity from renewable energy. Currently, we opted for a system comprising the use of portable Photovoltaic (PV) solar panels, which would be used to trickle charge lithium ion batteries. In an ideal scenario, the system which we aimed to create would have the capacity to operate solely from the use of the energy generated by the PV's. This would not be realistic in real operational scenarios and so the aim was to create a dynamic system that could operate directly utilising the energy from the PV cells, and divert excess charge to the lithium-ion batteries. Conversely, in times when insufficient electricity is generated to power a respective device, charge from the battery system can be utilised to sustain operations.

The overall system comprised of a commercial MPPT 75/15 solar charge controller system (Victron, Outback Marine, Australia) in conjunction with two 12V 55Ah LiFEPO4 batteries (EV Power, Australia) and two 150W silicon photovoltaic cell arrays (Australia Direct, Australia). The lithium-ion batteries utilised in this system were equipped with an in-build smart charge control systems which ensured that the system did not over charge, or full discharge, guaranteeing the integrity of the system. An additional fuse and switch were placed into the system as a secondary safety precaution. To monitor the power entering and leaving the nanogrid system, two inline power meters were placed into the system (Kickass, Australia direct, Australia) which allowed for direct readings of the power, voltage, current and historical data. Figure 2b) shows a picture of the system during initial testing and set up. The particular set up was designed to operate at 24VDC due to both the 3D printer (bed/hotend heaters) and Ecotruder (motor and heaters) components all operating at 24V. Therefore, to minimise losses due to voltage conversion and to remove the necessity for secondary power supply units, the system was designed to run seamlessly at 24V. This would allow for both devices to function in what was term ‘on grid’, using mains electricity, or ‘off grid’, using the nanogrid system.

3 Results

3.1 E-Waste Granulation

To measure the average granulation size of the ABS fragments, a methodology where twenty randomly selected granules were measured across their longest diameter and then averaged. In previous studies, waste 3D printed ABS material had been effectively ground down using a similar process to this study, attaining an average grain size of 3.8±1mm [14]. We found that we obtained a similar outcome using electronic waste ABS plastics, obtaining an average granule size of 4±0.8mm over five repeated cycles of granulation, with a maximum and minimum range of 2.6 to 5.7mm. Figure 3a) illustrates several of the electronic waste conversion phases, starting from discarded product to final granules. Our obtained results compare favourably to the average size of pelletised virgin ABS, which has been found to be approximately 3.4±0.4mm across a diameter range of 3 to 4.5mm [14].

3.2 Ecostruder testing

Following granulation, tests were performed to investigate the feasibility of extrusion into usable 3D printer filaments using the Ecostruder system. The Ecostruder system, unlike other commercially available benchtop extruder devices utilises three independent band heaters to allow for greater thermal control of the melt extrusion process and to allow processing of polymers beyond just ABS. The location of the heaters in the system can be seen in Figure 3b) and were essentially positioned at either extremity and in the centre of the extruder barrel. For this study, we only made use of the heaters at the barrel centre and the extrusion nozzle, which was found to be sufficient for processing ABS. Additionally, the use of fewer heater consumes less power, which is essential when considering ‘off grid’ functionality of the EcoPrinting system. In this study, heater two (centre of the barrel) was set to 185^{o}C and Heater 1 (nozzle) was set to 205^{o}C. Once the system had reached the desired set temperatures, the granulated material was loaded into the hopper and the motor was engaged to feed the granules into the barrel.

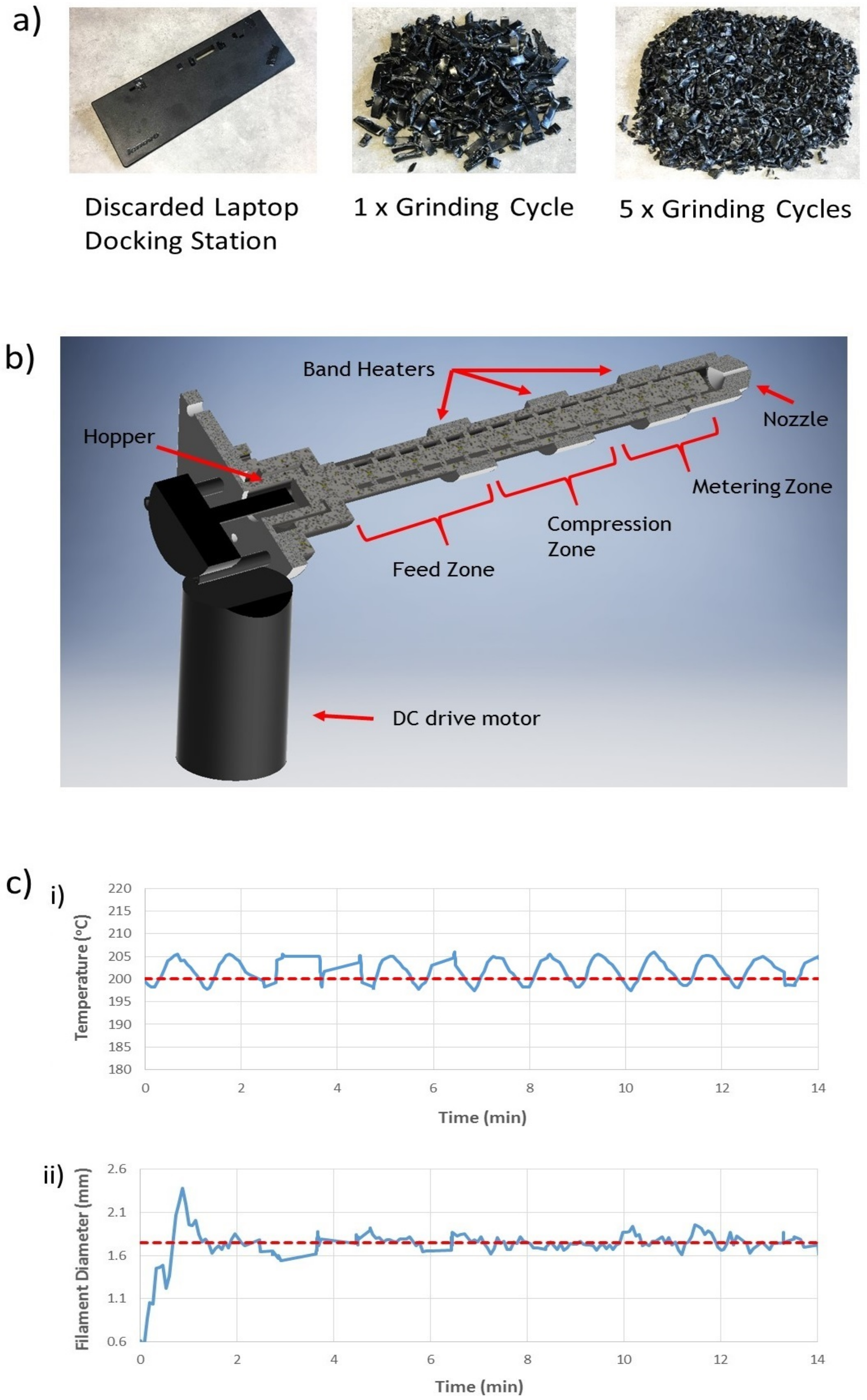


Figure 3: a) Photographs of the original e-Waste and the resulting ABS at various stages of granulation, b) A schematic of the Ecostruder system, highlighting the primary phase transition regions of the polymer within the extruder barrel and c) Data illustrating the change in the temperature response of heater 1 over time and the output from the filament diameter sensor.

Figure 3ci) shows data recorded from a temperature probe in contact with the band heater to provide insight into the stability of the band heater during the extrusion process. It can be seen that measured temperature oscillated by approximately 2^{o}C below and 5^{o}C above the desired set temperature. This yielded an average temperature over time of 201.8±2.86^{o}C. Examining the data more closely, the response of the temperature appears to be periodic over a one-minute period and is a direct result of the PID programming. Ideally we would aim to reduce this error though reprogramming of the microcontroller and further PID tuning, but for the purposes of this initial trial this degree of accuracy was sufficient to allow for repeatable processing of the ABS material. Figure 3cii) also shows data from the filament sensor output during the extrusion process. It can be seen that initially there is a relatively large deviation from the desired set diameter and the actual diameter of the filament. This reduces over the course of the initial 2 minutes of extrusion before the system begins to stabilise about the set point. When taking an average of the filament diameter, neglecting the initial period of instability, the diameter was found to be 1.76±0.1mm, which is comparable to the standard stated tolerances of commercially available filaments (1.75±0.05mm). As with the PID controller for stabilisation of the heater set temperatures, we believe greater system performance could be obtained by revision of the programming and tuning, and will be the subject of future revisions of the sensor system. Ultimately, the systems performance is considered acceptable for filament production and so the generated filaments were used for subsequent 3D printing tests.

3.3 Nano grid

3.3.1 Device Power Consumption Tests

Initially prior to system design it was necessary to determine the potential power requirements for the system relating to the peak power output, what voltage the nanogrid system would operate at and the desired charge and discharge capacity. To this end, preliminary power measurement were performed of the 3D printer and the Ecostruder systems. Measurements were performed using a bespoke live power reader system devised in house, which is placed in line with the power lead of the respective device and measures the continuous current and voltage. It is worth noting however that from in-house testing we found that there is a significant proportion of power that is lost in the conversion of the mains voltage to the voltage required for a device, in this instance 240VAC to 24VDC, and so the recorded results are anticipated to be an over estimate of the actual power readings. We believe this should provide an additional safety factor to ensure the devised nanogrid system outperforms actual requirements.

Figure 4 illustrates live power measurement from the Ecostruder and 3D printer systems. Results highlight periods of system warm up when respective heaters were transitioning to a given set point, before a period of sustained use, and in the case of the 3D printer, the period of cool down post printing. It was found that the Ecostruder system recorded an approximate peak power use of 297W and average continuous power usage of 175W, over initial warm up from 20^{o}C to 205^{o}C for heater 1 and 185˚C from heater 2. Over the 40 minute extrusion test period, an average energy usage of approximately 117Wh was recorded. The printer system was measured to have a peak power use of 188W and an average continuous power usage of 158W, over and initial warm up from 20^{o}C to a set temperature of 230^{o}C for the hotend and 100^{o}C for the heater bed. Over a period of approximately 21 minutes this gave an average energy usage of 55Wh.

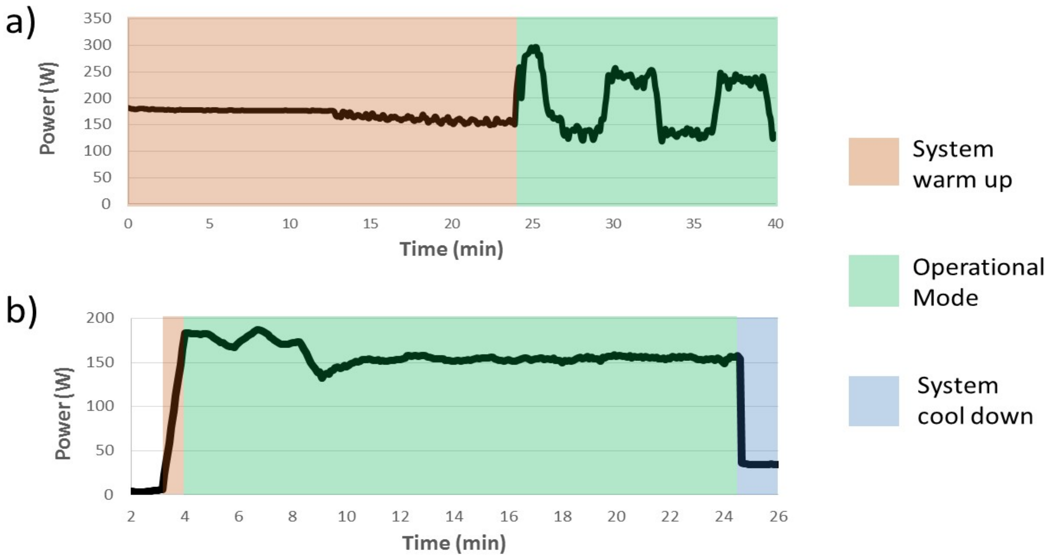


Figure 4: Graphs illustrating the recorded power usage over time for a) the Ecostruder system and b) the 3D printer

3.3.2 Nanogrid Power Generation

Initial tests were performed using the nanogrid system to examine the charge generation efficiency of the system. At this stage, tests were only performed for a period of ninety minutes over two different days which were specifically chosen to examine the efficacy of the system to generate charge in optimal and sub optimal weather conditions. Test 1 was performed on a day when full cloud cover in the sky was observed, and would act as out sub optimal benchmark. Test 2 was performed on a day when on a day when little to no cloud cover in the sky was observed, and would act as out optimal benchmark.

Figure 5ai) Illustrates data recorded from the power output of the solar panels. As anticipated, it can clearly be seen that there is a dramatic difference in the charge generation capacity on these two days. The average sustained power output was approximately 14W for test 1 and 210W for test 2 respectively. Examining test 2 more closely, it can be seen that the energy generation was relatively consistent over the analysis period, with the exception of a slight drop in power generation at approximately 70 minutes. This drop was attributed to cloud cover that persisted for a 5 minute period and which lead to a drop in power production by up to 25-30%. By contrast examining test 1 we find that the power generation is significantly less that for test 2 by up to a factor of 10 decrease. The implications of this would be that there may arise occasions when the weather patterns may not be conducive with the ability of the nanogrid system to generate sufficient charge to sustain printer/extruder usage over extended periods of time. However equally, there may be occasions where an excess of charge is produced which may not be immediately required for use by the devices. Ultimately, further testing is required to build more of an accurate picture of how power generation may vary based on the target locations where the system may be used. However, a strategy to mitigate the risk of depleting all power resources may be to build larger banks of batteries beyond the current system to continually store excess charge in times on peak generation to supplement days when power generation is suboptimal. Such modifications will be considered in future designs of the nan-grid system.

3.4 3D printing tests

The final element of the testing procedure was to determine the ability of the nanogrid system to operate in real working conditions. In this preliminary work, we aimed to focus on the operation of the 3D printer and so devised basic tests to establish the systems performance in real operating conditions. We had two primary objectives to test regarding AM. Firstly, to examine if we could operate the 3D printer in a simulated real scenario where the printer is operating ‘off grid’ exclusively using the nanogrid system. Secondly, to examine if the 3D printer could operate using the recycled electronic waste ABS to form complex structures such as pipe connectors which could function with similar performance to standard components.

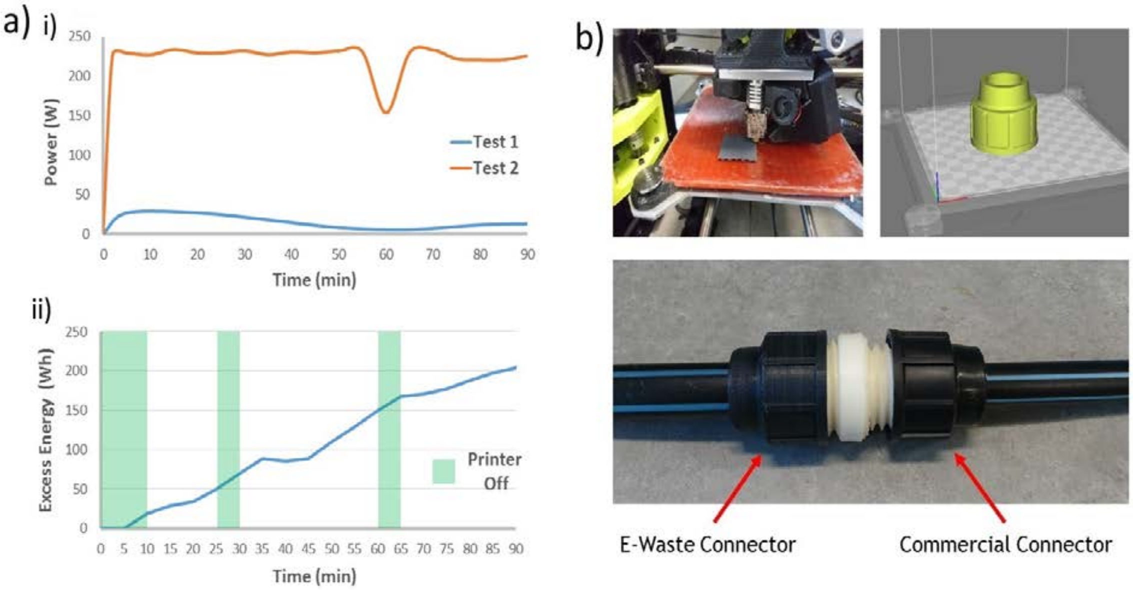


Figure 5: a) Graphs illustrating i) the variation in generated solar power of the nanogrid system over a 90-minute period on optimal and suboptimal test days and ii) the excess energy generated by the nanogrid when used during a live 3D printing test. b) Images of the pipe connector end cap design and the 3D printed part using e-waste. For comparison the 3D printed part is placed alongside a commercially available pipe connector end cap.

To test the printing performance in a real scenario we took the nanogrid and 3D printers outside to a location where there was clear exposure to the sun and set the system up to print three generic parts, comprising a 20x20x20mm cube, a 30mm diameter and 30mm height cylinder and a lattice structure with a cube of 30x30x30mm. The part geometries were arbitrarily selected from existing libraries of test structure we have in-house when optimising test prints and were primarily selected due to their relatively small size allowing for printing to be completed over a relatively short period of time, with the test being completed in approximately 90 minutes. The nanogrid batteries were initially in a state of partial depletion such that there was capacity to place additional charge in the system should the weather conditions be conducive. Figure 5aii) illustrates data representing a subtraction of the charge used by the printer against the charge generated by the solar panels, with times when the printer was in a state of idle being represented in the shaded regions. It was found that during the course of the test the system was capable of not only adequately powering the 3D printer system but produced an excess of energy, totalling approximately 204 Wh. This would potentially have been sufficient to power the Ecostruder for a period of just under 1 hour, or an identical secondary printer alongside the existing printer for a period of approximately 80 minutes. If we assume the same environmental conditions over a typical day of operation, which would comprise running the 3D printer for 8 hours and the Ecostruder for 2 hours, the generated excess energy would accommodate this usage whilst also charging the battery system by an additional 25Ah. Indeed, it is premature to assume that the average daily variations would contribute this level of energy generation and so further tests are required to examine daily, weekly and seasonal variations to gain a greater understanding of the systems potential. However, the results clearly demonstrate the feasibility of the system for use as an 'off grid' means of manufacturing and filament generation.

Finally, tests were performed to examine the print quality of the recycled ABS material. Figure 5b) illustrates a pipe connector that was designed and manufactured using the recycled material. Designs for the pipe connector were made using Inventor software (Autodesk, USA), which mirrored the design of a standard pipe connector end cap. Modification were made to the design to ensure that it could be printed using the FFF process without the necessity for support material. Once the design had been finalised, it was printed using the recycled ABS. It was found there were minor surface defects but beyond cosmetic issues the part was relatively robust. To test the device, we constructed a centre join section from commercially available ABS plastic and used the part to join a section of piping. On the same test structure, we implemented a standard pipe connector end cap (Figure 5b) and superficially tested the part by blocking the end of one piece of tubing, pressurising the system using a plumbing pressure testing device. It was found that the part held the water with no leakage issues up to a pressure of 5Bar, where at which point the blocking cap succumbed to the pressure in the system. In the future we hope to refine our set up to examine the final failure pressure of the device. Despite this, these preliminary results reveal there is much potential for the use of recycled ABS plastic to not only be used in cosmetic FFF 3D printing applications but also as functional items.

4 Conclusion

This study has conclusively demonstrated the Ecoprinting principal, whereby we realise a low carbon footprint means of recycling consumer waste using 3D printing technology. We have demonstrated that electronic waste can readily be processed using a relatively simplistic process into 3D printer filaments, which can then be used to manufacture mechanically robust parts, such as pipe connectors. The Ecostruder system has demonstrated not only the capacity to convert e-Waste into 3D printer filaments, but can do so with minimally refined source material to generate filaments close to the tolerances of commercial products. We have also demonstrated the potential of the nanogrid to not only power the 3D printing equipment in real time, but to generate excess energy to charge the systems batteries. We believe with the use of the battery storage system; we can sufficiently supplement the charge generation capacity of the system to allow for indefinite use of the system within reasonable daily usage timescales. However, we have found that the energy generation capacity of the nanogrid system shows considerable fluctuation on a day to day basis. Therefore, further testing of the system is required to better understand energy generation variances over different operational conditions. Finally, we have successfully tested the ability to 3D print parts with the generated waste plastic filament in 'off grid' circumstances. We therefore believe that the EcoPrinting system holds considerable promise as a tool for manufacturing with waste plastics in remote, 'off grid' settings, such as those experienced in low-socioeconomics environments as on the Solomon Islands. We hope in future studies to test the principal in actual field tests to better assess the potential of the system as a tool for humanitarian aid.

Acknowledgements

We would like to thank both the Deakin University School of Engineering and Centre for Humanitarian Leadership, alongside Plan International for their support and funding for the project. We would like to thank the English Foundation and members of the general public, who provided much needed financial support to the project following crowd funding efforts on the Start Some Good 3DWASH campaign. We would finally like to thank James Lamont and Michael Shanahan for their valuable technical support in the project.

References

[1] R. A. Malloy, *Plastic part design for injection molding*: Hanser Publishers New York, 1994.

[2] M. I. Mohammed, M. N. H. Z. Alam, A. Kouzani, and I. Gibson, "Fabrication of microfluidic devices: improvement of surface quality of CO2 laser machined poly (methylmethacrylate) polymer," *Journal of Micromechanics and Microengineering,* vol. 27, p. 015021, 2016.

[3] M. I. Mohammed and I. Gibson, "Design of Three-Dimensional, Triply Periodic Unit Cell Scaffold Structures for Additive Manufacturing," *Journal of Mechanical Design,* vol. 140, pp. 071701-071701-10, 2018.

[4] M. A. Kreiger, M. L. Mulder, A. G. Glover, and J. M. Pearce, "Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament," *Journal of Cleaner Production,* vol. 70, pp. 90-96, 2014/05/01/ 2014.

[5] J. Hopewell, R. Dvorak, and E. Kosior, "Plastics recycling: challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences,* vol. 364, pp. 2115-2126, 2009.

[6] A. M. Ragossnig and D. R. Schneider, "What is the right level of recycling of plastic waste?," *Waste Management & Research,* vol. 35, pp. 129-131, 2017/02/01 2017.

[7] I. Gibson, D. Rosen, and B. Stucker, *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*, 2 ed.: Springer-Verlag New York, 2015.

[8] S. M. Wagner and R. O. Walton, "Additive manufacturing's impact and future in the aviation industry," *Production Planning & Control,* vol. 27, pp. 1124-1130, 2016/10/02 2016.

[9] D. Mitsouras, P. Liacouras, A. Imanzadeh, A. A. Giannopoulos, T. Cai, K. K. Kumamaru*, et al.*, "Medical 3D printing for the radiologist," *Radiographics,* vol. 35, pp. 1965-1988, 2015.

[10] M. I. Mohammed, M. G. Ridgway, and I. Gibson, "Development of virtual surgical planning models and a patient specific surgical resection guide for treatment of a distal radius osteosarcoma using medical 3D modelling and additive manufacturing processes," presented at the Proceedings of the 28th Solid Freeform Fabrication Symposium, Austin, TX, 2017.

[11] W. E. Frazier, "Metal Additive Manufacturing: A Review," *Journal of Materials Engineering and Performance,* vol. 23, pp. 1917-1928, 2014/06/01 2014.

[12] M. I. Mohammed, A. P. Fitzpatrick, and I. Gibson, "Customised design of a patient specific 3D printed whole mandible implant," *KnE Engineering,* vol. 2, pp. 104-111, 2017.

[13] J. Jang, H.-J. Park, S.-W. Kim, H. Kim, J. Y. Park, S. J. Na*, et al.*, "3D printed complex tissue construct using stem cell-laden decellularized extracellular matrix bioinks for cardiac repair," *Biomaterials,* vol. 112, pp. 264-274, 2017/01/01/ 2017.

[14] M. I. Mohammed, A. Das, E. Gomez-Kervin, D. Wilson, and I. Gibson, "EcoPrinting: Investigating the use of 100% recycled Acrylonitrile Butadiene Styrene (ABS) for Additive Manufacturing," in *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*, 2017, pp. 532-542.

[15] M. I. Mohammed, M. Mohan, A. Das, M. D. Johnson, P. S. Badwal, D. McLean*, et al.*, "A low carbon footprint approach to the reconstitution of plastics into 3D-printer filament for enhanced waste reduction," *KnE Engineering,* vol. 2, pp. 234-241, 2017.

[16] J. Gwamuri, D. Franco, K. Khan, L. Gauchia, and J. Pearce, "High-Efficiency Solar-Powered 3-D Printers for Sustainable Development," *Machines,* vol. 4, p. 3, 2016.

[17] G. J. Listner and A. J. Sampson, "Single screw extruder," ed: Google Patents, 1970.

[18] A. L. Woern, J. R. McCaslin, A. M. Pringle, and J. M. Pearce, "RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament," *HardwareX,* vol. 4, p. e00026, 2018/10/01/ 2018.