# Product policy opportunities related to domestic 3D printing

Jonathan Wood
Consultant and Director
Tenvic Ltd
73 Sea Mills Lane,
Bristol, BS9 1DR
UK
jonathan.wood@tenvic.com

Catriona McAlister
Consultant and Director
Sea Green Tree S.L.
C/General Palafox 49 4-3
Castelldefels
08860 Barcelona
Spain
catriona.mcalister@seagreentree.com

## Keywords
policy-making, regulation, Ecodesign Directive (EuP/ErP), innovative technologies

## Abstract
Developing resource efficiency policy to address a moving target such as an innovative technology is a challenging undertaking. This study analyses how policy makers could approach the highly innovative area of 3D printing. 3D printing is undergoing such rapid expansion that constant monitoring is necessary to keep track of developments in the field.

Environmental policy currently in place does not adequately address the environmental impacts of domestic 3D printing, which relate to energy, resource use, emissions and waste. This paper outlines the opportunities for policy to have a powerful influence on the growth of the technology, diverting it from a potentially damaging path to one that positively improves the environmental impacts of domestic 3D printers. Projections of impacts of 3D printing show the potential savings that are achievable if policy makers act now could be higher than those predicted for ecodesign policy approaches addressing the conventional home printing area.

There are many opportunities throughout the 3D printer lifecycle for policy to have an influence – from the design stage to end of life. The foundation to policy work in the area will be the development of testing approaches and standards. Voluntary initiatives, accreditation schemes, endorsement labels, subsidy schemes, and user information can build upon these. In parallel, the creation of an evidence base projecting environmental impacts of 3D printing (for example an ecodesign preparatory study) can provide a valuable justification for environmental actions to be undertaken in the area. This can then provide solid support for the development of 3D printer specific regulatory requirements and/or labelling in the medium to longer term. Fast tracking this process could result in significantly more savings in the long term as environmental design features are encouraged in 3D domestic printers at an early stage in their development.

## Scope
Although many of the observations in this paper could also potentially be applied to additive metal processes, comparisons between this and 3D polymer printing have not been considered in detail. It should therefore be assumed that unless otherwise stated, observations made relate only to 3D polymer printing. Modelling activities were limited to domestic 3D printers using plastic feedstock due to i) the difficulties covering vast variations in the 3D printing market (feedstock, printer size, usage profiles etc.) and ii) the likelihood that consumer printers are those that will be responsible for negative overall environmental impacts (compared to the uptake of 3D printing technologies in the non-domestic area where utilisation will usually be higher and there is potential for manufacturing efficiency gains to be achieved depending upon the application and expertise of the operator).

## The status of 3D printing technology
3D printing, or "additive manufacturing", enables three-dimensional solid objects to be "printed" from a digital model by laying down successive layers of material. 3D printers were initially used in industrial environments to produce and refine prototypes ("rapid prototyping"). With reductions in cost, and

improvements in technology, they are quickly finding new applications, particularly to produce moulds/mould templates for use in mass production, and in short-run manufacturing where customisation is key.

3D printing can be very useful to manufacture complex geometries, precisely customised parts, parts in a variety of slight variations, or parts that need to be adapted frequently in their manufacturing lifecycle. Hence they now used in a range of industries to manufacture for example automotive parts, jewellery, plastic packaging, custom prosthetics, pharmaceuticals or scale architectural models.

Different materials and processes can be used for 3D printing, and printers can range greatly in size, from briefcase sized, to those large enough to print houses. The level of definition can also vary considerably, with some printers able to operate at microscopic levels.

There is a growing interest in 3D printers for home use, although the industry is still at a very early stage.

## Forecasts for growth of 3D printing

3D printing is an emerging market, with an increasing number of companies competing for a share of expanding sales. The number of 3D printing companies has been on the increase since 2010. Major players include 3D Systems Corporation, Bits from Bytes, envisionTEC, EOS, Hewlett-Packard, MakerBot®, Objet and Stratasys. Printer prices have reduced in recent years due to competition and economies of scale. In 2002 a budget 3D printer would have cost around €27,000, whereas in 2014 a desktop device can be purchased for well under €700. This has acted as a major driver to increase uptake, especially in the domestic market where sales are expected to more than double every year between 2015 and 2018. Sales growth in the EU to date has been strong. Although views on future sales are mixed, there is broad agreement that the following areas will see growth in the near term:

**Industrial** – Growth rates greater than 100 % year on year are expected, fuelled by reduced prices and sizes, expanded material options and diverse process options. Uses will include rapid prototyping and highly customised or small production runs, with growing interest from larger appliance, tool and industrial machinery producers. The potential for 3D printing to replace mass manufacture is limited to specific applications.

**Retail/Service** – After-market support such as demand printing of spare parts for small appliance and auto repair saw early adoption in 2012.

**Biomedical** – 3D printing will continue to grow where services are tailored precisely to patient ergonomics.

**Low-end consumer** – The focus has been on reducing costs and improving the usability of consumer products to encourage increased domestic uptake. Sales will continue in niche areas (mainly hobbyist/artistic applications), as both suppliers and users invent new applications. The dominant process will be single colour thermoplastic extrusion.

There are great uncertainties in estimating expected sales of IT products early in the development of their market, as witnessed by the now infamous statement made by IBM chairman, Thomas Watson, in 1943; "I think there is a world market for maybe five computers". Whilst some current estimates suggest that the global 3D printing market will reach $5.7bn (€5.2bn) by 2018[1], and that it will be one of the fastest growing industries in the US, others suggest more moderate growth taking into account technical limitations. A recent report stated "while 3D printers are expected to experience considerable growth in the long run, for the foreseeable future it will likely remain a specialised application that for the most part will complement, not replace, traditional forms of production"[2]. Dramatic forecasts of a third industrial revolution due to 3D printing may not come to fruition in the short to medium term. However, the industry will continue to grow in the highlighted niche applications.

Whilst there are no certainties around the magnitude of the growth of the 3D printer market, the chart below shows our best sales estimate for consumer printers in the EU to 2030. The sales values are based on published information[3] along with our assumptions over future growth rates. These predictions translate to approximately 1 in 9 households in the EU owning a 3D printer by 2025.

## Strengths and Weaknesses of 3D printing

3D printing has been hailed as the catalyst for the next industrial revolution[4] and the "democratisation of manufacturing", being viewed as having the capacity to shift manufacturing to a more local level – from mass-production to mass-customisation[5]. However, in reality the balance of pros and cons is more complex, and it is unlikely to have as strong an influence on traditional manufacturing as many sources have suggested. The diagram below summarises the non-environmental strengths and weaknesses, opportunities and threats related to 3D printing (environmental issues are discussed in the subsequent section).

Major strengths of the technology include the flexibility of design, the ability to print complex geometries, and the potential for customisation. However substantial limitations include material variety, cost and speed. 3D printers cannot synthesise materials with specific physical properties such as Pyrex cookware, or print electronic components such as processors or memory (although there have been some early developments in 3-D printing electronics using conductive ink, and the most recent commercial printers have more varied material choices). In the short to medium term, they are limited to producing objects compiled of a small number of distinct materials – or in most consumer printers just a single material. Likewise for colour, whilst basic colour printing can be achieved with some 3D printers, the capability to mix colours in the same way as traditional inks to produce an extended palette of colours has only become a reality in high-end commercial machines. A recent report concluded that "to produce even a subset of consumer goods used in the average household would require dozens to hundreds of different feedstock materials, many of which are not suited to the processes used in 3D printing"[6].

With respect to cost, in most cases, mass-produced products are likely to be substantially cheaper to manufacture than their 3D-printed counterparts due to economies of scale. A consumer printing dinner plates could incur costs 30 times more than if they purchased these plates in a shop[7]. Whilst many home printers are capable of printing books, this takes time, and it is usually more convenient to purchase them mass produced. In the same way, standard mass produced objects are likely to be more convenient than 3D printed ones, especially where large volumes of an object are required. This could present the big-

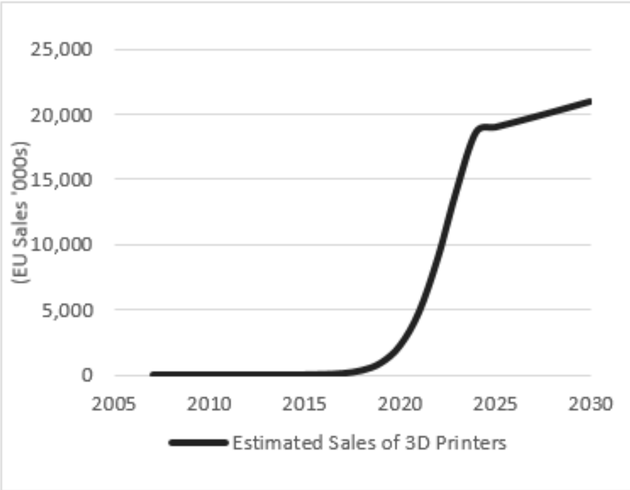


*Figure 1. Estimated Sales of Domestic 3D Printers. Sales volumes between 2006 and 2013 are based on a straight line interpolation between zero sales in 2006 and calculated sales in 2014 based on published information. Sales volumes from 2015 until 2019 are expected to double annually with sales growth then beginning to slow from 2025 onwards.*


*Figure 2. SWOT analysis of 3D printing in comparison to traditional mass production.*

gest barrier to the paradigm shift from mass to democratised 3D production. There is EU funded work underway to address these aspects[8]. Additional limitations include the strength of parts, and ethical considerations. Sharing of digital designs will need to be managed via appropriate policy frameworks to ensure that design rights, trademarks and patents are not infringed and ethical considerations are respected without limiting innovation and growth of the industry – for example, a recent case showed how a 3D printer had been used to print a gun. It is not clear where responsibility would lie in the event of injury as a result of use of a printed product. There might also be legal concerns regarding product quality.

## Environmental impacts of 3D printing

Environmental considerations relate to energy and resource use, as well as emissions and waste. The balance of lifecycle impacts of 3D printing have been investigated in some initial studies in the area, with the conclusion that electricity use in the in-use phase is the dominant environmental impact[9]. The embodied impacts of the manufacturing, transport, and end of life stages of 3D printers themselves have been found to represent a small proportion of the environmental impacts in high use scenarios, although they become more significant in low-use scenarios[10]. However, there are many uncertainties and variations in such analyses.

### MATERIAL SUSTAINABILITY

Whilst the more affordable printers tend to use plastics, there are many other possibilities for 3D printing materials – including glass, starch, ceramics, organic materials, elastomers, resins and metals. There are two main plastic feedstock options used at the moment in domestic 3D printers: Acrylonitrile butadiene styrene (ABS) which has a good strength and high melting point, but is subject to some shrinkage and requires a heated platform for printing to, and Polylactic acid (PLA), which is becoming the standard feedstock for consumer 3D printers. PLA is a corn-based and bio-degradable plastic, which has lower heating requirements (both in terms of production and use of the feedstock) which means reduced energy consumption. It also has lower emissions and results in better print quality due to reduced shrinkage, although may have reduced strength and durability due to a lower melting point meaning that it can soften and sag in a hot environment. Filament is sold in different diameters, with PLA usually costing slightly more than ABS. There is some potential for recycling of feedstock – see section on material waste.

There is a wood-based composite feedstock now available for use with consumer printers – a mixture of 40 % wood with a polymer binder that smells and behaves in a way similar to wood, including potential to cut, sand and paint like wood, and can require less energy than plastic feedstock. Home metal printers are in the early stages of development, with the potential to be even more affordable than plastic printers[11], but they require far higher operating temperatures resulting in much higher in-use energy consumption. Metal particles are also finding their way into plastic consumables such as copper and bronze powders embedded into PLA.

### MATERIAL WASTE

In the context of the wider lifecycle, waste is not a dominant lifecycle impact. Literature on 3D printers often states that due to parts being constructed one layer at a time, using only the necessary amount of material required for each part, waste levels are "near zero"[12]. However, in terms of waste, 3D printers do not necessarily compare favourably with traditional production techniques, especially when in a consumer environment with an inexperienced user who will be more likely to require trial prints before they achieve a satisfactory printed object. In addition, there will be waste material generated in the form of the print bed and supports necessary for complex geometries – which in some cases could be greater in mass than the final part, depending on geometry and orientation. Whilst waste itself does not represent a large proportion of environmental impacts, the energy use related to printing of the waste materials can still be significant, providing an additional driver for waste reduction. There are various best practice design approaches that can be applied to reduce material use and waste, such as printing hollow parts, or carefully orientating parts to avoid the need for support structures. The likelihood of consumer printer users taking such design approaches is small, but some waste-minimisation strategies could be supported in domestic environments by printing software.

Additional opportunities to address the waste impacts of 3D printing include cartridge and waste-plastic return and remanufacturing schemes offered by suppliers of printing stock, also reducing consumption of raw materials. There are products in development that are intended to enable a closed loop recycling process by turning waste prints into shavings for extrusion into new filament. Extrusion devices can save over 90 % of the costs of purchasing filament, and can enable production of filament on demand, in whatever length or colour is required for a specific job. However, the use of additional devices needs to be balanced with their added embodied energy and in-use energy impacts, and there is uncertainty about the potential to recycle waste material and printed parts due to changes in the material properties post-printing and pigments that may interfere with plastic separation processes. One alternative being investigated is the potential to create 3D printer feedstocks by recycling waste plastics from other sources for positive lifecycle impacts. In November 2013 an initiative was launched called 'The Ethical Filament Foundation', with the goal of producing 3D printing filament from recycled plastic waste. The scheme aims to provide stable incomes for waste pickers in developing countries. The first stage, currently underway, is standard development and accreditation to certify ethical producers.

#### EMISSIONS

3D printers are high emitters of ultra fine particles (UFPs) and the fumes emitted contain toxic by-products as a result of the plastic being heated to high temperatures[13]. ABS performs worse than PLA, creating "mild, tolerable fumes while being extruded which may be dangerous for people (or pet birds) with chemical sensitivities or breathing difficulties"[14]. The levels of UFPs emitted 3D printers appear to be the same as cooking indoors, but further work is necessary to determine exactly what UFPs 3D printers are emitting in order to fully assess the health risk. Fans can be used to divert fumes, but may adversely impact the operating temperature and therefore the print result. As a result some domestic users may set up their 3D printer with the addition of both a fan and an infrared lamp, causing increased energy impacts, whilst others may choose to place the printer in a sealed enclosure, conserving heat, excluding drafts and allowing better control of fumes.

#### ENERGY USE/POWER DEMAND

It has been observed that energy use is one of the biggest lifecycle impact of 3D printers, with them even being referred to as "energy hogs"[15] consuming a "frightening amount of electrical energy"[15]. Detailed information on power demand of 3D printing products is sparse, but it has been estimated that using a 3D printer could require 50 to 100 times more electrical energy than injection moulding an object of the same weight[15].

Power modes include:

- **Ready/Networked Standby/Sleep:** After switch on while waiting for a job, and after a job is completed.
- **Preheat/Ready:** Once a job has been sent, there will be a preheat mode to prepare the material for use.
- **Printing:** Active 3D printing. High temperatures are required to melt plastic for printing purposes – the exact temperature will depend on the feedstock used. Manufacturer data suggests that for a consumer device power demand when printing could be in the range of 40 to 400 W due to the need to heat the filament effectively for optimal results[1]. Print times vary with required resolution and size complexity. As an example, it currently takes approximately one hour to print a small phone case weighting around 35 g on a typical domestic 3D printer.
- **Off:** The printer may still have some power demand when switched off but plugged in at the mains.

Our projections of the energy use and consumable impacts of consumer 3D printers, throughout the EU, (Figures 3 and 4) suggest that in the near future they may have significantly higher impacts than traditional printers. For example, by 2025 we estimate that domestic 3D printers may be using 3.1 TWh/year of electricity compared to an estimated 0.28 TWh/year used by domestic laser printers and an estimated 0.08 TWh/year used by domestic inkjet printers. When including consumable plastics we estimate that domestic 3D printers could be using between 7.6 TWh/year and 11.0 TWh/year (dependent on consumable material type) compared to 2.4 TWh/year by laser printers and 1.3 TWh/year by inkjet printers when paper consumption is also included.

Consumer use of 3D printers is likely to be very sporadic, and much less than standard 2D printers, although it may increase slightly into the future as new applications are found for 3D printing. A lifecycle study found that in contrast to a high production scenario, printing just one part a week and leaving the machine on the rest of the time, had roughly ten times the impact of the same machine at maximum utilisation[9]. This suggests that use of the minimum number of printers to process the maximum quantity of jobs can substantially reduce the environmental impacts of 3D printing by amortising the impacts of printer manufacture, and reducing wasted energy use whilst idle. Therefore, a preferred usage approach is centralised use of 3D printers in a retail situation (e.g. a print shop is servicing many orders where the printer could be in constant use during hours of operation of the shop) rather than in the home.

#### TRANSPORTATION

As design files can be downloaded and printed at a location close to the point of use, many sources have highlighted the environmental advantages of 3D printers to reduce the supply

1. Manufacturer reported data was secured from a number of different manufacturer websites. Power demand data for 3D printers is currently limited in its availability.

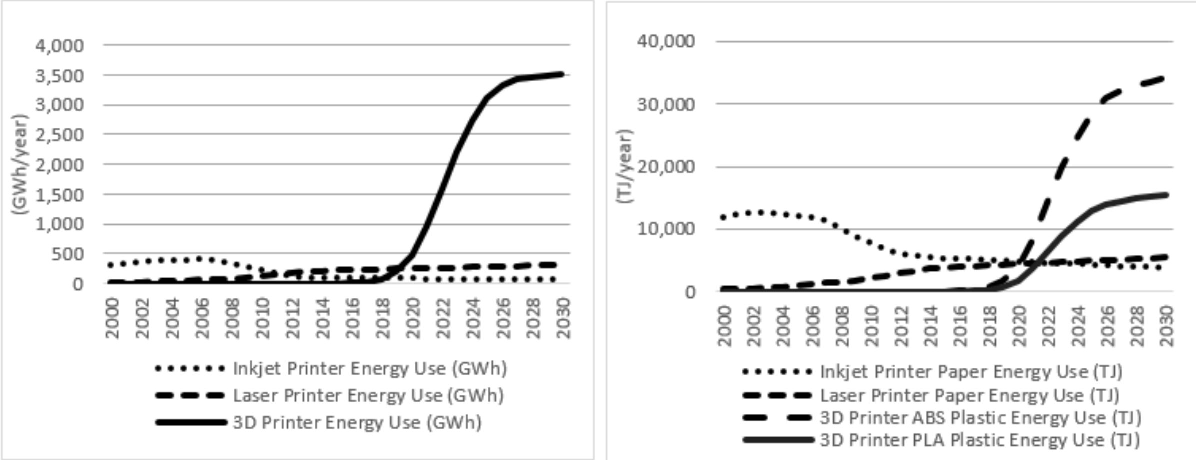


*Figure 3. In-use Energy (GWh/year) and consumable embodied energy (TJ/year) for Three Types of Domestic Printer.*

chain by eliminating the need for transportation of goods. Also highlighted has been the ability of 3D printing to manufacture up to 50 % lighter parts, resulting in fuel savings during in transportation at various points in the lifecycle[16]. However, whilst transportation requirements could contract to some degree, there will still be impacts in terms of the transportation of the printer to the user, the feedstock to the printer location, and the transport of any complex electrical components for use within printed devices. Even if transportation could be eliminated, this would not result in major reductions in environmental impact as transport represents a tiny proportion of lifecycle environmental impacts.

#### DURABILITY AND PRODUCT LIFETIMES

3D printing of spare parts enables the lifetime of existing products to be extended, and can also facilitate the "upcycling" or upgrading of existing products to add new functions. Whilst the combination of CAD tools and the design flexibility for optimisation that 3D printing offers could facilitate more durable designs in principle, there are currently limitations in the material qualities of parts printed with current standard plastic feedstocks. In many cases the part orientation when printed is an important consideration if it is to be placed under sheer or stress loading. 3D plastic printed parts would therefore need to be replaced more frequently in the short to medium term, with corresponding additional impacts in material and energy use than their mass-produced alternatives. Higher strengths may require feedstocks heated at higher temperatures, so a careful evaluation would be necessary of the advantages of greater durability compared against these additional energy impacts.

#### CONCLUSIONS ON ENVIRONMENTAL IMPACTS

The ideal implementation of consumer-level 3D printing in terms of minimising environmental impacts is the centralisation and sharing of the printer in a retail environment in order to optimise use, rather than the presence of an individual printer in each home. Consumer use of printers in the home may result in the printers sitting in idle mode for longer, many trial parts being printed, and parts being less durable so that they need to be printed more often. Use of electrical energy appears to be one of the largest environmental impact of 3D printers,

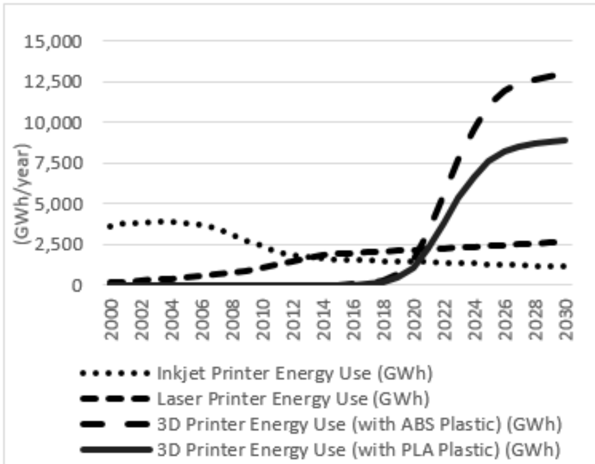


*Figure 4. In-use Energy and consumable embodied energy (GWh/year) for Three Types of Domestic Printer.*

but this could easily be overshadowed by the embodied energy used in the consumables (especially if large amounts of non-recyclable waste material is generated or if large amounts of plastic are used). Embedded energy (materials and energy used in the manufacture of the printer) will be more significant in low-use scenarios such as home use of 3D printers. Transport is not significant, but reductions in transport of products represents a convenience to the user. Health impacts of emissions during the printing process are still unclear.

## The need for policy to address 3D printing

Designs will be refined, prices will become more economical, and sales volumes of 3D printers will increase in future. There is a lack of awareness of environmental considerations, with little information available on energy consumption of consumer 3D printers, and little apparent awareness of energy consumption as a design consideration. Energy use does not currently appear to be tested nor declared in most product specification information – potentially due to a lack of established test methods. There also appear to be no established metrics for printing efficiency in terms of material use and waste.

Policy does not yet explicitly address 3D-printing specific environmental concerns. Governments have begun to look at incentivising the development of 3D printing, including US funding of $30 million (€27 million) for a National Additive Manufacturing Innovation Institute, a UK package of £14.7 million (€13.3 million) for 3D printing projects by innovative enterprises, speculation that the EC intends to set non-binding targets for Member States to invest in and expand the 3D printing industry, and investments of $500 million (€452 million) in Singapore for the development of 3D printing over the next five years. Various organisations have highlighted the need to revise legal rules relating to intellectual property, consumer protection and safety. Some established environmental policies may apply to the very basic aspects of 3D printing, including the standby regulation (EC No 801/2013), the external power supply regulation (EC No 278/2009) and legislation on packaging waste (Directive 94/62/EC), end of life of waste electrical and electronic equipment (WEEE) (2012/19/EU) and hazardous substances in products (ROHS 2011/65/EU). However, there is no legislation that addresses the product-specific environmental concerns that relate to 3D printing, such as energy in use, or waste by-products of printing. 3D printers are not currently a priority product to be addressed under the working plan for Ecodesign legislation (see later discussion).

A preventative approach to mitigate impacts is likely to be much more effective than a reactive approach after the impacts have already occurred. Without a clear policy framework, the 3D printer market is likely to grow without an awareness of energy efficiency considerations. Designs may become locked into less material and energy efficient approaches and opportunities to explore efficiency innovations may bee missed as the market prioritises lowering production costs and improving speed and usability. It is also likely to be more difficult and costly to manufacturers and policy makers to implement product policy for these products at a much later date. Whilst the 3D printer industry is at an early stage of development, there is still time to turn things around.

## Policy approaches to address 3D printing

Challenges to defining policy on 3D printers include the following:

- Definition of the functional unit and usage profiles for impact calculations.
- Gathering detailed product environmental data.
- Developing test methods and standardising metrics for products that vary considerably in design and size.
- Balancing approaches between the various lifecycle impacts.

Various actors will need to be engaged to address these challenges.

### ESTABLISHMENT OF TESTING APPROACHES AND STANDARDS

The foundation to policy work in the area will be the establishment of testing approaches and standards, through working with standards bodies and industry. The EC could publish a mandate for CEN/CENELEC to investigate the potential to develop standards to support this need. However, this can be a time consuming process. The specification, approval and publication of a standardisation request in the Official Journal of the European Commission can take 6 to 9 months. It is then subject to discussion and approval by the European Standards Organisations (ESOs) before standardisation work can commence. The average time for a standard to be produced from this point is 2 to 4 years for a full standard (it can be slightly less for a technical report or technical specification). As such, ideally the 3D printing industry would be encouraged to voluntarily lead the way and develop industry testing standards for 3D printer resource and energy efficiency on shorter timescales, with the view that it could provide a means of further differentiating their products. This could then provide the foundation for formal standard development.

### VOLUNTARY INITIATIVES

Once test methods are available, be they formal EN standards or industry standards, voluntary initiatives to provide the business drivers to reduce environmental impacts can be established such as:

- **EU level:** EU eco-labelling, Joint research centre (JRC) led Code of Conduct, where manufacturers would sign up to meet certain environmental performance targets.
- **Member state level:** Endorsement labels, subsidy schemes, stakeholder engagement on waste considerations, creation of an evidence base on potential environmental impacts which could be consulted on with stakeholders and presented to the European Commission to support 3D printers being considered under the EU Ecodesign Directive (see next section).
- **Industry level:** voluntary industry agreements, publication of eco-profiles/eco-declarations such as Ecma370. Such initiatives may be driven by a preference toward industry self-regulation over EC regulation under ecodesign.
- **NGO level:** Resource efficiency benchmarking initiatives similar to the Greenpeace guide to Greener Electronics[17] or Topten could be used to comparatively assess 3D printers, NGOs could also contribute to the building of evidence bases to support consideration of these products under the Ecodesign directive.

### EU ECODESIGN DIRECTIVE

The EU Ecodesign Directive (2009/125/EC)[18] is a key EU sustainability policy, addressing both competitiveness and sustainable development in line with Europe's 2020 Strategy. The directive aims to improve upon environmental performance of energy related products across the EU, by establishing a framework to set ecodesign requirements or to encourage manufacturer voluntary agreements.

One of the driving forces behind ecodesign is the desire for harmonisation of regulations across the EU, to avoid disparate national legislation that might present obstacles to intra-EU trade. As such, ecodesign can benefit both businesses and consumers, by enhancing product quality, reducing environmental impacts and facilitating free movement of goods across the EU.

Regulations or "implementing measures" may be product-specific ("vertical") or overarching ("horizontal"). For a product to be considered for inclusion under the directive some key attributes must be met:

- Minimum of 200,000 units placed on the EU market each year.
- Have a significant environmental impact within the EU market.
- Offer significant potential for environmental impact improvements without excessive costs.

Working plan studies are implemented periodically (approximately every three years) to assess if shortlisted products meet the above conditions to be formally included in the Ecodesign Work Plan – an indicative list of product groups that are considered as priorities for the adoption of implementing measures, and will progress to the next stage in the Ecodesign process. Industry insights suggest that simple inclusion in an Ecodesign (ErP) workplan is a powerful incentive to motivate a sector to become more efficient. Whilst 3D printer sales levels may not currently meet the minimum sales threshold of 200,000 units per year, it is estimated that such levels might be reached by 2018. The Commission will soon publish the next Ecodesign Work Plan for 2015–2017 so 3D printers could be considered within the following 2018–2020 Work Plan. However, for such innovative and expanding product groups, the Commission could consider allowing some temporary flexibility in the sales consideration for inclusion on the working plan, interpreting the requirement as "Minimum of 200,000 units expected to be placed on the EU market each year within the next 3 years". This would mean that by the time the preparatory studies are completed the sales level would be met in line with the directive requirement. Allowing such flexibility could enable greater agility to address innovative areas and maximise the reduction of implementation cost and environmental impacts.

Once the product group is included on the ecodesign working plan, the next stage is the implementation of a preparatory study which explores the options to improve the environmental performance of the product: This would provide the necessary insight on functional units, usage profiles, detail of environmental impacts and availability of standardised methodologies for measuring the impacts. Building upon this, the next phases in the policy process would include the impact assessment, the consultation forum, and the possible draft implementing measures or EU voluntary industry agreement (as shown in Figure 5).

Taking into account the need to act quickly, the most effective approach may be voluntary in the short term, as this could even be put in place whilst the preparatory study was underway. A shift to regulatory requirements could subsequently by achieved if the preparatory study and impact assessment showed this to be the most effective route (particularly if more stringent requirements than those voluntarily specified by industry are found to be necessary). A pre-requisite for the subsequent development of regulatory requirements would be standardised methodologies to ensure that accurate measurements of impacts can be made – therefore the priority would be to progress with development of standards in the short term.

Looking at the various stages of the 3D printer lifecycle, there are various aspects that could be addressed by policy makers.

#### DESIGN STAGE

Government organisations and NGOs could work to link up organisations working in energy and resource efficient product design with 3D printer manufacturers in order to establish design principles for energy and resource efficiency and create guidelines for an environmentally aware 3D printer design, e.g. energy-efficient operation, power supply sizing and efficiency, low material waste (print quality), durability, design for disassembly and recycling, ease of repair and upgrading, safety, emissions etc.

In order to provide a driver for such considerations to be taken into account, the promotion of efficient models could be achieved via Topten ranking initiatives, SEAD style design competitions etc. In addition, the creation of a forum for the waste management industry to engage with manufacturers and designers could identify opportunities for waste polymer recycling and reduced impact feedstocks – this could perhaps

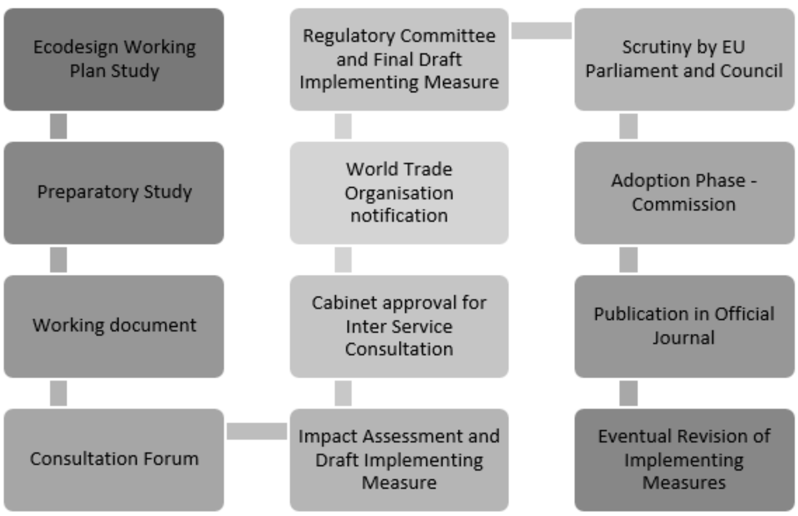


*Figure 5. The EU Ecodesign Process.*

be facilitated by engagement with groups already working with WEEE legislation for other products.

#### PRODUCTION STAGE

The key goal would be to encourage sustainable production taking into account energy and resource efficiency. Manufacturers could be encouraged to become accredited to energy and environmental management standards such as ISO 50001 and ISO 14001 via voluntary codes of conduct or similar so that they consider how to use energy and materials efficiently, use renewable resources where possible and treat waste and pollution as design failures. Manufacturers could also be encouraged to develop supply chain responsibility management programmes at an early stage in the evolution of 3D printers to ensure that supply chain issues are addressed from the beginning.

#### POST-PRODUCTION STAGE

Given the infancy of the 3D domestic printer industry no multi-stakeholder groups have yet been set up to investigate the environmental performance of these products. Organisations, such as the European Commission, could facilitate initial progress by inviting key stakeholders (e.g. manufacturers, policy makers, technical experts, NGOs etc.) to form discussion groups to:

- Facilitate development of test methods and standards for printer energy use and waste, and comparison of environmental and material qualities of feedstocks.
- Facilitate development of accreditation schemes for ecologically preferable feedstocks (i.e. ethical filament initiatives).
- Facilitate the frameworks to enable the gathering and benchmarking of environmental product information on energy efficiency, resource efficiency, feedstock properties etc. In particular this can be facilitated by the provision of templates to facilitate information provision in a clear and consistent way. In the first instance, manufacturers could be encouraged to communicate standardised environmental information about their products through industry declarations such as an adapted Ecma-370 declaration. Once communication of environmental information is an established concept in the industry, all manufacturers could be required to publish environmental declarations through policy measures such as the Ecodesign Directive. Communication of this data would allow comparisons between products which offer similar functionalities, thereby providing greater certainty about the savings potentials that policies could have on these product types.

#### PROCUREMENT STAGE

Many procurement initiatives attempt to encourage "green" or "sustainable" procurement through the development of labelling or specifications which are then integrated into procurement practices. Such initiatives are especially popular within Government procurement for EU Member States, and within EC procurement procedures. For domestic consumers, energy and environmental considerations are unlikely to be priority purchase considerations, especially considering the lack of current information. Therefore the following initiatives could be put in place to raise awareness of energy impacts with consumers and influence their buying decisions:

- Develop either a voluntary or regulatory label for 3D printers that accounts for energy and waste impacts. Current consumer considerations relating to selection of a 3D printer and feedstock would likely be speed, printer cost, choice and cost of usable materials, build volume (which limits the maximum part size), print quality (layer thickness), finish, colour options, dimensional stability and durability.
- Rank 3D printers according to their environmental attributes and list them in a ranking website for consumers and procurers such as the Topten approach (http://www.topten.info/).
- Develop a scheme/label for standardised information provision on feedstock environmental attributes. A label could communicate the relative environmental benefits of each feedstock such as the needs for heating, recyclability, recycled content etc. These labels could be established under existing schemes in the EU such as the EU Ecolabel, Blue Angel or Nordic Swan.
- Create incentives to encourage centrally located retail provision of 3D printers, rather than the purchase of 3D printers for the home. For example, retail provision of 3D printing could be made cheaper through the reduction or elimination of value added taxes. It is expected that market conditions will play a strong role in whether 3D printing is done in the home or within retail premises.
- Provide subsidies on the environmentally preferable options, which may otherwise have a price premium attached to them, such as recycled feedstock, wood-composite feedstock, and the best performing eco-3D printers. Some EU Member States have supported programmes in the past that provide financial incentives for consumers to purchase the most energy efficient products (e.g. Carbon Emissions Reduction Target [CERT] funding in the UK). These kind of policies could be considered in further detail for 3D printers and their consumables.

#### Use Stage

The environmental impacts of a 3D printer are very sensitive to the way in which that printer is used. Therefore user education on efficient use is essential, via:

- Provision of easily understood information on best practice printing, which could be developed by key stakeholders such as the European Commission, Member States or voluntary schemes, addressing aspects such as:
  - How to reduce active, idle/standby and heat up times.
  - How to choose the lowest impact best quality feedstock options for the job (it may be possible to provide a software tool to facilitate decision making).
  - How to maintain the printer to minimise environmental impacts.

  – How to minimise waste in the printing process, use printers efficiently (i.e. saving up items to print as one job in one sitting, instead of several over a larger time-scale) and avoid frivolous printer use.
  – How to recycle failed prints and support structures.
  – How to operate printers safely, in a way that minimises the risk of UFP exposure or injury.
  – How to use printers economically (as the costs and environmental impacts of 3D printers are closely correlated). Whilst the costs of using a 3D printer are unlikely to be prohibitively expensive for most consumers, neither are they likely to be inconsequential, especially if printers are used often.
- Facilitating the design of efficiently printed parts by development of software plug-ins that can be used on designs to refine them to minimise material use and printing time.
- Working with industry to establish initiatives for feedstock cartridge, canister and spool return – moving toward voluntary agreements/commitments if possible. Return of used cartridges in the traditional imaging equipment market is well established and so best practice could be adopted by the newer 3D printing industry. Again an interested party such as the European Commission, Member States or voluntary initiative could draw up a best practice document covering return and recycle programmes for 3D printer consumables and wastes.

### END OF LIFE STAGE

The end of life stage is already covered to some degree by legislation such as the WEEE directive. Product-specific standards could also be developed by CEN/CENELEC to support reducing the end of life impacts of these products – for example addressing durability and upgradability.

## Potential Savings Achievable through Basic Policy Actions

Whilst it has been possible to outline many of the policy actions that could lead to savings in energy and resource use from the operation of 3D printers, attempting to quantify these savings is challenging given the changing nature of this relatively new class of domestic products. For example, identifying power demand reductions in the active mode of these products is problematic since power demand in active modes is closely correlated to functionality during use, which itself is still undergoing rapid development and change. This is a common issue in electronics products where attempts to address energy efficiency in active modes can often result in claims that functionality of a product will be impacted. Where active/operational modes are difficult to address, policy actions on other electronics products often concentrate on achieving increased energy efficiency in low power modes and through the implementation of power management technologies.

A model was developed to estimate the energy use of 3D printers on the EU market, and adapted to estimate the savings that would be achieved by policy measures focussing on low power modes and power management technologies[19]. By ensuring that products are power managed to reduce the amount of time they are left needlessly warming up and that average power demand in low power modes is eventually reduced to 2 W (compared to an average of approximately 8 W seen in current products), it is estimated that savings of around 16.8 TWh between 2018 and 2030 could be achieved. Most of these savings would be achieved by ensuring that the power management functionality, standby and low power modes of these new types of imaging products come under the scope of the EU Ecodesign Regulation on standby[20]. The EU Ecodesign Regulation on standby includes exemptions for certain types of imaging products and exemptions on measures where they are deemed "inappropriate for the intended use". It is believed that these exemptions would not apply to most domestic 3D printers but the appropriate authorities in the EU Member States would need to confirm this assumption in order that these savings could be realised. The results of these calculation can be seen in Figure 6.

It is clear that through the implementation of simple policy measures a large amount of savings could be achieved in these products. Further resource savings could be achieved through policy measures that aim to control the type of consumable material used in domestic 3D printers. Figure 7 shows the impact that using PLA rather than ABS could have on the overall energy use of domestic 3D printers on the EU market. It should be noted that PLA is gaining in popularity over ABS and so many of these savings may already be achieved through consumer choice alone but these savings are not guaranteed. It is estimated that policy measures on power management, low power modes and consumable material choice could result in savings of 48.7 TWh between 2018 and 2030. Additional savings could also be achieved by tackling any inefficiencies in the energy used during operation of printers. Potential savings from these other power modes will be investigated in future work. The Ecodesign Preparatory Study on imaging products identified a total of 20.4 TWh difference between their reference case and best practice cases over a 15 year timeframe[21]. Given that the Ecodesign Preparatory Study addresses both domestic and a large number of non-domestic imaging products it is clear that the potential savings from policy measures aimed at domestic 3D printers are considerable.

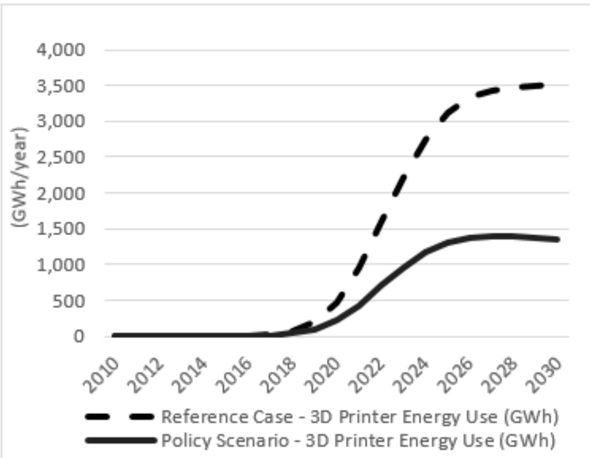


*Figure 6. Reference case (business as usual) and Policy scenario in-use energy resulting from policies addressing power management and low power modes.*

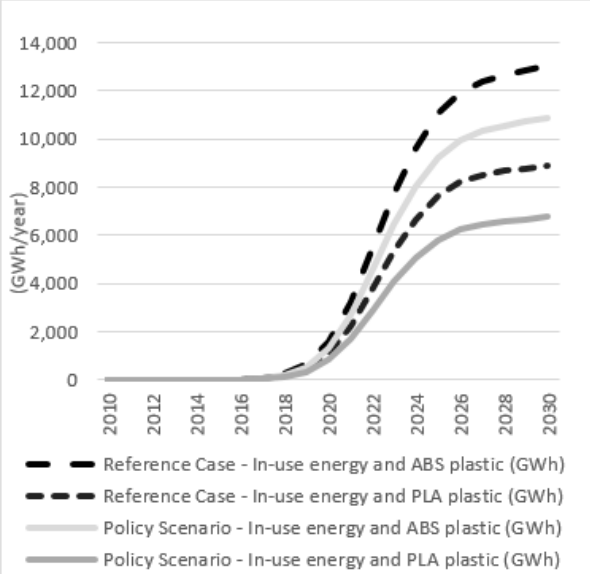


*Figure 7. Reference case (business as usual) and Policy scenario in-use energy resulting from policies addressing power management and low power modes as well as impact of plastic consumable type.*

## Conclusions

Dramatic forecasts of industrial revolutions where mass manufacture is replaced by localised 3D printing should be viewed with some scepticism – it is not something that is likely to happen in the short to medium term, due to current restrictions in materials, cost and usability. However, domestic 3D printing is still likely to be subject to considerable growth both in terms of market and environmental impacts. There is scope for considerable improvement in the environmental impacts of 3D printing, but in order to achieve these improvements it is essential that policy makers act now, rather than waiting for 3D printers to establish themselves within the EU market.

## Endnotes


1 3D Printing 2014 Accelerates from 2013, Pete Basiliere, Gartner Blog, January 2, 2014, http://blogs.gartner.com/pete-basiliere/2014/01/02/3d-printing-2014-accelerates-from-2013/.

2 Technology, Media & Telecommunications Predictions 2012, Paul Lee and Duncan Stewart, Deloitte Global Services Limited, 2012.

3 Gartner Says Worldwide Shipments of 3D Printers to Reach More Than 217,000 in 2015, Gartner, 27th October 2014, http://www.gartner.com/newsroom/id/2887417.

4 A Third Industrial Revolution, Paul Markillie, The Economist, UK, Apr 21st 2012.

5 3D printing, Digital Agenda for Europe – Futurium, https://ec.europa.eu/digital-agenda/futurium/en/content/3d-printing.

6 Technology, Media & Telecommunications Predictions 2012, Paul Lee and Duncan Stewart, Deloitte Global Services Limited, 2012.

7 Z Corporation 3D Printing Technology – Fast, Affordable and Uniquely Versatile, Z Corporation, United States, 2005.

8 A 3D-printed key to the factory of the future, Horizon 2020 – The EU Framework Programme for Research and Innovation, European Commission Newsroom Editor, 18th December 2013, http://ec.europa.eu/programmes/horizon2020/en/news/3d-printed-key-factory-future.

9 Environmental Impacts of 3D Printing, Jer Faludi, UC Berkeley mechanical engineering department, December 2013.

10 Technology, Media & Telecommunications Predictions 2012, Paul Lee and Duncan Stewart, Deloitte Global Services Limited, 2012.

11 Low-cost metal 3D printer could be the next step in home manufacturing revolution, The Independent, James Vincent, UK, 10th December 2013.

12 How 3D printing can revolutionize sustainable design, Asheen Phansey, 29th May 2014, http://www.greenbiz.com/blog/2014/05/29/3d-printing-revolutionize-sustainable-design.

13 Ultrafine particle emissions from desktop 3D printers, Brent Stephensa, Parham Azimia, Zeineb El Orcha, Tiffanie Ramosa, Atmospheric Environment Volume 79, November 2013, Pages 334–339, Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA and National Institute of Applied Sciences (INSA de Lyon), Lyon, France.

14 FAQs: 3D Printer/Filament Usage, ReprapCentral, 2013, http://www.reprapcentral.com/General/faqs.html.

15 Is Eco-Friendly 3D Printing a Myth? Melba Kurman, Triple Helix Innovation and Hod Lipson, Cornell University, United States, July 20, 2013.

16 News article: ATKINS Project: a low-carbon manufacturing solution, Loughborough University, 15th January 2009, http://www.lboro.ac.uk/service/publicity/news-releases/2009/03_ATKINS.html.

17 http://www.greenpeace.org/international/en/campaigns/climate-change/cool-it/Campaign-analysis/Guide-to-Greener-Electronics/

18 Ecodesign Directive (2009/125/EC), European Commission, http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/.

19 Adapted version of CADENCE – Appendix O, Modelling Approach. Kevin Lane, 2000, Environmental Change Institute, University of Oxford, UK.

20 Commission Regulation (EU) No 801/2013, European Commission, http://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri=OJ:L:2013:225:0001:0012:EN:PDF.

21 EuP Preparatory Study Lot 4 (Imaging Equipment) Final Report Task 8, Fraunhofer for European Commission, May 2008, https://circabc.europa.eu/sd/a/6b13a5b7-8aac-4be4-bc61-de8a1ea531f8/Lot%204_T8_ Final_Report_2008-05-07.pdf.