Additively manufactured nanoporous foam targets for economically viable inertial fusion energy

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Abstract:

Nuclear fusion is receiving tremendous global interest due to its promise as a source of clean and abundant energy. Although scientific breakeven was recently demonstrated via inertial confinement fusion, economic breakeven has not yet been achieved in any form of fusion. A key barrier for economic viability is the high cost of fabricating the fuel containers (i.e., the targets). Here, we present a quantitative framework and apply it to generate a target manufacturing technology development roadmap to enable economically viable inertial fusion energy. We examine the impact of our recent work in nanoscale additive manufacturing (i.e., 3D printing) and identify the next steps toward economically viable fusion energy. Our analysis has implications for manufacturing technology developers, fusion power plant designers, funding agencies, and policy makers. It demonstrates that economic target manufacturing cannot be achieved by merely increasing the industrial capacity; instead, novel affordable manufacturing technologies must be developed.

Keywords: Clean energy, inertial confinement, fusion power plant, 3D printing, target manufacturing

Social Impact: Affordable and Clean Energy via Nuclear Fusion

Ensuring access to affordable, reliable, sustainable, and modern energy is a major societal challenge of the 21st century and it has been adopted as one of the 17 United Nations Sustainable Development Goals (SDGs). The SDGs were adopted by United Nations Member States in 2015 as an urgent call for action toward achieving peace and prosperity for people and the planet [1]. Specifically, SDG 7 calls for action to ensure access to affordable, reliable, sustainable, and modern energy. At present, more than 80% of the global energy consumption is served by burning fossil fuels [2], which are unsustainable sources of energy, generate massive amounts of greenhouse gases, and have significant adverse effects on the climate, environment, and health [3]. The remaining energy demand is primarily served by renewables and nuclear fission, which are cleaner and more sustainable energy sources. However, renewables, such as solar and wind, are unreliable due to their intermittent nature and many countries are phasing out nuclear fission plants due to radiation safety concerns. Thus, there exists an urgent need to develop an alternate source of clean energy. Toward this goal, nuclear fusion is a promising source of clean, reliable, and abundant energy with minimal radiation risks [4]. However, due to significant technological barriers, it has not yet been possible to develop a fusion power plant (FPP) that can generate more energy than it consumes. One major barrier is the lack of manufacturing capability to rapidly and economically produce the fuel containers that must be routinely burned in a future FPP based on inertial fusion. Here, we focus on examining the path to overcoming the technological barriers to manufacture these fuel containers toward achieving the overall goal of developing an economically viable commercial FPP.

Nuclear fusion is ubiquitous in nature as it is the source of energy generated by the sun and other stars. However, achieving and controlling nuclear fusion on earth has been notoriously difficult. Nuclear fusion refers to the reactions wherein multiple smaller atomic nuclei merge (i.e., fuse) together to form a larger atomic nucleus that has a slightly lower mass than that of the reacting nuclei. This loss in mass is released as energy, and can be quantified through Einstein's famous mass-energy equivalence relationship, $E=mc^2$. As atomic nuclei tend to repel each other, the reacting nuclei must be confined so that they can fuse. On the stellar scale, this confinement is achieved via the inward gravitational pull of the stars themselves. On earth, the confinement is achieved on a smaller scale by applying either magnetic forces or inertial forces. Uncontrolled fusion reactions that generate more energy than they consume have been achieved in thermonuclear weapons for more than half a century. In contrast, such controlled fusion reactions were demonstrated for the first time only recently in December 2022 via inertial confinement fusion (ICF) experiments performed at the Lawrence Livermore National Laboratory (LLNL) in California, USA [5]. These experiments overcame a major scientific barrier to harnessing nuclear fusion for clean energy production by demonstrating scientific breakeven, i.e., by demonstrating that more energy can be produced via a controlled burn of the fusion fuel than is required to burn it. Nevertheless, significant technological barriers still exist toward building an FPP.

One major technological barrier that prevents achieving economically viable inertial fusion energy (IFE) production in a commercial scale FPP is the inability to produce the fusion fuel containers rapidly and economically. These containers are called as capsules or targets in the ICF literature [6]. ICF targets are typically in the form of pea-sized spherical shells that contain the nuclear fuel. Common nuclear fuels are mixtures of deuterium and tritium, which are isotopes of hydrogen. To burn the fuel via nuclear fusion, the targets may be compressed either directly by illuminating with lasers or indirectly by X-rays generated with lasers. Although each individual target is small, target fabrication is slow and expensive because the targets must meet stringent geometric requirements to achieve fusion. The cost of each target can be in the order of thousands of US dollars [7], and fusion targets are produced today to satisfy burn rates of about one target per day at LLNL laser facilities [8]. As the total fusion energy content of each target is on the order of 20 kWh [6], producing industrial scale electricity necessitates dramatically reducing the cost of the targets and increasing the burn frequency. Thus, significant improvements are required in both the rate and the cost of manufacturing the targets to enable a commercial FPP based on inertial fusion. Here, we present a quantitative framework to determine the improvements that are required in the target manufacturing rate and cost for economic feasibility of FPPs. We also apply the framework to generate a target manufacturing technology development roadmap to enable economically viable inertial fusion energy.

Our focus here is on examining the impact of nanoscale additive manufacturing (AM) technologies on enabling rapid and economic manufacturing of the targets. It has been found that more fusion energy can be produced per target if the targets were to be made from nanoporous foams instead of bulk solid material [9]. Therefore, developing the manufacturing capability to produce nanoporous foams rapidly and affordably is of significant interest to enable economically viable FPPs. However, stochastic foams that are produced by conventional fabrication techniques often fail to meet the stringent geometric requirements. Nanoscale AM techniques, that can deterministically print the nanoporous foam structures, are well suited to satisfy the geometry-based requirements for IFE. Here, we: (i) demonstrate that our recent work on nanoscale AM advances target manufacturing along the desired path to develop economically viable FPPs [10], and (ii) identify directions for further development of nanoscale AM technology for IFE.

Methodology: Cost and Rate Requirements for Target Manufacturing

Herein, we have generated a framework to quantitatively compare the impact of improvements in the performance of nanoscale AM technologies on the economic viability of IFE. Within the context of target manufacturing, the following two conditions must be met to develop a commercial FPP: (i) the cost of fabricating a target must be low enough so that it can be fully recovered by selling a fraction of the fusion energy generated per target and (ii) the targets must be produced at a sufficiently high rate to generate industrial-scale power by frequently burning multiple targets. The second constraint represents the desired production capacity for targets. If the first constraint is satisfied, the second constraint can be readily satisfied by installing more machines to fabricate the targets. Therefore, here we focus on the conditions that satisfy the first constraint to quantify the desired cost and rate of fabricating the nanoporous foam targets.

We quantify the desired fabrication cost by introducing the concept of the energy budget per target (E_t). It is the amount of energy that is available to be sold to recover the cost of fabricating each target. In an FPP, this energy will be generated by burning the target and it will be a fraction of the total fusion energy generated per target (E_f). Here, we have used the energy budget terminology to highlight that for economic viability, the revenue generated from selling the fusion energy must be allocated across the different expense sources. The two energies are related as: $E_t = f \eta E_f$. Here, η is the plant efficiency and it represents the fraction of the total fusion energy generated that can be sold, whereas f represents the cost recovery fraction, i.e., the fraction of the sold energy that can used to recover the cost of fabricating the target (C_t). For economic viability, the cost C_t must be no more than the selling price of the energy budget per target. If C_e is the selling price per unit of energy, this constraint can be represented as:

$$C_t \leq E_t C_e \tag{1}$$

We quantify the desired rate of fabrication by first evaluating the cost of manufacturing the targets as a function of the production rate and then evaluating the production rate at which the cost of manufacturing will satisfy the economic viability constraint represented by equation 1. In general, the cost of manufacturing a product is determined by three distinct sources of expenses: (i) the cost of the raw material, (ii) the cost of the consumable tooling, and (iii) time-based costs that are incurred due to the need to recover the capital cost of the manufacturing equipment over a period of time and to pay for operating costs that are incurred per unit time during production. For AM processes, the tooling cost is absent because no part-specific tooling is required. For foam targets, the material cost per target is negligible (i.e., < \$0.01). This is because each foam target can be made out of less than 1 mg of polymeric material if the density is <1 g/cm^3 [9], and the volume is approximately 1 mm^3 [6]. Thus, the cost of fabricating targets via nanoscale AM is determined by the time-based expenses. These expenses can be split into two major sources: (i) the initial capital cost of the printer which must be recovered over the lifetime of the printer (T_p) and (ii) the recurring cost of operating the printer which is driven by the overhead cost per unit time. For simplicity, here we consider that the equipment cost of the printer (C_p) is the only capital cost, and that the electricity cost of operating a printer of a fixed wall power (P) is the only overhead cost. The time required to produce each target (t_t) can be evaluated from the printed volume of each target (V_t) and the volumetric rate of 3D printing (R_t) as: $t_t = V_t/R_t$. The fabrication cost of each target can then be represented as: $C_t = t_t\,(C_p/T_p + C_e\, P)$. The first term inside the parenthesis represents the capital cost and the second term represents the recurring overhead cost. By representing t_t in terms of the printing rate and substituting the cost relationship in the constraint equation 1, the following constraint on the rate of 3D printing can be obtained:

$$R_t \geq \frac{V_t}{E_t}\left(\frac{Cp}{C_e T_p} + P\right) \tag{2}$$

To quantify the desired cost and rate of printing, we substitute realistic numerical values for the parameters in equations 1 and 2. The printed volume of the shell of the target is on the order of V_t =1 mm^3 [6]. For the printer, P= 2 kW, C_p = \$0.5 million and T_p = 10000 hours are reasonable estimates. The printer lifetime corresponds to the advertised lifetime of commercial femtosecond lasers that drive these printers. The wall power and cost correspond to the values for operating and buying commercial femtosecond lasers and other off-the-shelf commercial components of the printers, such as those used in the custom-built printer in our recent work [10]. For the selling price of energy, we use an estimate of C_e = \$0.3/kWh, which is on the higher end of the retail price of electricity in the U.S. market. The most challenging parameter to estimate is the energy budget per target (i.e., E_t) because commercial FPP designs are not readily available at this time. Nevertheless, here we have used the December 2022 LLNL fusion demonstration to estimate E_t. In those tests, 3.15 MJ of total fusion energy was generated by burning 4% of the fuel contained in a single target. Therefore, a maximum fusion energy of E_f = 79 MJ may be generated by fully burning the fuel. We consider a plant efficiency of η=0.25 and the cost recovery fraction f of 0.36. This plant efficiency is equal to the global average efficiency of fossil fuel power plants in the early 1950s [11], and it is lower than the efficiency of current U.S. coal power plants (0.33). The value of f is similar to the cost recovery factor for coal fuel in coal power plants. Our choices for efficiency and recovery factor are somewhat arbitrary because these will vary with the specific design of the FPP. Nevertheless, making these selections here allows us to quantify the minimum printing rates for representative FPPs. The numerical values can be revised later, within the framework presented here, when more accurate estimates are available. Considering these values for η and f is equivalent to considering that the cost of fabricating the target is 9% of the total fusion energy content of the target. With these values, E_t = 7 MJ. By applying constraint equations 1 and 2, the fabrication cost per target must be less than \$0.6 and the volumetric rate of printing must be greater than 90 mm^3/hr.

Our recent work on 3D printing of nanoporous foams using the projection two-photon lithography (P-TPL) technique achieved a volumetric printing rate of 1 mm^3/hr [10]. At this rate, each target can be fabricated in an hour and at a cost of \$50 per target. Thus, the 3D printing performance that we achieved is about 100 times worse than the desired rate and cost for an economically viable FPP. Nevertheless, our work represents a factor of 100 improvement over past demonstrations of nanoporous foam printing wherein a rate of printing of 0.01 mm^3/hr was achieved [12]. This lower rate would result in an estimated cost of \$5000 per target, which is comparable to the cost of targets used in ICF experiments [7]. It is noteworthy that although faster nanoscale AM techniques have been demonstrated, including our own past work on P-TPL [13], these techniques are inappropriate for target manufacturing because the ability to produce the desired nanoporous structures has not yet been demonstrated with these techniques.

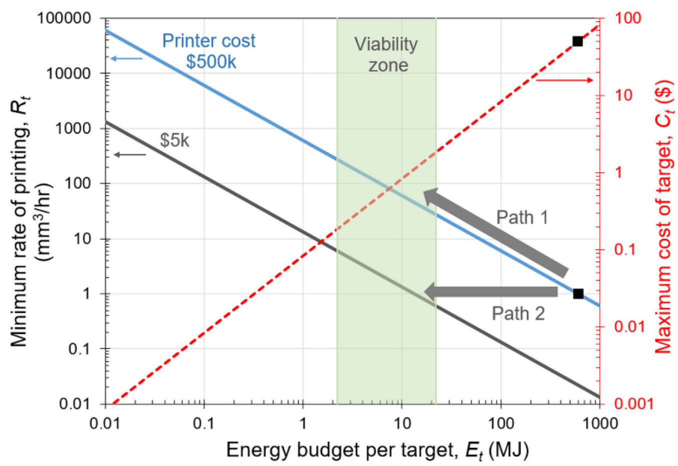

Figure 1: Limits of the rate of printing and the cost of each target for economic feasibility of target manufacturing as a function of fusion energy budget per target. The roadmap for the development of nanoscale additive manufacturing to enable economically viable inertial fusion energy is marked as 'Path 1' and 'Path 2'.

We have generated a technology development roadmap for target manufacturing by quantifying the rate and cost constraints for various combinations of printer cost and energy budget per target. This roadmap can help clarify the amount of improvement that is necessary to achieve economically viable IFE. The rate and cost limits are shown in Figure 1. For a specific value of the energy budget per target E_t, fusion will be economically viable when the rate of printing is above the rate limit and the cost of the target is below the cost limit. The cost constraint is guaranteed to be satisfied when the rate constraint is satisfied because the rate constraint was derived from the cost constraint. The rate and cost constraints become more relaxed when the energy budget per target increases. However, increasing the energy budget is technologically challenging because that would require burning more fusion fuel per volume of the target material. We have marked a band around our estimated E_t value, which spans one decade of E_t, and it represents the desirable region for the cost and rate of nanoscale AM to enable economically viable IFE. The rate and cost of target manufacturing for our work (i.e., [10]) are also marked on the figure with solid square symbols. It is noteworthy that the rate and cost for the previous work (i.e., [12]) are so inferior that the markers fall outside the range of E_t shown in the figure. To achieve economic viability, the rate of printing must be further increased by about 100 times. This technology development path is marked as 'Path 1' in the figure.

We have also shown an additional rate limit curve for a hypothetical printer that costs 100 times less. For this lower-cost printer, economic viability can be achieved without any further improvements in the printing rate. Thus, an alternative technology development path would be to reduce the cost of the printer by at least 100 times (i.e., 'Path 2' in the figure). By applying equations 1 and 2 for various combinations of printing rate and printer cost, one may generate additional paths that arrive at economic viability through a combination of improvements in the printing rate and printer cost.

Results and Implications: For Economically Viable Inertial Fusion Energy

The contributions and implications of this study are summarized in Figure 2. Our key contributions are: (i) the development of a quantitative cost analysis framework to determine the improvements that are needed in target manufacturing to enable economically viable inertial fusion energy, (ii) estimation of relevant fusion energy production performance metrics based on the 2022 LLNL inertial fusion scientific breakeven demonstrations, and (iii) comparison of the current target manufacturing capabilities with the desired manufacturing capabilities for the estimated fusion performance. Although our estimates of fusion energy production are expected to change with advances in IFE, the analysis presented here has broad implications for various stakeholders. Specifically, our analysis has implications for additive manufacturing technology developers, target manufacturers, inertial fusion energy-based power plant designers, funding agencies in the area of fusion energy, policy makers for clean energy, and other relevant stakeholders.

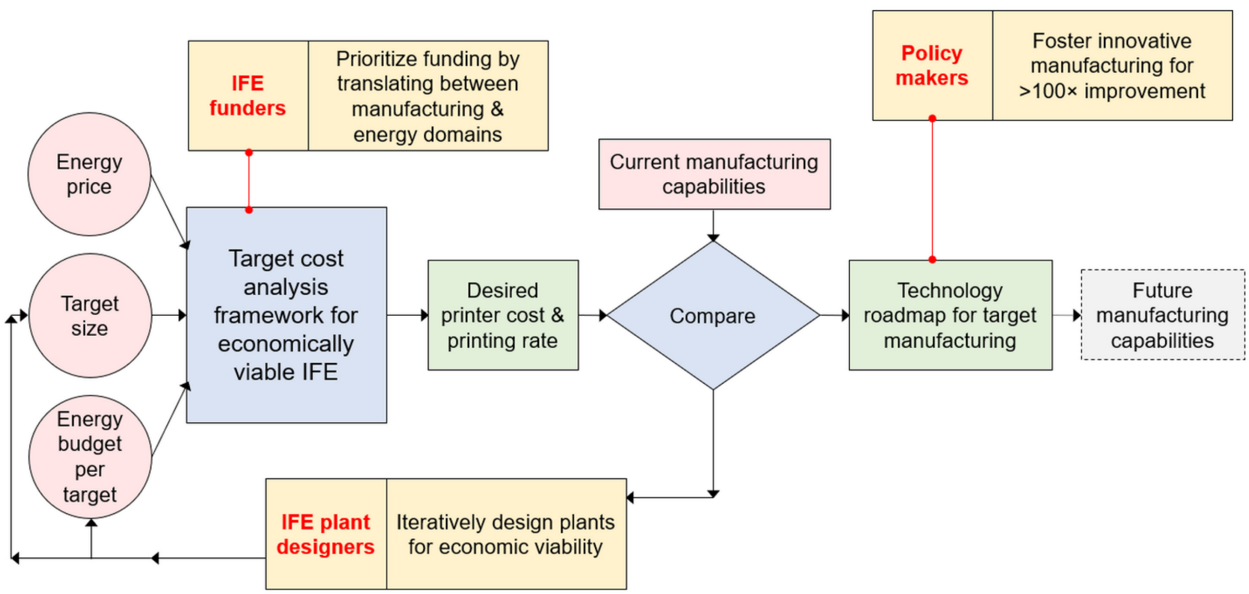

Figure 2: Contributions of this work and its implications for enabling economically viable inertial fusion energy.

Researchers and practitioners in nanoscale additive manufacturing can help enable economically viable inertial fusion energy by focusing on further increasing the volumetric rate of 3D printing per equipment by at least a factor of 100 times to a desired rate of 100 mm^3/hr. Alternatively, they may focus on reducing the cost of the printer by 100 times, while maintaining the current rate of printing. These two approaches are marked as 'Path 1' and 'Path 2' on Figure 1. Additionally, it must be ensured that the fabrication technique can indeed satisfy the stringent geometric requirements for fusion targets. Target manufacturers who want to use non-additive processes can also determine the improvements that will be required in the fabrication rate and cost by mapping their current performance in Figure 1. For this mapping, the numerical values on the rate axis (i.e., the left-side vertical axis) can be directly interpreted as the number of targets produced per hour per machine because a benchmark target volume of 1 mm^3 was used here.

FPP designers who would like to make design decisions based on economic feasibility can apply the analysis presented here to determine whether their designed plant efficiency, total fusion energy generated per target, and the recovery factor would be economical for a given cost of the target. The cost axis in Figure 1 (i.e., the right-side vertical axis) can be generalized to represent the total cost of the target including the cost of the fuel. In such an analysis, the recovery factor (f) must be interpreted as the recovery factor for the total cost of the target. FPP designers can also apply the analysis presented here to identify the design goals for energy budget per target based on current or projected target manufacturing capabilities. For example, it can be deduced from Figure 1 that with the current state-of-the-art nanoscale AM, economically viable IFE can be achieved with a plant design that allocates an energy budget per target of at least 600 MJ. This design goal is highly ambitious, but it will change with improvements in the cost of the printers and the rate of printing. Various designs that vary in the plant efficiency, recovery factor, total fusion energy generated per target, and target size may be explored to achieve the desired energy budget per target.

As several different types of IFE-based FPP designs are actively being pursued around the world, funding agencies and other stakeholders can compare the relative economic viability of the designs by using the concept of the energy budget per target. This is the amount of energy that must be sold to recover the cost of the target. In a commercial FPP, it must always be less than the sellable fusion energy generated per target. FPP designs may vary widely in terms of the output power, the target gain (i.e., the ratio of fusion energy produced to energy input required per target), and the plant efficiency. Consequently, it is challenging to compare different designs without delving into the technical details. The energy budget per target helps overcome this challenge by providing an implementation agnostic means to compare the economic viability of FPP designs within the context of target manufacturing. For example, plant designs that have a low energy budget per target cannot become economically viable without significant improvements in the target manufacturing capability. It is important to note that this conclusion remains valid even if the plant efficiency and the recovery factor for the specific FPP design differ from the values used in our numerical estimates. This is because the constraint equations 1 and 2 quantify the cost and rate limits directly in terms of the energy budget per target and do not depend on the specific values of the plant efficiency and the recovery factor. If the energy budget per target is specified for a plant design, the plots in Figure 1 can be used to quantify the degree of improvement required in the cost and rate of 3D printing to achieve economic viability with respect to target manufacturing. This kind of information is highly valuable in determining funding priorities for IFE technology development.

Finally, national and international policy makers can appreciate that the target manufacturing capabilities that are required to enable economically viable inertial fusion energy cannot be achieved by merely building more factories to manufacture the targets. Instead, we need novel ways of making the targets so that the cost of the targets can be drastically reduced. This is an important insight because it demonstrates the need for policies that can promote manufacturing innovation. Achieving this innovation will require significant and sustained investment of economic resources and human capital on the research and development of advanced manufacturing technologies for targets. Such an investment is sorely lacking today.

Conclusions

Although inertial fusion is a promising source of clean and abundant energy, many technological barriers must be overcome to enable economically viable production of electricity from fusion. A key barrier is the inability to rapidly and economically produce the fuel containers, i.e., the targets. Here, we have analyzed the relationship between target manufacturing capabilities and the economic viability of inertial fusion energy for the specific case of nanoscale additive manufacturing technology. We have developed a quantitative cost analysis framework to determine the improvements that are required in the target manufacturing capability to achieve economically viable fusion energy production. As part of the framework, we have introduced the concept of energy budget per target, which is the amount of energy that must be sold to recover the cost of the target. We have used the data from the 2022 LLNL inertial fusion scientific breakeven demonstrations to estimate a range of expected energy budget per target. By using these estimates, we have developed a technology development roadmap for nanoscale additive manufacturing to enable economically viable inertial fusion energy. The roadmap calls for an increase in the rate of printing by 100 times or a decrease in the cost of the printer by 100 times, relative to our past work. Our past work had increased the rate of printing by 100 times over the state-of-art, but further improvements are necessary. In future, fusion power plant designers can apply our framework to set up their design goals for the energy budget per target and the target size based on current or projected target manufacturing capabilities. Further, funding agencies and investors can determine funding priorities for inertial fusion energy technology development by applying the cost analysis framework presented here to translate improvements in manufacturing capability to improvements in fusion energy. Perhaps the most important implication of our work is for policymakers to appreciate and act on the insight that achieving economically viable inertial fusion energy will require significant and sustained investment of economic resources and human capital on the research and development of advanced target manufacturing technologies.

Ethics Statements

This manuscript adheres to the guidelines for Ethics in Publishing.

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Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The author is a co-inventor on multiple pending and issued patents related to nanoscale additive manufacturing, and the rights for these inventions are assigned to either Georgia Tech Research Corporation or Lawrence Livermore National Security, LLC.

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