



Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Additive manufacturing for sustainable energy production in pico hydroelectric power plants

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Additive manufacturing
Selective laser melting
Sustainable manufacturing
Pelton turbines

ABSTRACT

Additive manufacturing has proven to be a reliable method of producing components that are often difficult to produce using traditional methods. The growing worldwide energy demand requires the development of new innovative approaches to sustainably produce energy. This necessitates the development of small pico-hydroelectric power plants, which are more sustainable and practical for decentralized energy production. This study investigates the capacity of additive manufacturing to fabricate tiny, miniature hydroelectric power turbines using Selective Laser Melting. The study goes on to explore ways to make it more sustainable, such as modifying process parameters to achieve a minimum surface roughness and using a parametric design approach. The results of the methods used were validated by measuring the surface roughness and dimensional accuracy using profilometry and reverse engineering techniques. The findings showed that the methods used in this study could be used to obtain a customizable solution for manufacturing pico-turbines sustainably without the need for additional post-processing.

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Selection and peer-review under responsibility of the scientific committee of The International Conference on Additive Manufacturing for a Better World.

1. Introduction

The global energy demand is predicted to increase by 50 % by the year 2050 [1]. It is of utmost importance to develop systems to produce clean and sustainable energy to cater for these energy demands. Out of all the energy solutions, renewables are the most promising solution to the present energy crisis. Hydroelectric power generation is the most tested and used form of renewable energy for ages. In an industrial context, it has already attained its maximum capability and there are few adjustments that need to be done in this sector. Even though hydroelectric power generation is considered a renewable source of energy production, it is still not entirely deemed sustainable factoring in the numerous environmental impacts caused by its huge reservoirs and the unnatural flow downstream. There is an alternative in hydroelectric power generation that considers smaller water basins, streams, and aqueducts. Micro or Pico turbines may be utilized to produce electricity for small communities often in remote locations in a much more sustainable manner. These localized energy generation

systems can also eliminate the need for costly transportation and conversion systems, which contribute to significant environmental damage.

Owing to its small size and complex shape, additive manufacturing (AM) could be a go-to option when it comes to the fabrication of these turbines. AM is also inherently a sustainable manufacturing process with minimum material wastage, process reduction, recyclability of the raw materials etc. [2]. The use of AM for various sustainable energy production is reviewed in [3]. It is also economical for these highly customized small batch productions. The manufacturing process, specifically the process parameters and scan strategies, has the most impact on defect formation and has been studied by numerous researchers [4–7]. The process parameters can be adjusted in such a way to obtain desired final part qualities and thereby minimize the further stages of manufacturing like post-processing.

Processes like electrochemical finishing, laser beam finishing, high and low energy mass finishing, and controlled 5 axis milling, are the usual post-processing operations performed on the AM manufactured parts. Out of this, the first two processes are difficult to perform owing to the complex geometry of the turbine impeller. High energy methods can in turn finish off the delicate details

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which are critical for the impellor. Even though CNC is a realistic solution for eliminating surface roughness, its adoption comes at a high expense, both in terms of machining time and the time required to design the toolpath for a four or five-axis machine. Boschetto et al. [8] have developed a model to predict the surface roughness as a function of local part geometry that is also capable of considering the staircase effects and other actual defects, such as balling. According to numerous studies, the stratification angle (α), defined as the angle formed by the vector normal to the considered surface area and the stratification vector, has a significant impact on the final surface roughness. Calignano et al. [9] found out that for angles between 6°–115°, the average roughness obtained was around 20 μm , and for angles lesser than 6° (almost horizontal surface), the average roughness is around 6 μm . When the stratification angle is above 115°, the worst surface roughness is obtained at around 45 μm . This paper provides a customizable solution using AM to design and manufacture a pico-hydroelectric turbine that caters to specific flow rates and energy requirements. A design of experiment was done to find process parameters to obtain the desired surface roughness that can avoid further post-processing.

2. Materials and methods

2.1. Selection of technology and materials

The research aims to sustainably manufacture a turbine using additive technologies that can be easily implemented in a pico-hydroelectric project. Since the turbine blades must deal with large hydraulic forces with preferably long life, it is advisable to select a technology that can fabricate metal parts. Out of the different additive technologies, Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) is the most popular choice for metal fabrication [10]. However, the latter frequently results in final products with poor surface quality and tolerances, which is undesirable for producing a complicated geometry with tight tolerances such as a turbine. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) are all part of the PBF category [11]. SLM is now the most widely used technique because it enables finishes and tolerances that are impossible to achieve with other methods [12].

There are a broad variety of materials that can be used with SLM which includes steels, cobalt-chromium alloys, tool steels, nickel alloys, stainless steel, tungsten, titanium alloys, precious metals. The key factors considered when selecting the materials are the cost, the weight, the production speed, and recycling. Considering the cost associated with the materials, the most expensive materials were first excluded. Later, the materials with higher powder densities that could contribute to the weight were also excluded. Thus, three materials were shortlisted, which have a good strength-to-weight ratio and are commonly available for the SLM process (Table 1). There is no doubt that the aluminum alloy comes out to be a clear winner from the comparison. It is also the most sustainable option with easy recyclability as it requires almost 95 % less energy compared to making the metal from its original bauxite ore [13]. It can be also seen that it has the highest production speed providing the best solution for faster manufacturing.

Table 1
Comparison of three shortlisted materials.

Material	Cost (€/Kg)	Density (Kg/dm ³)	Cost per liter (€/dm ³)	Production speed (cm ³ /h)
Steel 316L	100	7.8	780	7.2
Titanium Ti6Al4V	150	4.8	660	13.5
Aluminum AlSi10Mg	70	2.8	189	18.6

2.2. Selection and design of turbine

The selection of a turbine comprises technological, environmental, economic, and other considerations. The selection approach was devised to discover a suitable turbine unit, estimate its primary dimensions, and project its performance quickly based on technological and economic factors. Looking into the previous research in mini hydroelectric power generation [14,15], it was found that the Pelton turbines are the best choice for 30 to 300 m head and a minimum discharge of 0.5 L/s. The Pelton turbine is a form of impulse turbine that generates power from a high head using a spear and nozzle combination. The water shoots out of the nozzle and into the bucket; its velocity decreases, producing an impulsive force that causes them to spin. The design of the micro-Pelton turbine was conducted by studying the guide by Eisenring [16]. This includes head calculations, flow calculations, power calculations, speed calculations, velocity calculations, diameter calculations, and the respective bucket dimensions.

The research examines how the entire system must be customizable and provide a quick and cost-effective impeller manufacturing solution for unique applications. The construction of the turbine solid model is the first hurdle to the plan's quick execution; hence a parametric design was considered. This allows us to validate the solid model using only the turbine parameters as input. The turbine's CAD models were developed using Autodesk Inventor software.

2.3. Selecting the SLM process parameters

The idea is to minimize the surface roughness of the functional surfaces so that no extra post-processing would be required. In the Pelton turbine, the surfaces in contact with the fluid and the surface coupling with the hub are both important functional surfaces to consider. An experimental plan was undertaken to develop models for predicting the average roughness as a function of the processing parameters. It is an extension of the work [17]: the same geometry with four surface angles, namely 0°, 45°, 90°, and 135° (Fig. 1a), was employed in a Box-Behnken design. It is an independent quadratic design where the combinations of the factors are at the midpoints of the edges of the process space and the center [18]. It is rotatable and requires three levels of each factor. For horizontal surfaces, i.e., the 0° surfaces, the well-known Volumetric Energy Density (VED) was considered, varying the laser power (P), the hatch distance (Hd), and the scanning speed (v) according to the design space and levels shown in Fig. 1b. Other slopes are affected by the contour processing parameters, namely P, v, and the contour offset (Co). The levels and design space are shown in Fig. 1c. The modification of the processing parameters is applied only to the scanning of the surfaces by adding a contour strategy to the standard EOS exposure sequence. This way, the internal hatching and the bulk properties of the final component are not affected. Conversely, the application of different VED and linear energy density (LED) will result in a surface roughness modification is expected.

The blades are manufactured from AlSi10Mg using the SLM process, as mentioned in the previous section. For the part's fabrication, an EOS M290 machine was chosen. The configurations used

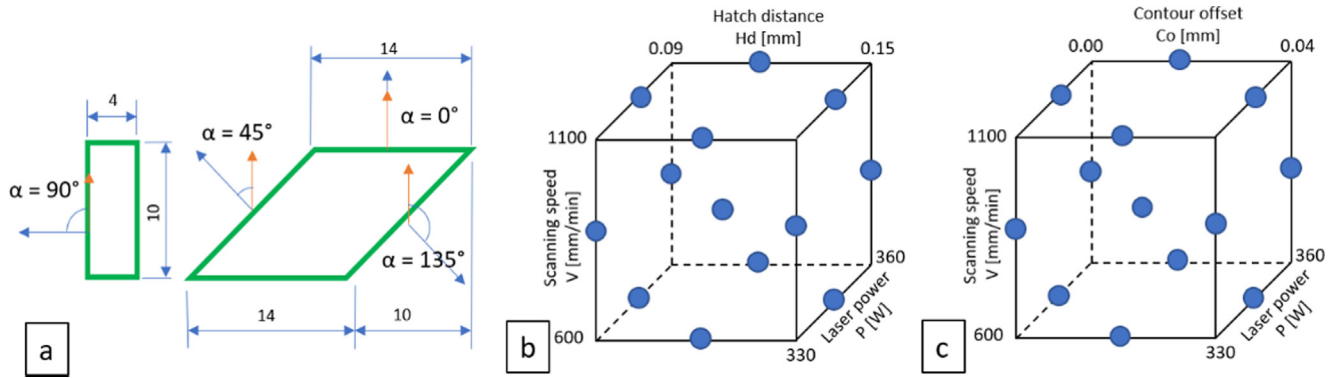


Fig. 1. Specimen geometry (a), experimental design for up skin (b), experimental design for contours (c).

were 160 °C platform temperature, 150 mm/s recoater speed, and argon protective gas recirculating at a differential pressure of 0.38 bar. Only five blades with different orientations to the base plate, namely 0°, 22.5°, 45°, 67.5°, and 90°, were manufactured for this study.

2.4. Validation of the process

In this step, the produced components will be assessed utilizing Reverse Engineering (RE) and roughness assessment techniques. The approaches used in this study are validated by analyzing the functional surfaces of the turbine and calculating their divergence from the desired values.

2.4.1. Roughness measurement

For all five orientations, the surface roughness of the critical surfaces, i.e., the inside of the bucket, is measured with a Mitutoyo Surftest SJ-412 roughness tester. For data filtering, the following parameters were used: 12.5 mm sampling length, 2 μ m stylus fillet radius, 1.5 μ m spatial sampling frequency, and a spline filter with cutoffs of 2.5 μ m and 8 μ m, respectively [19]. The measured regions are as shown in Fig. 2.

2.4.2. Reverse engineering

The geometrical accuracy of the manufactured parts was validated using RE techniques on an ATOS SO 4 M machine. The RE method is preferred over traditional measurement techniques owing to the complexity of the manufactured parts, with support structures still attached to the smallest of holes. The blades were attached with markers for the subsequent alignment during the measurement stages. The blade with five different orientations was considered for the analysis, and the point clouds were converted to an STL file, cleaned, repaired, and aligned with the origi-

nal STL file using the minimum distance algorithm in the GOM inspect software. The 3D color maps were created to show the manufactured part's minimum and maximum deviation from the original STL.

3. Results and discussion

The parametric design provides a customizable solution that removes the technical barriers for implementing and designing complex hydroelectric turbines. This in turn promotes the public administration to easily adopt micro-hydroelectric power generation as a viable option for sustainable energy production.

3.1. Turbine design

The parameters obtained for the turbine design are summarized in Fig. 3a. A turbine with 20 blades can produce 2.94 kW. This is a multi-jet configuration with 6 nozzles with a wheel diameter of 0.175 m, nozzle diameter of 0.018 m and an Ns of 49.7. Looking into the characteristic speed (Ns), the choice of Pelton turbine is validated as a Pelton with multiple jets usually has an Ns between 25 and 70. The modelling of the turbine was done in Autodesk Inventor, and a parametric approach was taken to automatically change the shape and sections through formulas. This was added to an excel program in which all the design parameters were correlated to fundamental quantities like fluid head and flow rate (Fig. 3a). This is a highly flexible approach to obtaining turbine design with just two fundamental parameters that can be implemented without prior training and engineering expertise. This way, the 3D model is automatically generated (Fig. 3b), as well as the STL necessary for the AM processing (Fig. 3c).

3.2. Selecting the process parameters

The processing parameters selection was the result of multiple optimizations of remelting strategies to obtain Pelton turbines in a single step technology, i.e., without the need for a secondary finishing operation. The experimental plan allowed us to find the significant factors for each surface slope. Only factors with p-values less than 0.05 were considered. Non-linear regression was used, which resulted in regression results that confirmed the goodness-of-fit. Each model's lack-of-fit was greater than 0.05, and the residual analysis revealed that the differences between fitted and experimental values follow a normal distribution, confirming the regression assumptions. The Anderson-Darling test on these data yielded a p-value much higher than 0.05. The simplified models (Eqs. 1–4) show that the processing parameters affect the achievable surface roughness in vastly diverse ways. It is worth noting that the con-

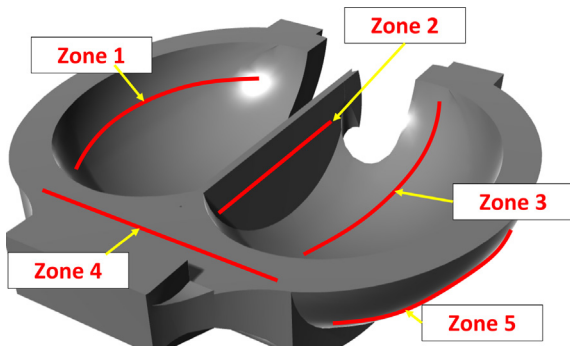


Fig. 2. Roughness measurement zones.

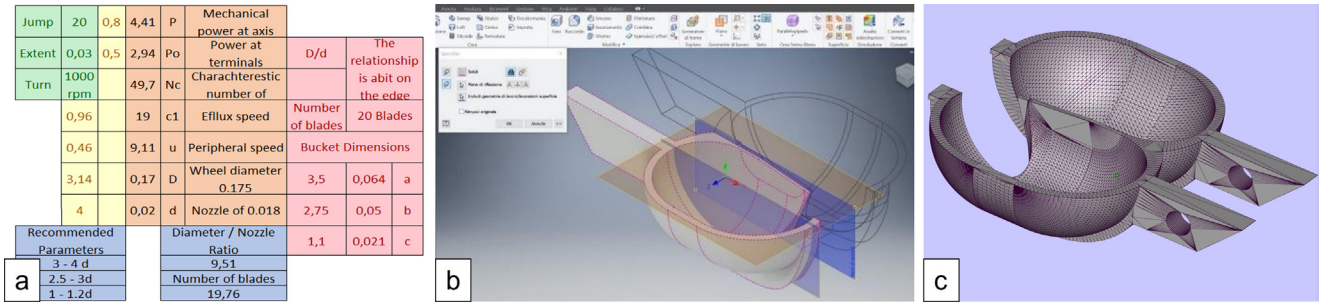


Fig. 3. Turbine design input table (a), automatic generation of the geometry (b), STL file of the blade (c).

tour offset has no effect on surface quality for 45° orientations (Eq. (2)), but it does for the other inclined surfaces. The quadratic terms affect the results for many slopes, highlighting a marked curvature in the response.

$$Ra(0^\circ) = 7.61 - 0.01382P - 0.01421v + 71.5Hd + 0.000006v * v - 389.3Hd * Hd + 0.0402v * Hd \quad (1)$$

$$Ra(45^\circ) = 78.4 - 0.499P + 0.0592v + 0.000858P * P + 0.000027v * v - 0.000236P * v \quad (2)$$

$$Ra(90^\circ) = 57.6 - 0.03004P - 0.00518v - 210.7Co + 0.000442P * P + 0.000026v * v - 0.000042P * v + 0.606P * Co \quad (3)$$

$$Ra(135^\circ) = -49.2 + 0.1351P + 0.2545v - 790Co - 0.000644P * v + 2.99P * Co - 0.644v * Co \quad (4)$$

Equation (1) can be optimized to provide the best parameters for improving attainable roughness on horizontal surfaces. The outcome is shown in Fig. 4a. In the case of inclined surfaces, it is not possible to optimize each angle separately; hence, an overall solution must be included in an optimal region, leading to a certain degree of compliance with the proposed criteria. The desirability function is one of the most widely used approaches in the industry [20, 21]. In Fig. 4b, the graphical representation of the multi-response minimization is shown. The obtained composite desirability is 0.9165, which indicates an exceptionally satisfactory solution. The whole exposure parameters used for both hatching and contour operations are given in Table 2.

3.3. Fabrication and validation

The blades were manufactured with an EOS M290 machine in five different orientations, as shown in Fig. 5. The support structures were not removed to avoid surface damage that must be measured in the validation stages. The final part quality is validated using the methods explained in Section 3.5. The final roughness values obtained in five different zones are given in Table 3. A homogeneous roughness value is obtained for all the zones, indicating the effect of remelting in standardizing the final part quality at desired locations. The largest deviation, in terms of percentage error, occurs at the horizontal surface, which also has the best surface quality. The surface roughness in all the zones is between 3.5 μm and 5 μm, which can be considered decent quality. For checking the dimensional accuracy, RE techniques were used, and the point clouds obtained for all the five orientations are shown in Fig. 6.

The measurements of the 67.5° orientation showed a variation of only -0.5 to 0.5 mm as compared to the original STL file. The highest deviation can be seen in the areas where the support structure has not yet been removed. It can also be observed that the internal areas of the buckets only have a deviation of 0.2 mm. This can be considered a good result considering that the critical areas of the components still have only the expected deviations, and no unwanted effects were introduced by the manufacturing process. The results obtained for all the orientations are given in Fig. 7. For blade orientations of 0° and 45° are identical to those for 67.5°. The deviations seen on the internal surfaces of all blades are less than 0.2 mm. Only the 90° configuration shows considerable deviations; inaccuracies of over 0.3 mm are observed inside the spoon. Because the blades were not subjected to any additional post-processing, the overall results are quite satisfactory.

3.4. Total manufacturing time and material wastage

The entire manufacturing time for the blades is determined by several parameters, including setup time, fabrication time, and post-processing time. The EOS Print 2.4 software can directly calculate the fabrication time, which includes recoating, laser exposure, and platform lowering times. The blades were nested to enable the production of the maximum number of blades in a single orientation. Different numbers of blades ranging from 85 to 25 are manufactured on a single platform, for orientations from 90° to 0°. The setup, fabrication, and postprocessing times for a single blade at the examined orientations are depicted in Fig. 8.

As expected, the setup time decreases as the number of blades increases. Fabrication time is determined by the volume of the supporting structure, which increases as α decreases. The recoating time of an oriented model is proportional to its height; for example, at 90°, we have the maximum height, but the time it takes to build one blade decreases as the number of blades increases. The amount of time required for post-processing is influenced by the manual processes conducted, and it is primarily governed by the supported area, which lowers as α rises. At 0°, the increased number of on-part support structures necessitates greater caution when removing them, prolonging the process. So, the orientation in 67.5° is the most sustainable option in terms of production time. The overall quantity of material wasted may be estimated by considering the amount of material wasted as support structure material and the amount lost during recycling, which is a constant percentage of the residual powder. The 90° orientation has the lowest material wastage and is the most sustainable case since the support structure volume in this orientation is the lowest.

4. Conclusion

Additive manufacturing, especially SLM, can be used as an effective tool for sustainable energy production in pico-hydroelectric

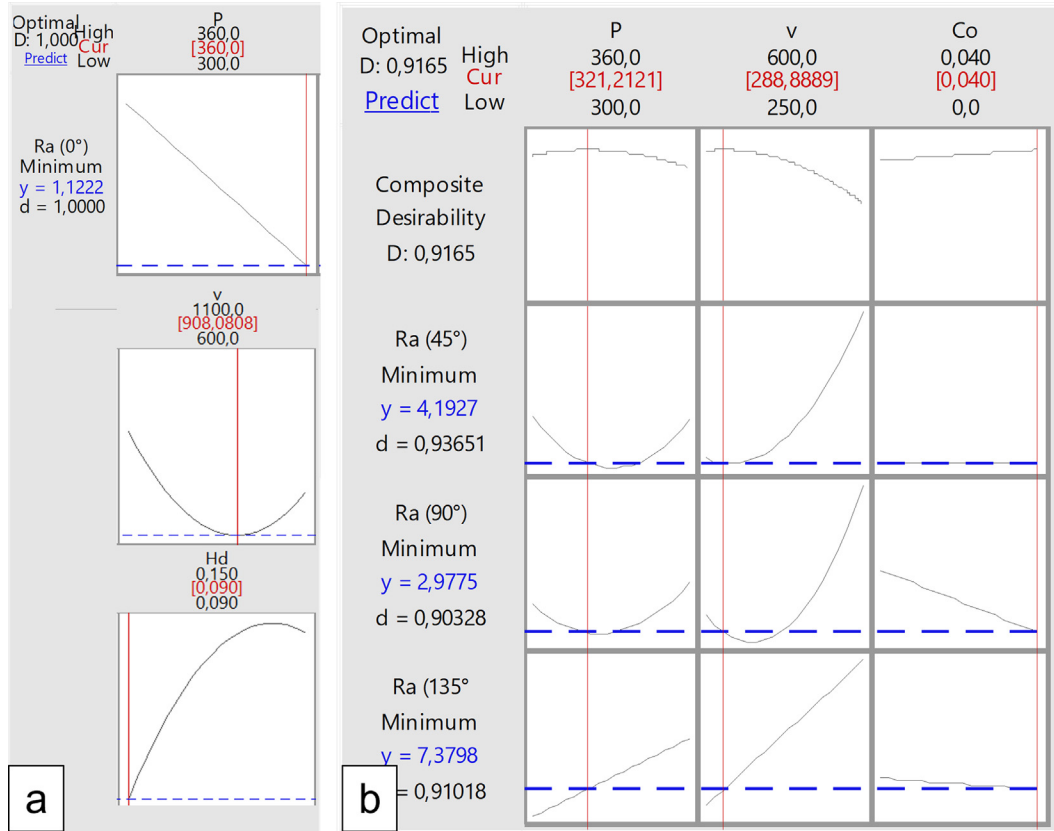


Fig. 4. Optimized parameters for upskin (a) multi-objective optimization for inclined surfaces (b).

Table 2

Exposure parameters for hatching and contour operation.

Hatching operation					Contour operation			
Variable	Infill	Upskin	Downskin	Remelting (Experimental)	Variable	First contour	Second contour	Third contour (Experimental)
Pattern	Stripes	Nil	Nil	Nil	Contour offset	0.02 mm	0 mm	0.04 mm
Stripes width	7	Nil	Nil	Nil	Number of layers	2	2	2
Laser power	370 W	320 W	320 W	360 W	Corridor	0.06 mm	0.06 mm	0.06 mm
Scan speed	1300 mm/s	1850 mm/s	1500 mm/s	908 mm/s	Laser Power	95 W	120 W	334 W
Hatching distance	0.13 mm	0.09 mm	0.1 mm	0.09 mm	Scan speed	900 mm/s	900 mm/s	331 mm/s



Fig. 5. Manufactured buckets in different orientations.

power plants. The use of parametric design, as demonstrated in this research, can further reduce the difficulties associated with turbine development, making it easier for the public administration to implement these projects without heavy investment in research and development. The techniques established in this

study are quite successful in fabricating complicated turbine designs with excellent surface finishes. The remelting procedure was able to reduce the average roughness values of the functional surfaces to about $3.5 \mu\text{m}$. The dimensional accuracy of the final part was verified using RE techniques and found to be

Table 3
Roughness values in different zones.

Measurement Zone	Blade Configuration				
	0°	22.5°	45°	67.5°	90°
Zone 1	4.5 μm	3.5 μm	4 μm	4.5 μm	3.5 μm
Zone 2	3.5 μm	3.8 μm	4.9 μm	4.2 μm	3.9 μm
Zone 3	5.1 μm	3.4 μm	4.8 μm	5 μm	4.1 μm
Zone 4	3.1 μm	5.5 μm	4.1 μm	4.2 μm	4.3 μm
Zone 5	8.5 μm	7.1 μm	5.6 μm	4.5 μm	4.5 μm

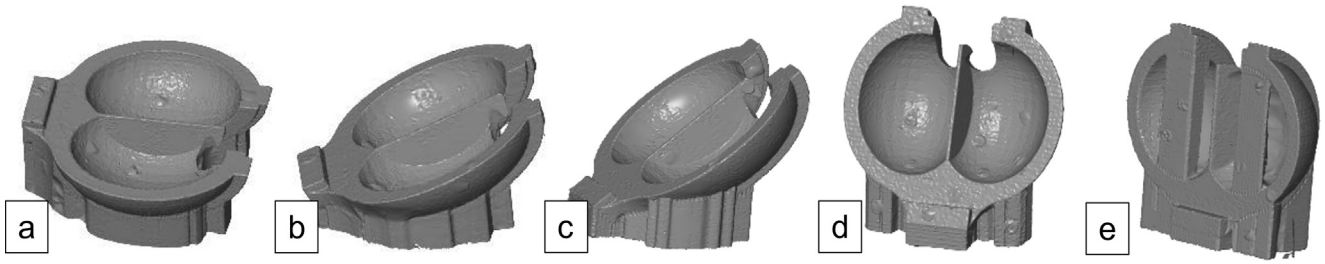


Fig. 6. Point clouds of the Pelton blades in different orientations.

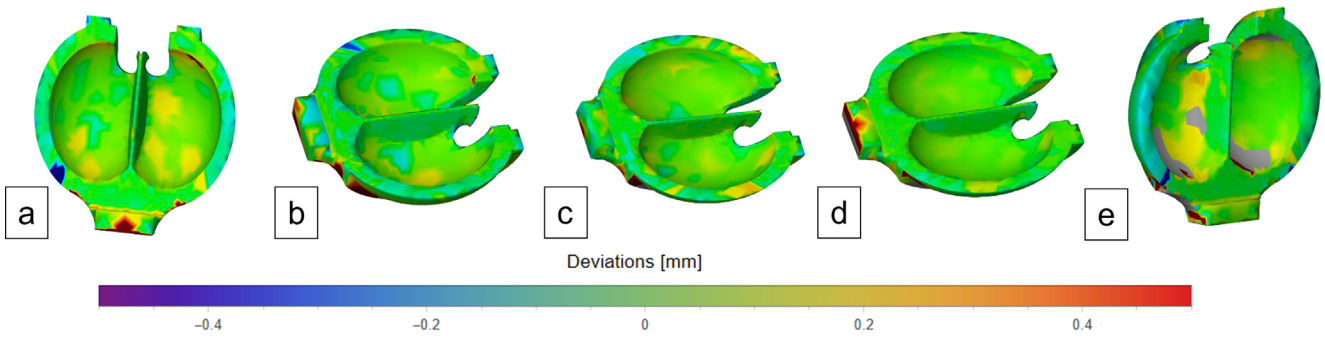


Fig. 7. Deviation for all the blades of orientations: 67.5° (a), 0° (b), 22.5° (c), 45° (d), 90° (e).

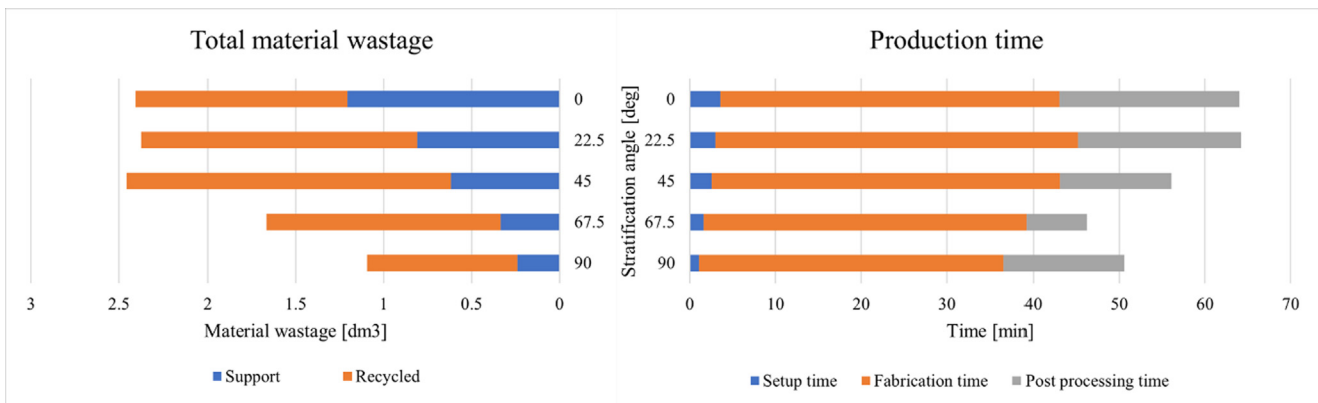


Fig. 8. Total material waste and total production times.

under 2 mm at the functional surfaces. As a result, turbines made using these techniques can be utilized for their intended purpose immediately, with little post-processing, making the entire process more sustainable. The total fabrication time and material wasted during the process are also estimated to find the best solution for sustainable turbine production. The future scope of this research would be to implement the turbine in a real case study and to ana-

lyze the material strength and fatigue life cycle to evaluate how well they can survive the stresses imposed by the hydraulic forces and to understand the energy output that can be obtained in real life from these systems. This research can open new avenues for micro and pico-energy generation that can solve the energy problems in remote regions in combination with the existing renewable solutions.

CRediT authorship contribution statement

Alberto Boschetto: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Luana Bottini:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Jacob Jose:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Somayeh Vatanparast:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Francesco Veniali:** Conceptualization, Validation, Supervision.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prof. Alberto Boschetto reports equipment, drugs, or supplies was provided by Italian Ministry for the Economic Development (MISE).

Acknowledgements

This work has been supported by the Italian Ministry for the Economic Development (MISE) through the projects “1.3 Materiali di frontiera per usi energetici” (CUP: I34I19005780001) within the Three-Year Plan 2019–2021 of the National Electric System Research Fund.

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