To be published in proceedings of 29th
IAHR Symposium on Hydraulic Machinery
and Systems 2018, Kyoto, Japan, 16-21
September, which should be cited to
refer to this work.

Design of a New Kaplan Pico-Turbine Runner Blades

M. Chiarelli[1], L. Favre[1], N. El Hayek[1], Dr. E.-L. Niederhäuser[1] and L. Donato[2]

[1] Energy Institute, University of Applied Sciences of Western Switzerland, CH-1700 Fribourg,
elena-lavinia.niederhaeuser@hefr.ch

[2] SeSi Institute, University of Applied Sciences of Western Switzerland, CH-1700 Fribourg,
laurent.donato@hefr.ch

E-mail: `maxime.chiarelli@hefr.ch`

Abstract. Within the frame of the design of a pico-hydro power plant for developing countries, the University of Applied Sciences of Fribourg (Switzerland) aims to develop a low-cost Kaplan turbine with a power output of at least 1 kW. The current paper presents the study and the results of the development of this new turbine as well as the seeming paradox to use advanced simulation technics in order to design a low-cost turbine. At first, a turbine with twisted blades was designed to obtain the best performance. Numerical simulations (CFD) and experimental tests were performed to characterize the turbine performance. The first prototype is manufactured by a 5-axis CNC machine. Nevertheless, in developing countries this technology is not accessible and therefore, a new approach for the design has to be considered and applied. The manufacturing processes within these countries is studied and presented. The best known manufacturing techniques for those countries are those based on metal sheets and welding. Hence, a pico-turbine which can be completely realized using these techniques is designed and investigated. The challenge was to determine the optimal thickness, the guide blade angle and the best bending of the runner blades, which are then welded on a hub. The turbine performance is characterized by CFD simulations. By varying the parameters mentioned above, the best compromise between feasibility and performance is found. The results show that the low-cost turbine has a reduced mechanical power of 50 % compared to the standard turbine. Nevertheless, the achieved overall power output is by far sufficient for the intended application and the simplicity of design guarantees an uncomplicated maintenance. Currently, the concept is validated and tested in Madagascar. Besides the use in developing countries, the turbine has the potential to be installed in mountain regions or any other isolated regions within developed countries.

1. Introduction

When an infrastructure is remote from the grid and a low-flow water resource with a small head is available, installing a small-hydro power plant to produce electricity can be a solution. Nevertheless, the implementation of this technology in developing countries is not simple and requires adaptation of the manufacturing techniques used. Indeed, one of the major problems in implementing and realization of renewable energy projects in developing countries is the lack of qualified personnel and the lack of modern and adapted infrastructures [1] for manufacturing in particular. Moreover, the investments costs (manufacturing and installation) of these power plants should be very low to guarantee a return on investment over a reasonable period. Thus, the purchase and use of modern production machines is not possible and the product must be adapted to the skills and means of local production means available in these countries.

In this context, the Institute for Applied Research into Energy Systems (ENERGY) [2] and the Sustainable Engineering Systems Institute (SeSi) [3] of University of Applied Sciences of Fribourg in Switzerland have developed, in collaboration with the Albert Schweizer Ecological Center (CEAS) [4], a 1 kW low-cost hydropower plant. This paper presents the advantages of a 1 kW pico turbine with simplified design of the blades compared to a "standard one" with profiled blades, for developing countries, and designed in Fribourg. The comparison takes into account economic factors due to manufacture and operation (efficiency) but also to the design process.

2. Approach

Initially, pico-turbine with profiled blades is conceived and developed by numerical simulations (CFD) to produce 1 kW power output at 55 l/s. In addition to a performance analysis, complete analyses of the design and manufacturing cycles are performed. Thus, this turbine is manufactured by a 5-axis CNC machine (Computer Numerical Control). The numerical results are validated by experimental tests.

Secondly, a complete analysis of the manufacturing techniques available and mastered in developing countries (project with the Centre Ecologique Albert Schweizer [4] in Madagascar) allowed to develop a second turbine of 1 kW with simplified blade geometry. The manufacturing techniques used are welding and sheet metal. Thus, the turbine has a cylindrical hub that can be turned on conventional machine and the blades are welded on the hub. The sheet metal blades with constant thickness are bent using a wooden die with the desired radius. Numerical simulations (CFD) are performed to find the optimum sheet thickness and bending radius to achieve the best performance for the same flow conditions previously set for the profiled blade turbine. Similar analyses are performed as for the turbine with profiled blades.

Finally an economic evaluation and comparison between the 2 developed turbines is carried out by taking into account the operation of the turbine. Indeed, the decrease in efficiency between the two types of turbines can be assimilated to a loss that can be compensated by cheaper manufacturing techniques.

2.1. Geometry of the turbine

The figure **??** represents the geometry of the turbine as studied. It is installed in a 175 mm diameter pipe. 6 fixed guide vanes and 4 runner blades are foreseen.

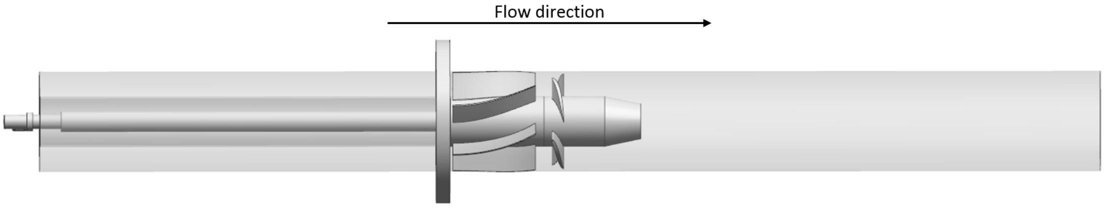

Figure 1. Geometry of the studied turbine

2.2. Hypotheses of the numerical analysis

To characterize the different turbines performances, the simulation boundary conditions are kept identical. The numerical model consists of four meshes corresponding to 4 domains as shown in figure **??** . The first one is the upstream pipe with an annular cross-section corresponding to the shaft. The second mesh comprises six fixed guide vanes used to pre-rotate the fluid before it enters the runner. The third mesh includes the runner blades and finally the fourth mesh consists of the turbine nose and the downstream pipe. The meshes sizes remain unchanged for all calculations except the third mesh, which adapts to the shape of the blades. Periodic flow hypothesis allows the use of symmetry to lighten the model. Each geometry is divided into symmetrical portions as shown in figure 2. Steady-state RANS simulations (Reynolds averaged Navier-Stokes) are performed at constant rotation speed of 1000 rpm by varying the volume flow rate from 35 to 70 l/s. k-ϵ turbulence model is used for all simulations.

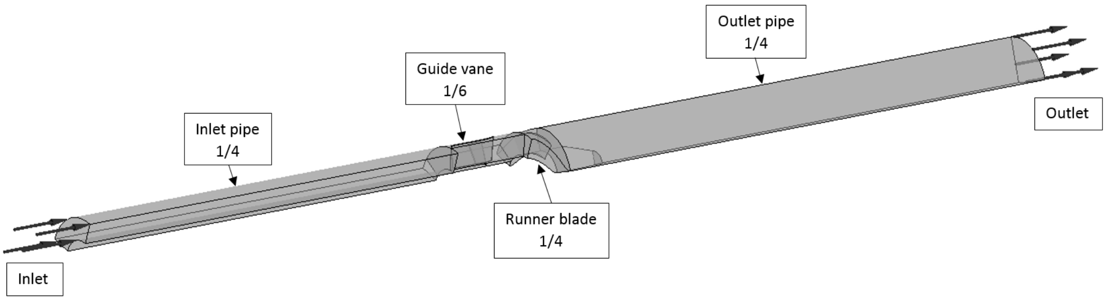

Figure 2. Boundary conditions and domains used for CFD calculations

2.3. Hypotheses of the economic analysis

The development, manufacturing and operating costs are based on the Switzerland tariffs to compare the two turbines and only the relative differences shall be considered. Thus, the hourly development cost is 60 CHF. The manufacturing costs depend on the used materials and the manufacturing techniques. They are based on the rates of the mechanical workshop of the University of Applied Sciences in Fribourg. The economical return on the investment is calculated according to the average electricity price in Fribourg in 2018, which is 17.86 cts/kWh [6]. The turbine's operating time is estimated at 4400 $hours/year$ [7] at full load equivalent.

3. NACA profil runner blades

As shown in figure 3, the profiled turbine is composed of 4 blades NACA 4408 [9]. The NACA profile is kept constant over the entire blade height, simplifying thus the design and the manufacture of the blade, but decreasing the turbine performances. The guide vanes and the runner blades are fixed to simplify the manufacturing of the different parts as much as possible. The NACA profile is positioned on the hub using the velocity triangles at the inlet and at the outlet. The average velocity triangle is calculated at half blade height for a flow of 40 l/s at 1000 rpm. This turbine, developed during a project leaded by the ENERGY Institute of the University of Applied Sciences in Fribourg, is a prototype validated by experimental measurements.

3.1. Design and manufacturing

Figure 4 shows the three main steps used for turbine design and production with complex (profiled) blades. The design loop begins with the analytical sizing. The specifications (nominal operating point) are used to determine the velocity triangles. The blades is then modelled in 3D by CAD (Computer-Aided Design) and numerical simulations (CFD) are performed for several operating points It is an iterative process allowing to find the optimal geometry for the imposed flow conditions. Once the geometry validated, the 3D CAD model is used to define the machining program for the CNC machine. The turbine is built in one single block with a 5-axis milling machine. This allows the turbine to be machined in a single setup. Thanks to CAM software,

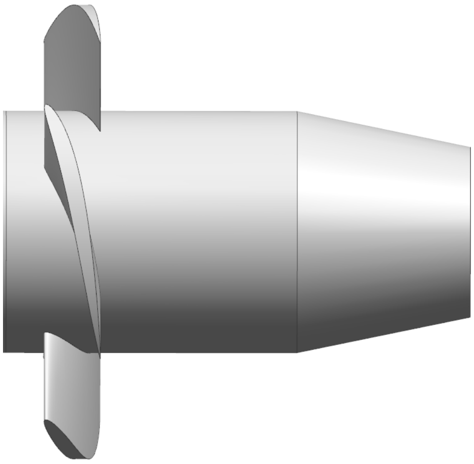

Figure 3. Geometry of the NACA profiled turbine

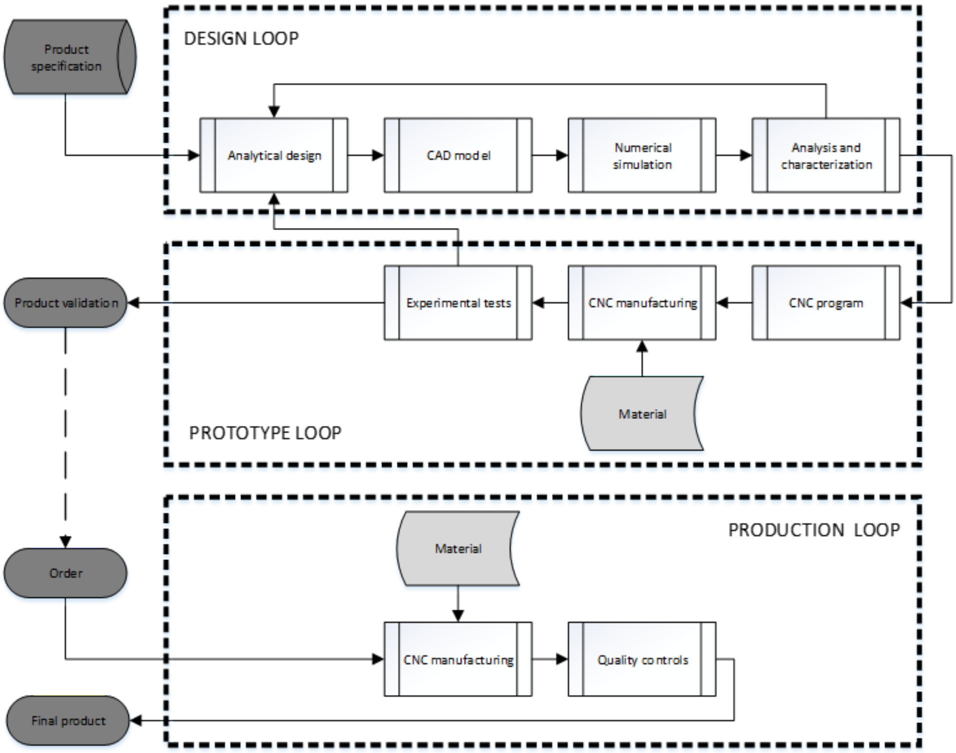

Figure 4. Diagram of processes of design and manufacturing of the profiled blades

the machining program of the CNC machine can be defined largely automatically from the 3D CAD model. The prototype is afterwards tested to validate the numerical results and the turbine performances characteristics. If the experimental results are conclusive, the geometry is validated and the turbine can be produced in series. Otherwise, the design process starts again.

3.2. Performances analysis

First the torque on the turbine shaft is read and the mechanical power output calculated according to the equation 1.

$$P_{mec} = \frac{2\pi N}{60} T_{mec} \tag{1}$$

where N represents the rotation speed in rpm while the T_{mec} expresses the torque measured at the turbine shaft in Nm.
This first step allows checking if the desired output mechanical power of 1kW is achievable. Then, the hydraulic power is calculated according to the equation 2 with Q the volume flow rate in m^3/s, ρ the water density and H the head of the turbine in m.

$$P_{hydro} = Q\rho gH \tag{2}$$

Finally the equation **??** allows to evaluate the hydraulic efficiency which represents the ratio between the produced mechanical power and the extracted hydraulic power.

$$\eta = \frac{P_{mec}}{P_{hydro}} \tag{3}$$

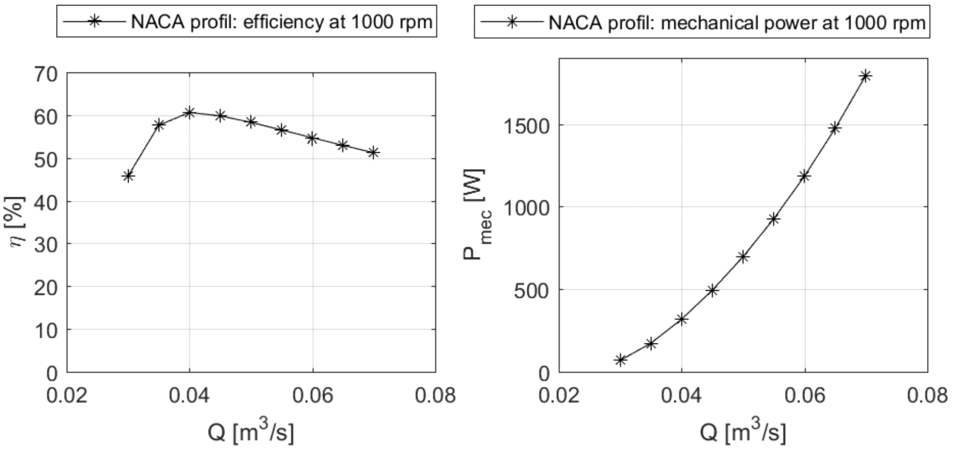

Figure 5. Performance characteristics of the profiled blades turbine

As shown in figure 5, the best efficiency point (BEP) is characterized by 60.6 % of efficiency at a volume flow rate of 0.04 m^3/s. This efficiency value is characteristic of this type of pico-turbine [10]. The mechanical power output obtained at this operating point is only of 320 W. Thus, to achieve a mechanical power output of 1 kW, it is necessary to increase the volume flow until about 0.057 m^3/s. Since the performance curve is quite flat after its peak, the losses corresponding to this operating point (characterized by 0.057 m^3/s) are only 5 % related to the BEP. The power output of 1 kW is therefore not reached under optimal operating conditions. As the NACA runner blades are directly machined in the mass, their position is fixed and cannot adapt to flow variations.

3.3. Economic analysis

The development and manufacturing costs of the turbine prototype are shown in table 1. The annual production of the turbine is 4400 kWh (4400 $h/year$) representing a yearly electricity savings of 790 CHF. The return on the investment time for the turbine, excluding development costs, is 3 years.

Table 1. Distribution of the costs of devlopment and manufacturing of the complex turbine

Process	Duration [h]	Cost [CHF]
`Design`	100	6000
`CNC program`	16	960
`Manufacturing and material`	16	1630
`Product validation`	40	2400
`Total prototype cost`	172	10990
`Cost per unit`	24	2100

4. Simplified runner blades

The simplified blades are cut from a 3 *mm* thick sheet and bent. They are welded on a turned hub. The parameters influencing the turbine's runner geometry are therefore, the thickness of the metal sheet, the blade surface, the bending radius and the angle of the blade with respect to the hub. To analyse the influence of these parameters, three different designs are designed and simulated. The figure 6 shows the geometrical details of each design considered.

The first design comes directly from the blade angles calculated from the velocity triangles. Since the guide vane angle is fixed, it is possible to calculate the runner blade angle using the nominal flow rate and the rotational speed. No rotational fluid is considered at the runner outlet for the BEP. The velocity triangle is considered at half-height the blade and allow a guide vane angle of 35° and a blade angle of 23° for a volume flow rate of 55 l/s at a rotational speed of 1000 *rpm*. The bending radius is 400 *mm*.

The second design respects the guide vane angle of 35° but the bending radius is reduced to 250 *mm*. The blade angle is then reduced to 16°. The purpose of this design is to evaluate the influence of a smaller bending radius on turbine performance.

The third design has no bending radius. The flat blade is positioned on the hub at a 29°.

4.1. Simplified approach

For a product or a technology to last in developing countries, it must be locally controlled and produced. The missions carried out together with CEAS in Madagascar showed that the machining of the blades with a profile was not possible. Moreover, CNC machining is not yet integrated into the current production processes. Thus, an alternative manufacturing solution, based on conventional machining, welding and sheet metal skills, was then studied. The aim was to provide manufacturing drawings and cut-out templates required for mass production. Thus, in addition to mastering manufacturing technologies, the service provider should be able to manage independently the maintenance process.

4.2. Design and manufacturing

Figure 7 shows the three main steps used for turbine's design and production with simplified blades. The design loop is almost identical to that for the profiled blades. The difference is that the only parameters changing to achieve the best performance are the constant blade thickness and bending radius. Once the geometry validated, a prototype can be manufactured. Unlike

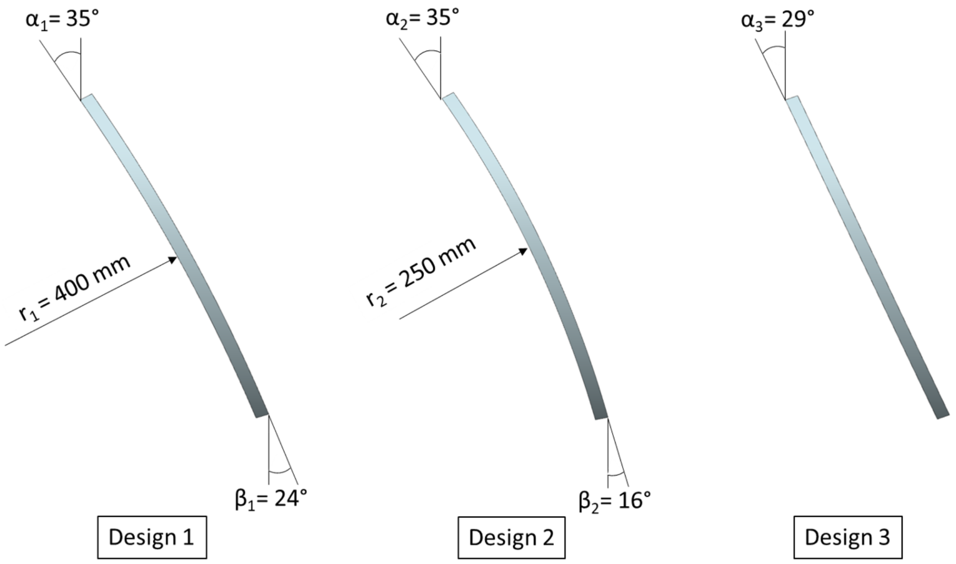

Figure 6. Geometrical dimensions of the three simplified runner blades design

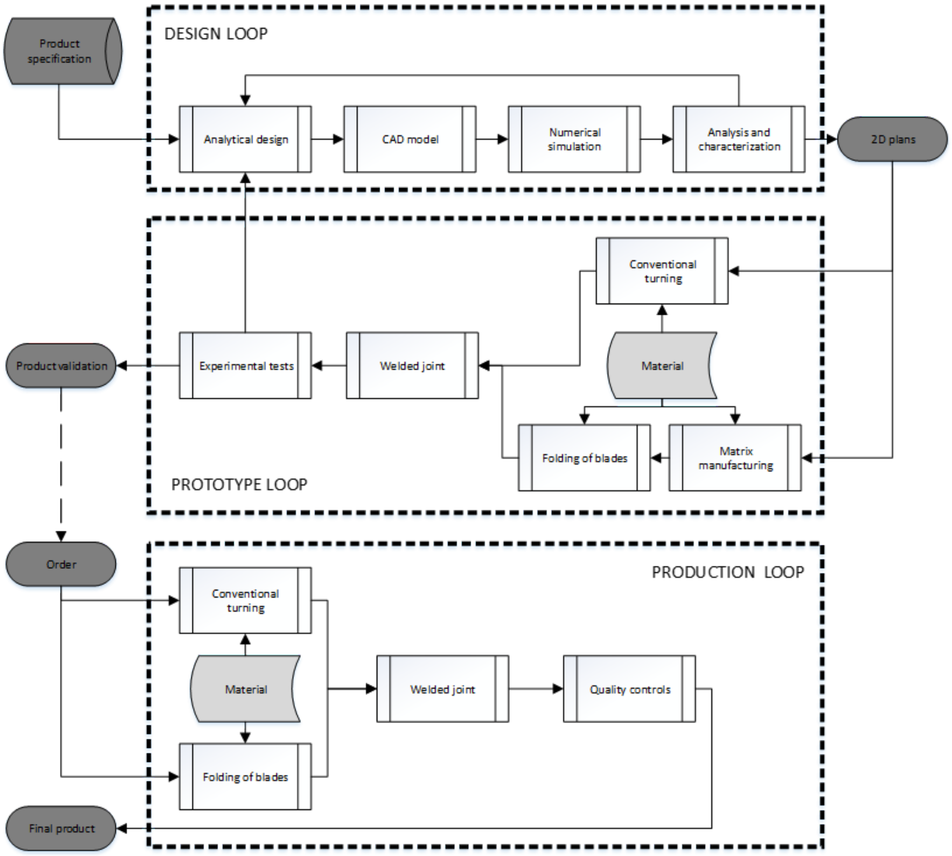

Figure 7. Diagram of process of design and manufacturing of the turbine with simplified runner blades

the other turbine, machined in one single block, the simplified turbine is a mechanically welded assembly. In the beginning of the prototyping loop, the turbine's hub must be manufactured by conventional turning. In the same time, a die to bend the runner blades, which are cut in a sheet metal, is manufactured. Stamping is done manually. Finally, the curved blades are welded to the hub. The prototype is then tested to validate the turbine performances. If the experimental results are conclusive, the geometry is validated and the turbine can be produced in series.

4.3. Performances analysis

Five operating points per runner blade design are simulated. They are all located around their respective BEPs. The analyses of the results are carried out in the same way as for the profiled turbine. Mechanical power and hydraulic power are calculated using the equations 1 and 2, while the hydraulic efficiency is calculated using the equation 3. The figure 8 compares the performances of the three designed and simulated designs. It appears that the three efficiency curves are similar in shape but have different offsets. The design no. 2 has the best efficiency of 59.2 % for a volume flow rate of 0.06 m^3/s. The BEPs of designs no. 1 and no. 3 are both at a flow rate of 0.07 m^3/s. For the design no. 1, the best efficiency reaches 58.4 % while for the design no. 3 only 55.2 %. Concerning the shaft power output, the three curves obtained have also the same shape with offsets related to the volume flow rate. To achieve a mechanical power output of 1 kW with design no. 2, the flow required is about 0.067 m^3/s, whereas for designs no. 1 and no. 3 the flow rates required are 0.072 and 0.074 m^3/s respectively.

Thus, from all studied designs of simplified runner blades, the design no. 2 is the most interesting, both in terms of its maximum efficiency and its flow rate for a power of 1 kW. It is interesting to note that for this design, the 250 mm bending radius is the smallest of the three.

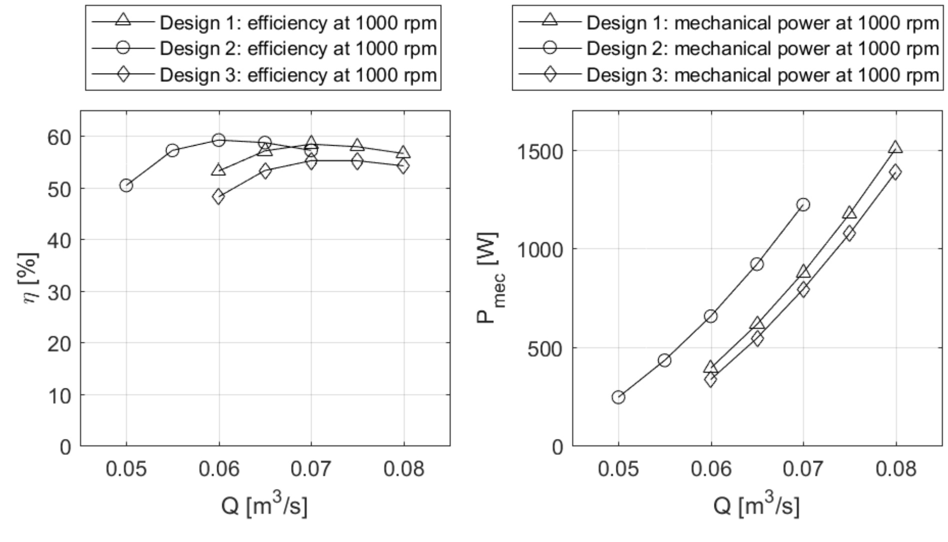

Figure 8. Performance characteristics of the simplified blades turbine

4.4. Economic analysis

The development and manufacturing costs for the turbine prototype are illustrated in the table 2. The annual production of the turbine is 2200 kWh (4400 hours of full load operation) equivalent to an annual saving of 400 CHF. The return on the investment time for the turbine, excluding development costs, is 6 years.

Table 2. Distribution of the costs of devlopment and manufacturing of the simplified turbine

Process	Duration [h]	Cost [CHF]
`Design`	80	4800
`Conventional turning and material`	1	180
`Matrix manufacturing and material`	2	210
`Folding of blades and material`	4	290
`Welded joint`	16	1280
`Product validation`	40	2400
`Total prototype cost`	143	8520
`Cost per unit`	32	2230

5. Comparisons

5.1. Performances comparison

As described in subchapter 4.3, the design no. 2 provides the best performance of the turbine for the studied simplified runner blades. Therefore, only its results in terms of performance efficiency and economy will be compared to the ones obtained with the NACA profiled blades. The maximum efficiency value of the two turbines is very close with a difference of only 1.4 % at their respective BEPs. On the other hand, the BEP of the NACA profiled turbine is achieved at 0.040 m^3/s while for the simplified turbine with design no. 2 it is at 0.060 m^3/s. Moreover, for a nominal flow rate of 0.055 m^3/s, the two turbines provide similar efficiency values with 57.2 % for the simplified turbine and 56.5 % for the NACA profile. When looking at the mechanical power output, the NACA profiled turbine satisfies entirely the power expectations with about 1 kW mechanical power produced at 0.057 m^3/s. The simplified turbine allows also to produce 1 kW mechanical power output but for a higher volume flow rate of 0.067 m^3/s.

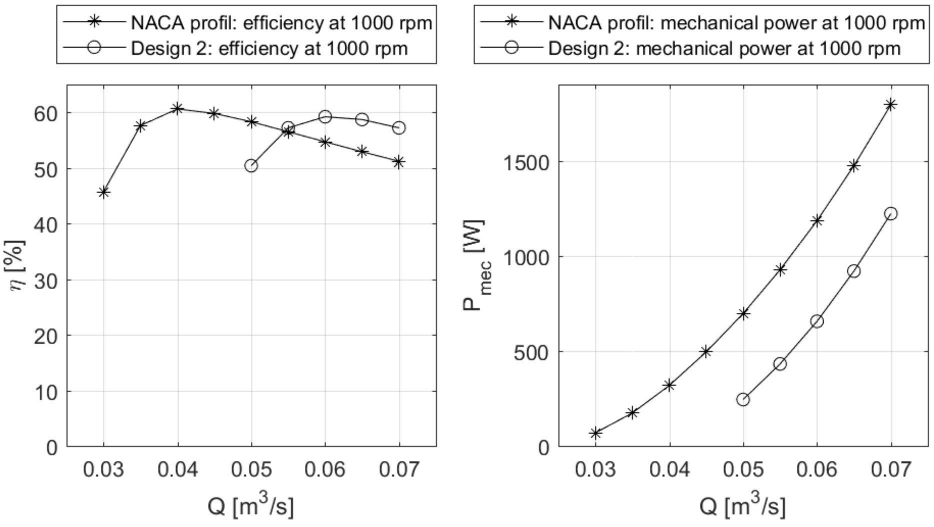

Figure 9. Performance comparison between the NACA profiled turbine and the simplified turbine with design no. 2

5.2. Economic comparison

Based on the production costs in Switzerland, it appears that the turbine with profiled blades is slightly cheaper (2100 $CHF/unit$) than the turbine with simplified blades (2200 $CHF/unit$). This is mainly due to the manufacturing time, relatively decreased when using advanced manufacturing technologies. However, CNC-5-axis machines, which are essential for machining profiled blades, have an acquisition cost that is exorbitant for developing countries and thus one should consider only the simplified runner blades approach to have a competitive pico turbine in order to ensure the necessary power output.

6. Conclusions

This article presents the different steps when sizing a low-cost pico turbine for developing countries. Three simplified turbine designs were proposed and investigated. They were compared with a standard profiled turbine with NACA runner blades. The simplified turbine geometry is based on conventional manufacturing methods available in developing countries, while the one with the NACA blade profile requires very expensive CNC machining operations. CFD simulations showed that the BEP is characterized by 59.2 % at 0.060 m^3/s for the simplified turbine with blade design no. 2 and by 60.4 % at 0.040 m^3/s for the turbine with profiled blades. The mechanical power output of 1 kW is reached for a flow of 0.057 m^3/s with the NACA turbine against 0.067 m^3/s for the simplified turbine with design no. 2. Considering that the stream allows reaching a volume flow rate of 0.067 m^3/s, the simplified turbine (design no. 2) is thus very interesting considering its simplicity of manufacture. A manufacturing cost estimate reveals a production price of 2200 $CHF/unit$ for the simplified turbine and 2100 $CHF/unit$ for the NACA profiled turbine. However, the price of a CNC-5 axis, indispensable for machining a profiled blade, is extremely high. Therefore, the simplified turbine is a pragmatic solution, adapted to developing countries, with a very small difference in efficiency compared to a conventional turbine with profiled blades.

7. References

[1] Gabriel C-A 2016 What is challenging renewable energy entrepreneurs in developing countries? *Renewable and Sustainable Energy Reviews* **64** 362-74

[2] Institute for Applied Research into Energy Systems, University of Applied Sciences of Western Switzerland, https://energy.heia-fr.ch/EN/presentation/Pages/core-competences.aspx, read in December 2017.

[3] Sustainable Engineering Systems Institute, University of Applied Sciences of Western Switzerland, https://sesi.heia-fr.ch/EN/presentation/Pages/core-competences.aspx, read in December 2017.

[4] Centre Ecologique Albert Schweizer, Swiss NGO, http://www.ceas.ch/, read in December 2017.

[5] School of Engineering and Architecture of Fribourg, https://www.heia-fr.ch/fr/, read in December 2017.

[6] Average price of electricity to Fribourg (2018), Federal committee of the electricity, https://www.prix-electricite.elcom.admin.ch/Map/ShowSwissMap.aspx, read in Januar 2018.

[7] Contribution of the technologies of production to the supply in electricity (2016), Association of the Swiss electric companies, https://www.strom.ch/fileadmin/user_upload/Dokumente_Bilder_neu/010_Downloads/Basiswissen-Dokumente/22_Contributions_des_technologies_fr.pdf, read in December 2017.

[8] JavaFoil, Software of 2D digital blower, https://www.mh-aerotools.de/airfoils/javafoil.htm, read in December 2017.

[9] NACA aerofoil profile, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930090976.pdf, read in December 2017.

[10] Samora I, Hasmatuchi V, Münche-Alligné C, J. Franca M, J. Schleiss A and M. Ramos H 2016 Experimental characterization of a five blade tubular propeller turbine for pipe inline installation *Renewable Energy* **95** 356-66