Low-Tech Waterwheel

Concept for a Simple and Small Hydro Power System for Remote Areas in Nepal

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***Abstract*—Despite the continuously increasing access to electricity in Nepal, millions of its inhabitants still live without electrical energy, and many more have a very unreliable supply connection. Simultaneously, Nepal has enormous hydropower potential thanks to its mountainous topography, but only a fraction of this potential has been taken advantage of. Rural communities in remote areas are already experienced in the manufacture and operation of traditional water mills *pani ghattas*, and could thus adopt similar technology to produce electrical power. Consequently, this paper presents a modular concept for a small-scale hydropower system, optimal for the unelecrified remote regions of Nepal. The design is simple, cost-effective and robust, and all individual components of the system are manufactured or otherwise readily available locally. The concept is based on a classical overshot waterwheel with a horizontal shaft, ideal for low heads and small volume flows, and it was developed in collaboration with craftspeople, researchers and operators in Nepal. The modularity of the concept makes it adaptable to different operating conditions, resulting in a wide spectrum of possible power outputs. The proposed system was developed for off-grid operation, and offers a viable alternative to high-tech hydropower plants. This paper presents results from first Nepalese prototypes of the proposed waterwheel.**

Keywords—waterwheel; modular concept; off-grid; rural electrification; hydro power; Nepal

I. INTRODUCTION

In industrialised countries, reliable and universal access to the electricity grid is mostly taken for granted. In developing nations, this is very often not the case, however, and approximately 1.1 billion people worldwide are still living without electricity [1].

Nepal has seen a rapid change in its overall electrification rate, rising from 15 percent in 2000 to 77 percent in 2016 [1], but the difference between urban and rural energy access is still considerable, at 97 and 72 percent, respectively [1]. Seeing that over 80 percent of Nepal's inhabitants reside in rural areas [3], the negative implications on development become clear. Overall, almost 7 million of Nepal's nearly 29 million inhabitants still live without access to electricity [1], [2].

Even today there are vast regions within Nepal where the electrical power supply is either non-existent or of very low quality. The so-called remote areas in the North, and especially the Northwest, of the country have essentially no connection to the national grid [4]. Due to the complex terrain and the sparse population of these regions, grid extension is not cost-effective, and so the local households will not get connected in the near future. Even in places where a connection to the main grid has been established, frequent and long power outages are a problem due to insufficient power capacity to meet the demand, as well as due to component failure. Notwithstanding, both the electrical energy consumption per capita and the population have been rapidly increasing in the past [5], and estimates of the Nepalese government suggest that energy need may more than double in the next ten years, aggravating power stability problems [6], [7].

At the same time, Nepal has an immense hydro resources due to its steep mountainous topography. The total hydropower potential was assessed at 83,500 MW in 1966 by Dr. Hari Man Shrestha. In 2003, it was evaluated at 179 TWh/a [8], and in 2007, the National Planning Commission (NPC) of the Government of Nepal proposed a figure of 42,000 MW of economically and technically feasible hydro capacity [6]. However, despite all this potential, Nepal currently generates only around 867 MW hydropower [9].

The hydropower resources in Nepal‘s remote North are especially noteworthy, and people there have a long history of successfully operating simple and small-scale water mills, called *pani ghattas*, for local food production. The pani ghatta has blades made out of wood or metal, and a vertical shaft, but a relatively poor efficiency. Approximately 25,000 pani ghattas are still in use in Nepal today [10].

Analogously to the old water mill, decentralised small-scale hydropower systems could be utilised by the same communities to produce electricity for their own needs. The objective is thus to develop a robust hydropower plant to improve the power supply in rural and remote areas. The design must be simple, cost-effective and durable, in order to ensure reliable and economical electricity access. In the best-case scenario, all components will be available locally, and the plant can easily be operated without expert knowledge.

Furthermore, the design should enable flexible deployment depending on the available head of water and flow rate, and the electrical power output of the proposed prototype should be about 100 to 200 W.

II. METHOD

A. Selection and modification of proven technology

Waterwheels are a proven technology for small-scale hydropower production, with heads up to 7 m, and a maximum flow rate of around 5 m³/s [11]. They were first used over 2000 years ago, and thus represent one of the earliest waterpower technologies [11]. Waterwheels are constructed by conjoining individual chambers or buckets, and are characterised by their simplicity; only one inlet channel without additional pressure lines or other complicated peripheral components is needed, which substantially decreases the amount of material and experience required to install and operate them. According to relevant literature, slow-rotating waterwheels are an affordable and sustainable energy source for rural electrification [12].

Three types of waterwheel exist, namely undershot, breastshot und overshot wheels. They differ in structure, and in how water enters the wheel [11], but each utilises a horizontal shaft. Out of the three wheel types, overshot waterwheels have with 89 percent the best mechanical efficiency, as well as the best part-load behaviour [13]. Hence, overshot wheels were chosen for this project, and are the only type discussed further. An overshot waterwheel is fed with water at the top by a chute, and the weight of the water entering the topmost bucket makes the wheel turn. At the bottom of the wheel, the water is discharged. The working principle relies solely on the potential energy of the incoming water, and the effect of kinetic energy is negligible. Ease of maintenance and extreme robustness are guaranteed through the simplicity of the wheel's structure. Unlike water turbines, waterwheels are highly resistant against impurities and clogging, and their operational lifetime can span to over 50 years [14].

Overshot waterwheels offer an optimal solution to Nepal's energy problems in terms of cost-effectiveness, simplicity, and power rating. They operate best with heads between 1 to 3 m and small volume flows of 10 l/s (0.01 m^3/s) and above. The numerous irrigation channels and terrace fields found in Nepal could be harnessed for power production without major changes, and thus the waterwheels could easily adapted for the needs of rural households in even the most remote regions of Nepal.

B. Cooperation and knowledge transfer

To ensure the sustainability and continuous operation of the chosen technology in Nepal, establishing information exchange with local communities is essential. For this purpose, thorough analyses were conducted in close co-operation with local craftspeople, researchers and potential operators. The availability of various materials and tools, and the possibility of manual production were studied and requirements on transportation and assembly on-site were determined.

Fig. 1. Prototype overshot waterwheel at Söllbach, Germany.

The objective is to develop a simple and reproducible concept of a small-scale hydropower plant that could be developed in continuous collaboration between all involved parties. This concept serves as the cornerstone for the large-scale construction of waterwheels in Nepal.

Multiple prototype plants were built and assembled in Germany (see Fig. 1). These prototypes served as a platform to study material characteristics, and behaviour under adverse circumstances such as fouling and freezing.

The local communities' full wealth of experience in the operation and maintenance of pani ghattas is essential for the success of the whole project, and especially for the construction of the peripheral components of the proposed waterwheels in the remote areas of Nepal.

III. RESULTS

A. Modular concept

The requirement of easy transportability and adaptability to various head heights and volume flows led to the choice of a modular construction concept for the waterwheel. Thin galvanised steel was chosen as base material due to its wide availability in Nepal, its extremely low price and its ease of processing.

One module of the wheel comprises an individual standardised bucket, consisting of four sheet metal parts as shown in Fig. 2. The only work stages needed to construct such a module are cutting, bending, drilling and riveting.

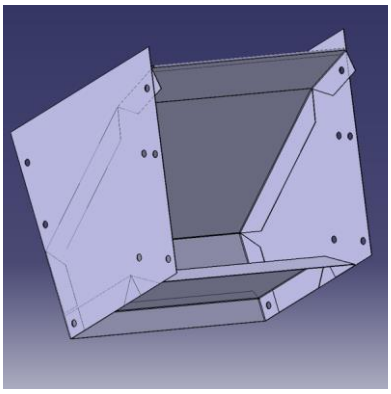

Fig. 2. Base module of the concept: individual bucket consisting of four sheet metal parts.

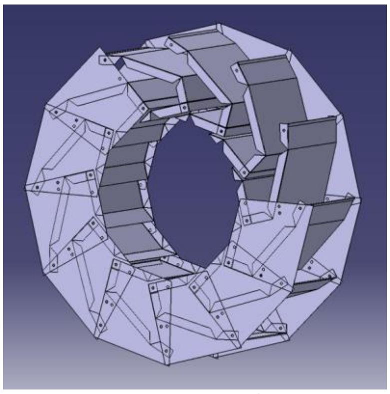

Fig. 3. Many base modules connected together form a complete waterwheel.

The diameter of the waterwheel is governed by the number of modules used, and so adapting the wheel for different head heights is very straightforward. An example of a complete waterwheel may be seen in Fig. 3.

The standard module (one individual bucket) has a width of either 20 or 30 cm, allowing for the construction of wheels for heads between 1.0 and 2.3 m. Modules wider than 30 cm would not be stiff enough to withstand the mechanical stress inflicted on them during operation. Thus, in case of increased flow rate or wider inlet chute, two or more wheels of the same size are mounted in parallel on one shaft, as shown in Fig. 4.

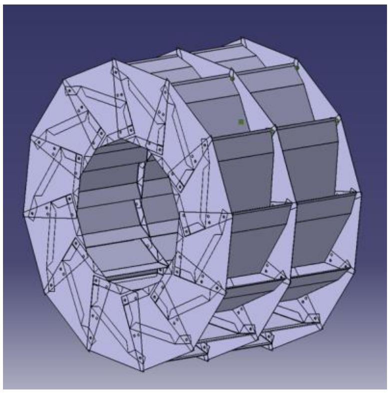

Fig. 4. Parallel assembly of two waterwheels.

For flow rates ranging from 0.02 to 0.1 m^3/s, a total width of 20 to 80 cm is needed, which corresponds to up to four parallel wheels. Under the above mentioned operating conditions, the expected mechanical power output varies between 120 and 1400 W. In order to minimise losses, the form of the base module was optimised in terms of fluid mechanics, so that the water intake and discharge lead to a maximised power output.

B. Software for dimensioning and site assessment

The modular concept of the waterwheel gave rise to a Matlab and Python-based software tool for the validation of potential hydropower locations. The only input parameters needed are the available head and flow rate (m^3/s), along with the dimensions of the base module. Subsequently, the software delivers the needed number of modules (buckets), the resulting wheel diameter, the optimal total width, and the position of the inlet chute for the minimisation of losses. Additionally, the programme outputs data for the expected operating point, including torque, rotational speed, mechanical power output and efficiency. Based on these parameters, the price of the proposed waterwheel and the generated profit for the operator may be approximated.

IV. First Prototype in Nepal

The first Nepalese prototype is currently being manufactured and assembled in the vicinity of Kathmandu, and operation will begin in February 2018. The first results obtained from the prototype plant will be handed in to the scientific board of ICDRET'18 at the end of February, comprising, one full page of this paper.

V. Discussion & Conclusion

The prototypes constructed in Germany and Nepal have shown the feasibility of the proposed modular waterwheel concept. Its main advantages are its simplicity and low cost. All needed materials are readily available in Nepal, and the wheels can be manufactured with simple machinery, accessible even in rural areas.

Numerous other benefits result from the modularity of the waterwheel, making it easily adaptable for a range of operating conditions. Furthermore, in case of damage, individual modules may be replaced, leading to fewer and shorter downtimes and lower maintenance cost. This is in strong contrast to high-tech power plants, the repair of which is usually complicated, cost-intensive and impossible to realise on-site.

Lastly, the modular construction concept allows for centralised, and often cheaper, manufacture in urban areas where the needed tools are more accessible. The individual modules can easily be transported to their end location, where the final assembly can be realised quickly with simple tools. Additionally, the provided software tool enables fast and uncomplicated design and optimisation of waterwheels without extensive experience in the field.

Some disadvantages of the concept also exist. The dimensions of individual modules of the waterwheel are not customised for specific locations, and the design was optimised for heads of 1.0 to 2.3 m. If used for a larger or smaller head, the waterwheel will suffer from loss of efficiency compared to a design optimised for different heads.

When the number of single buckets in a wheel grows, the angle between them changes. In large wheels, a small gap appears between the modules, causing some spillage and a lowered efficiency. The effect of spillage will need to be studied further, and could potentially be reduced by introducing a simple rubber plate to block the gap. Another option would be to design more than one base module to span the interval of 1.0 to 2.3 m heads. The latter would lead to a more complicated manufacturing process, however. All in all, the flexibility and cost-effectiveness of the proposed concept outweigh its disadvantages.

The modular overshot waterwheel is characterised by very low rotational speeds and resulting high torques. A bulky design is thus necessary to compensate for the latter, resulting in a rather large shaft diameter for the given power class. This increases the material costs but allows for higher fabrication tolerances, as the same variations are less prominent in larger systems. Moreover, research during the setup of the first prototype in Nepal has revealed that local workshops are more experienced in manufacturing bulky and large products. Thus, a voluminous design also offers advantages when manufacturing precision is low.

The presented modular waterwheel concept offers an advantageous option for the improvement of the electrical power supply in remote areas of Nepal, but is not always the optimal solution. For each location, a thorough analysis must be conducted, and the best technology chosen individually. For very large heads, a Pelton turbine might be considered, and photovoltaic panels will be beneficial in regions with little hydropower potential. In many cases, a hybrid system gives the best results.

VI. Outlook

The waterwheel prototypes in Germany and Nepal will be studied further in order to analyse long-term effects of on-site operation. The prototypes will also serve as a platform for possible measures to improve and optimise the proposed concept of modularity. Furthermore, more wheels based on this concept will be installed, notably in the Langtang and Annapurna regions. The objective is to construct five to ten additional plants to gather more experience in their construction, installation and operation. An additional goal is to build acceptance for the technology in the remote communities by exposing them to it. Once local families become familiar with the wheel's manufacturing process and advantages, they are more likely to adopt it.

Waterwheels are low-speed machines, with rotating speeds ranging from 10 to 30 rpm. To convert the mechanical power of the wheel to electricity, commercially available three-phase asynchronous motors could be used. The advantages of such motors include their robustness, reduced need of maintenance, low price and availability. However, synchronous machines need high rotational speeds which calls for the use of a gearbox to connect one to a waterwheel. This may lead to a significantly higher capital cost of the proposed hydropower system. Further research is needed to determine the optimal generator for the system.

Depending of the dimensions of the modular waterwheel, the system will provide 100 to 800 W electrical power output. This amount is enough to provide for one family with lighting, TV and small additional appliances in a remote area. Integrating battery storage would allow for higher consumption peaks during the day, and improve the utilisation ratio of the system as the battery would be charged with excess energy in the night-time. In such a scenario, high-power water cookers or rice cookers with a rated power of about 1 kW could also be used in the day-time, leading to less exposure to conventional fuels in cooking, and thus to improved indoor air quality.

The waterwheel project is open-source, and its details will be made available for the general public in the near future in the form of a project homepage. All technical details and manufacturing instructions will be provided so that members of the public may build and test their own prototypes. Long-term collaboration with Nepalese craftspeople, vocational schools and Kathmandu University will enable the continuous improvement and development of the modular waterwheel concept, and further ensure the continuity of the project.

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