A new, more efficient waterwheel design for very-low-head hydropower schemes

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Abstract:

Very-low-head hydropower constitutes a large untapped renewable energy source, estimated at 1 GW in the UK alone. A new type of low-impact waterwheel has been developed and tested at Abertay University in Scotland to improve the economic viability of such schemes. For example, on a 2·5 m high weir in the UK with 5 m3/s mean flow, one waterwheel could produce an annual investment return of 7·5% for over 100 years. This paper describes the evolution of the design and reports on scale-model tests. These show that the new design harnesses significant potential and kinetic energy to generate power and handles over four times as much water per metre width compared to traditional designs.

1. Introduction

For millennia waterwheels have powered flour mills, weaving mills and machine shops. However, when hydrodynamic theory and manufacturing improved sufficiently to alter designs, water turbines had already replaced industrial waterwheels. Modern materials have improved waterwheel

efficiency to 96% (Quaranta and Revelli, 2015: p. 322). Despite this, recent attempts to repurpose waterwheels to harness very-low-head (VLH) hydropower have failed economically (Figure 1). These attempts used traditional systems based on eighteenth-century understanding of force and energy transfer. Electricity generation requires new systems.

This paper describes the concept, design and testing of a new waterwheel type. By applying hydrodynamics to basic design, the wheel differs from traditional waterwheels in the same way that wind turbines differ from windmills.

Waterwheels have several advantages over turbines, for example low environmental impact, simpler technology, higher profitability and public acceptance. While thousands of wheels have been studied, gaining accurate data, these studies were done under one set of conditions. This is because the wheelpowered mechanisms would be damaged if sped up, or stop working if slowed down. Unfortunately, few model tests have ever been accurately recorded using major differences, such as water flows.

Figure 1. New 32 kW waterwheels at Canavese Canal, Turin

2. New design basis

The existing drive towards cheaper more efficient water turbines ignores the simpler solution of using more water to generate more electricity. The approach arises from environmental agencies

limiting the amount of water extracted from water courses to avoid causing ecological damage.

To use more water, new systems must be developed that cause less environmental damage than conventional, outflow systems (Figure 2). To achieve this, a new waterwheel has been developed (Figure 3) for use with inflow systems (Figure 4).

Increasing efficiency while reducing turbine costs only improves the economics a little. This is because the scope for efficiency improvement is limited – conventional system efficiencies range from 84% (waterwheels) to 95% (Kaplan turbines). Also, the total cost of all mechanical equipment is approximately 30% (NWHRM, 2009), so even halving this cost has less impact than doubling the quantity of water.
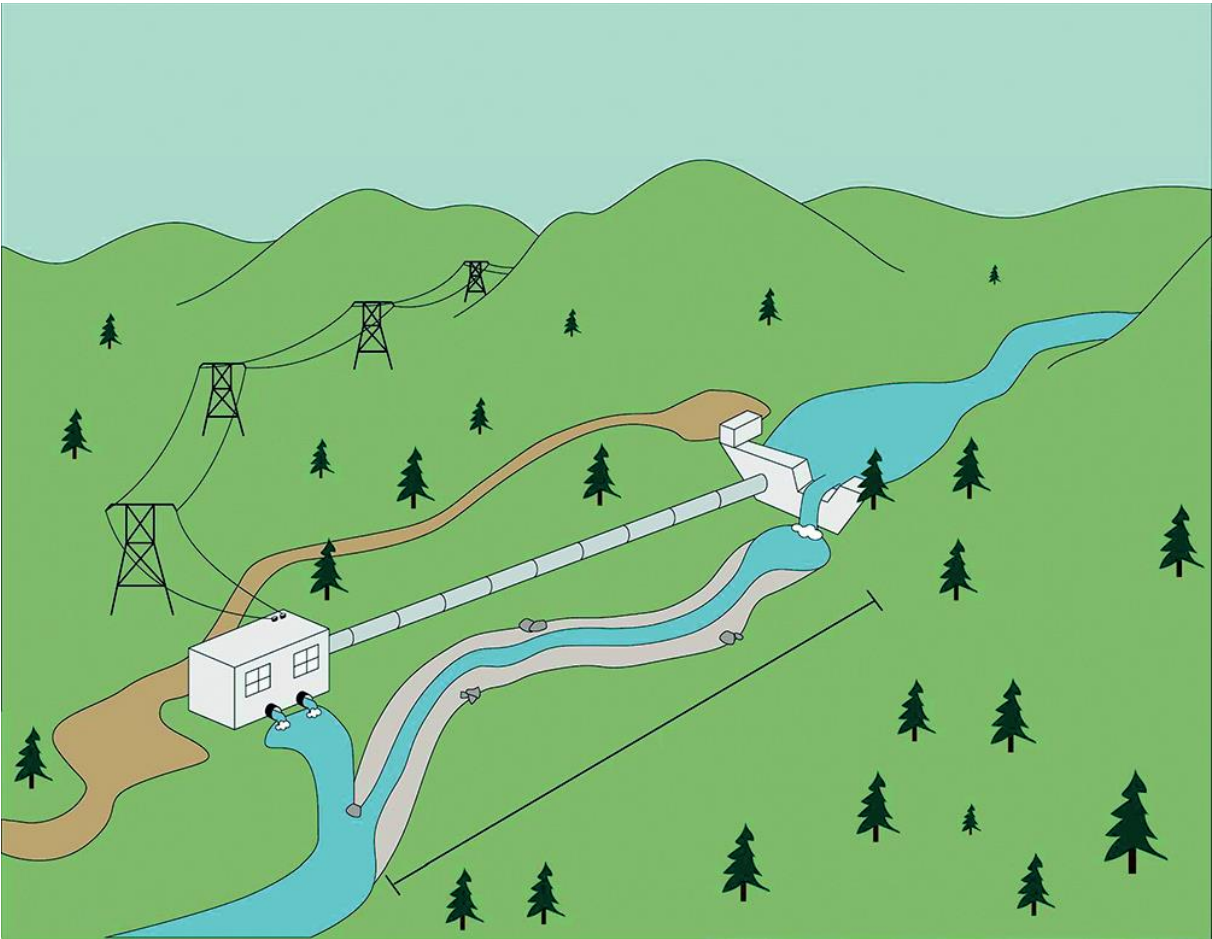

Figure 2. Conventional outflow system for low-head hydropower schemes (Gibeau et al., 2017). (Canadian Science Publishing)
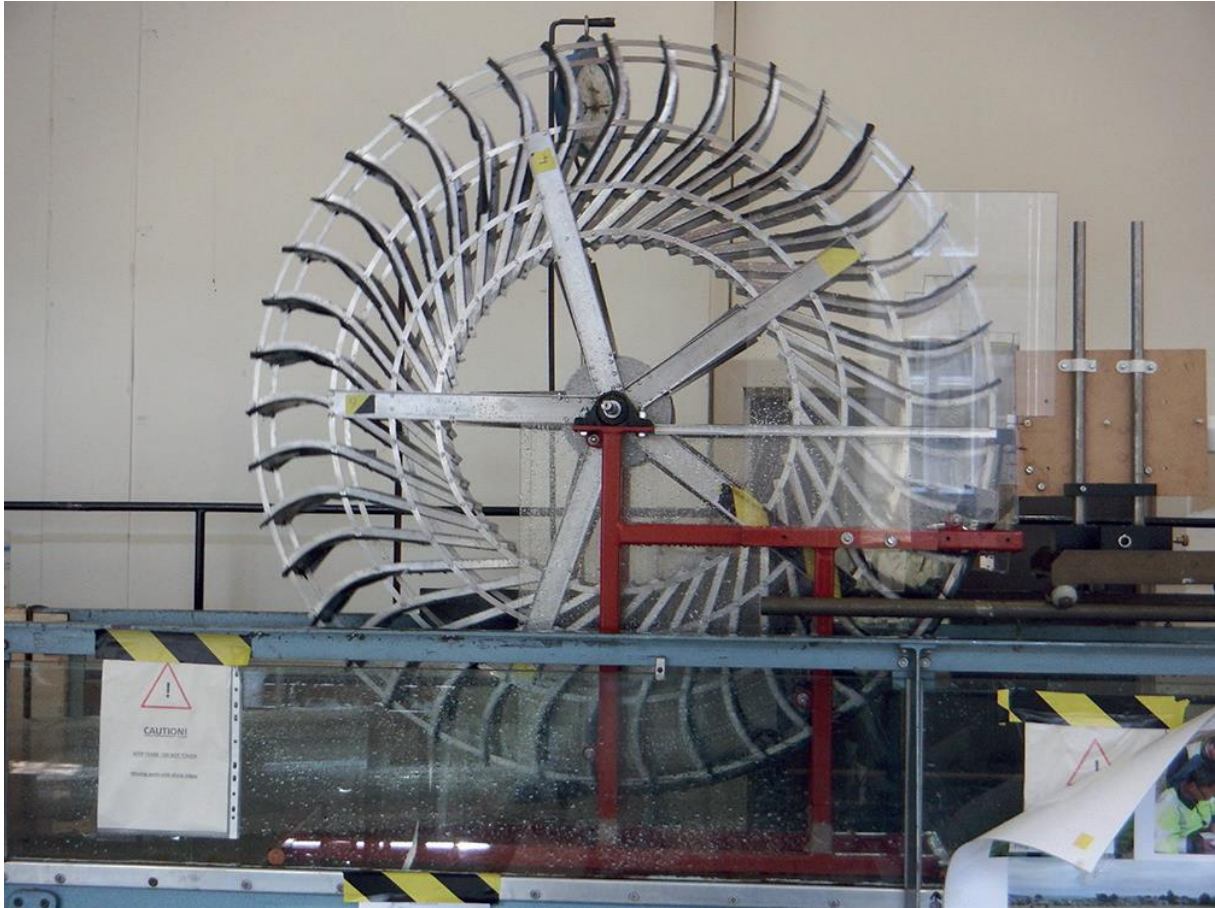
Figure 3. 1:10 scale, 1·2 m dia. model of a new waterwheel design developed for use with an inflow system
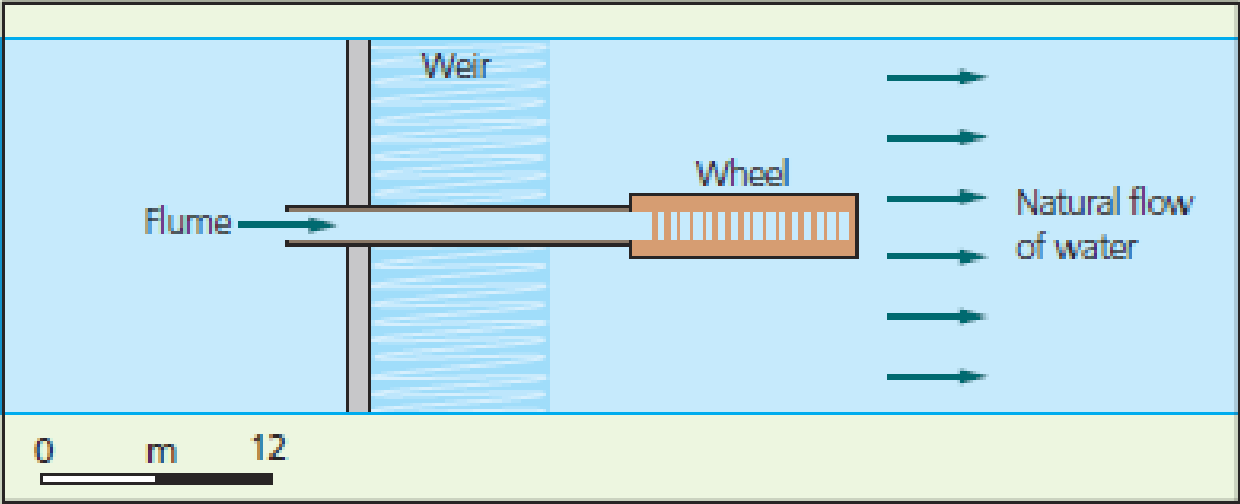

Figure 4. Location of waterwheel in an inflow hydropower system

2.1 Basic design assumptions

The basic design assumptions for the new waterwheel design are as follows.

Minimising adverse ecological effect is important. By not removing water from the watercourse, adverse ecological effects are almost eliminated. At best the river's ecology may be improved, with good hydrology and civil engineering. Increasing utilised water volume increases electricity output and profitability while reducing carbon dioxide emissions. For example, the Scottish Environment Protection Agency (SEPA) allows high water use where no water extraction from the river is required. However, utilising a large percentage of a river's naturally highly variable flow requires high efficiencies over a greater flow variation than current technologies can handle.

Smooth flow reduces turbulence, and thus energy loss. Wheels are also more fish friendly with higher water volumes and smoother flow. In addition, both kinetic (KE) and potential (PE) energy can be harnessed. Modern hydrodynamic theory and materials can be applied to improve waterwheels, for example a 1:2 scale model at Politecnico di Torino (Quaranta and Revelli, 2015: p. 322) achieved efficiency of 96%.

Finally, lower land usage is good. Inflow systems allow installation in urban sites with no riverbank land available. Urban locations also reduce grid costs, transmission losses and civil engineering costs.

2.2 Previous assumptions

Conventional assumptions continue to be made in recent papers. For example, it is often wrongly assumed that fundamental waterwheel design cannot be improved, with only evolution rather than revolution being possible. In reality, modern hydrodynamics can be used to minimise losses due to turbulence and splashing. Additionally, adjusting the inlet and tailrace configuration can increase power output. The Politecnico di Torino (Quaranta and Revelli, 2015) reports a combined 19% energy loss at a conventional inlet/outlet.

Another misconception is that the maximum flows waterwheels can handle cannot be significantly increased. Instead of directing the water to strike the blades (Figure 5), the new wheel allows the water to flow horizontally deep into the blades (Figure 6) allowing greater volumes to be handled per rotation.

It is also wrongly assumed that existing designs need not be changed for variable flows, as efficiency curves are relatively flat. Traditionally designers concentrated on maintaining steady power output levels. Maximising electricity production requires all flows to be efficiently harnessed, generating maximum output over the seasons.

Waterwheels are generally considered to harness mainly KE or PE, but not significant amounts of both. This is correct with water extracted from a millpond into a channel, but not with an inflow system.

In the UK, subsidies are considered essential for the development of renewable energy due to the very low returns on investment. By using three to four times more water than outflow systems, the new waterwheel allows three to four times more electricity to be produced, revolutionising hydropower economics.

Finally, the ecological effect of run-of-river hydropower schemes is often considered insignificant, since urban rivers are heavily modified and polluted. In reality outflow systems can significantly damage a river's ecology (Anderson et al., 2015), while inflow systems meet SEPA's low impact question 'Will the scheme be powered by the flow of water through an existing weir or dam (i.e. without removing water from the river channel)?' (SEPA, 2015: p. 11), thereby gaining provisional approval.
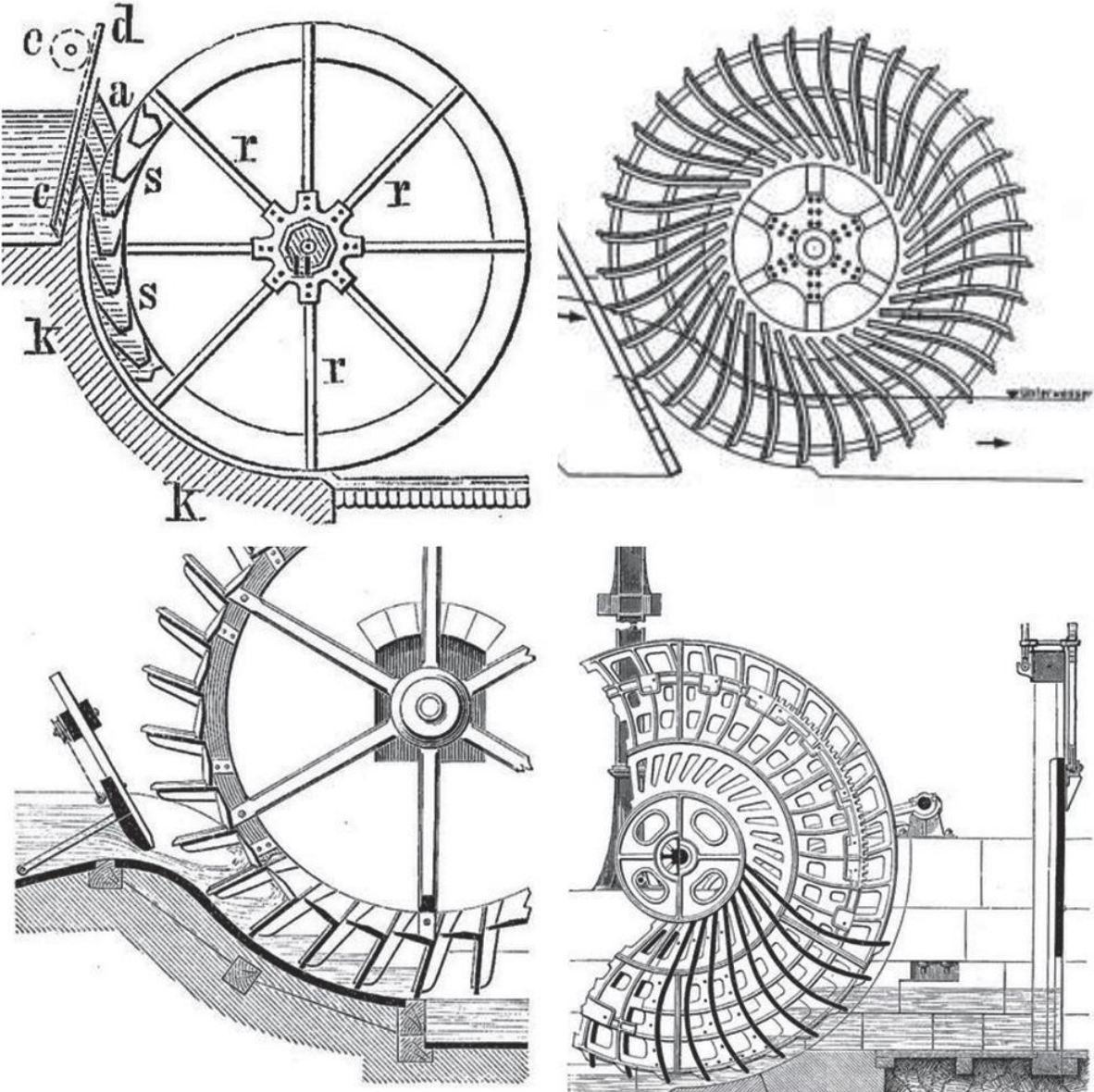

Figure 5. In traditional waterwheel designs, the inflowing water strikes the blades (Bibliographischen Institute, 1905)
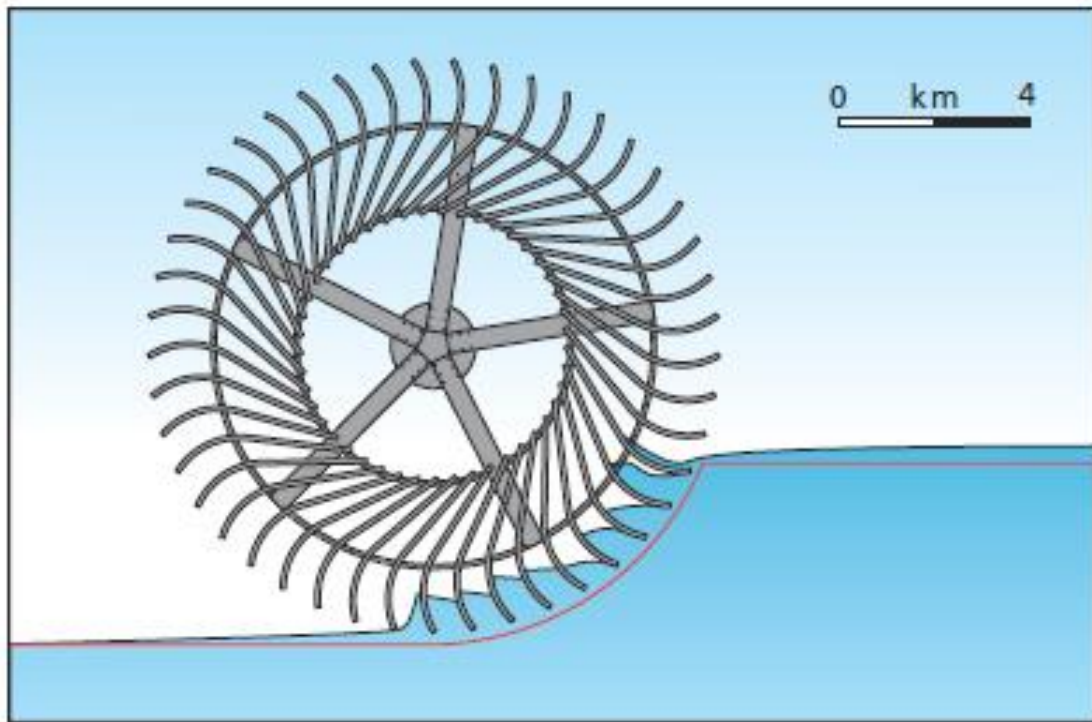
Figure 6. In the new waterwheel design, water flows horizontally into the blades

Figure 7. Test set-up at Abertay University (Picture annotation to show: Kelvin dynamometer, V-notch weir, Level flume, Stilling tank)
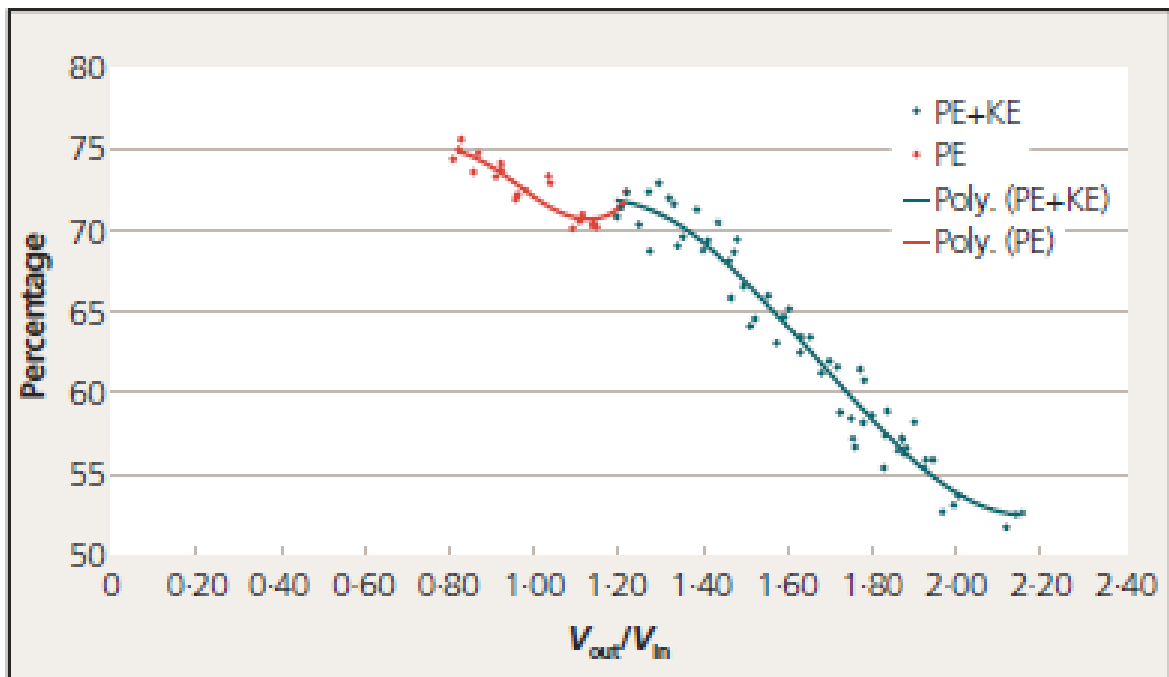
Figure 8. Waterwheel efficiency – energy output increases steeply as the circumferential speed reduces below the inlet water speed

3. New design

A new design has been developed which allows the water to run smoothly onto the blades without impact, with the blades gently spiralling inwards (Figure 3). While harnessing PE with similar efficiency to traditional wheels, KE is transferred by the forces generated as the water changes direction flowing around the curved blades, first into the wheel by momentum and then, as the wheel rotates, down the blade by gravity.

Traditional waterwheel design theory assumes any water movement relative to the blade/bucket is a source of energy loss, so water was stilled by directing it as close as possible to 90o onto the blade surface (Figure 5), also maximising the impact force. State of- the-art waterwheel mathematical modelling ignores momentum, which leads to skewed conclusions (Denny, 2003; Schneider et al., 2009).

To test both the structural stability and hydraulics of the new design, tests were undertaken under a wide range of flows and inlet heights in a model tank at Abertay University in Scotland. A 1:10 scale, stainless-steel model of the new wheel was tested, measuring 1·2 m in diameter by 0·1 m wide and with sheet plastic in place of the proposed wooden blades (Figure 7). The 1:10 scale allowed the angle and channel sections to be modelled using 1 mm thick plate.

The wheel has 41 blades, representing a distance apart of 1 m at full scale. This is slightly less than typical traditional waterwheels, resulting in more blades than any previous model known to the authors.

In the tests, the inlet water flowed from a header tank through a V-notch weir, into a stilling tank, then by way of a horizontal, rectangular flume into the waterwheel. The water speed was calculated from volume and water depth 40 mm before the flume outlet. The rotation speed was measured electronically.

The tests' main purpose was to show KE being harnessed by the same device that efficiently harnesses PE. Figure 8 shows that, as the circumferential speed reduces below the inlet water speed, the wheel energy output suddenly increases steeply. This increase indicates KE capture. No previously published results show this effect. Efficiency curves, measured in the conventional manner, would show this increase if present.

The secondary aim was to prove that the structure shows no dynamic instability, despite the high flexibility of the individual members and small width/diameter ratio. Despite handling much more water than anticipated, with consequential increased power output and stresses, the wheel structure remained solid and moved smoothly. Nevertheless, two dynamometers were overloaded, damaged and replaced, as the impressive power output potential became clear.

The tests confirmed the belief (Müller, 1899: p. 30, Teil 2) that axles should be 0·7 m to 1·0 m above the inlet water level, or approximately a tenth of the wheel diameter. The efficiency of the wheel was measured at four different water flows, with the efficiency increasing as the flow increased. The limit of this effect could not be established as further pump capacity was needed.

The increased ability to handle flow raised questions concerning hydraulic similitude, with the only model test known to the authors addressing this subject being that of Smeaton (1759: p. 101). The Reynolds numbers are 1·5 × 106 full size, and 1·5 × 104 model size, meaning that a full-size waterwheel would be clearly in the range of turbulent flow, more so than the model.

Simple turbulence inducers were fitted close to the end of the model flume, but no measurable change occurred. This confirmed that the new waterwheel accepts a greater volume of water per metre width (>4 m3/s) than traditional breast-shot wheels. Combining this with the ability to handle greater variations in water flow allows a reasonable wheel width to handle the maximum percentage of river flow allowed by SEPA (up to 80%). Historically, wrought-iron wheels broader than 5 m (5 m3/s) proved to be dynamically unstable, which may set an upper limit on capacity, or could be a result of the large impact forces in traditional design.

The Froude similitudes are close, almost identical at maximum flow. Rebuilding the test rig, considering the higher flow volumes, will enable maximum flow capacity to be determined accurately, the losses due to mechanical friction to be measured and the precise efficiency of the new wheel to be calculated. The surprisingly high flows required the blades to be extended to prevent water loss over the ends.

4. Applying modern knowledge to a modern problem

In maximising electricity output, supply variation is not a problem as variable flows cause power output changes much smaller than wind turbines. No conventional waterwheel, screw or turbine can perform at high efficiency over the range of flows in a river. If the traditional design assumptions are ignored and a new type of waterwheel is placed directly in the river, the following advantages are gained.

■ Inflow systems (Carruthers et al., 2015) reduce the ecological impact, so allowing a larger percentage of the river flow to be used compared with an outflow system, thereby generating more electricity.

■ Any inflow installation will have a smaller footprint than an outflow system (Mackie, 2015; SEPA, 2015, p. 11).

■ Construction costs will be reduced (Harvie, 2015).

4.1 Greater volume

Zuppinger wheels have long been recognised as handling the largest volume of water per metre width (1·2 m3/s per metre width) and as the most forgiving for variable flows (Rennie, et al., 1849: pp. 45–46). The new wheel harnesses PE in the same way as Zuppingers and, at first glance, looks very similar, but tests show it can handle four times the volume per metre width, and harness KE.

Water enters the new wheel smoothly along the blade, while traditional breast-shot wheels direct inlet water downward either by a coulisse or an over-weir utilising the Coandă effect (Müller, 1899; Müller and Wolter, 2004) to minimise motion on the blade. It is not safe to assume traditional practice was correct, being based on an incomplete understanding of the nature of energy (Carnot, 1803). Nevertheless, many modern papers state that movement of the water on the blades results in lost energy, 'a portion of the kinetic power dissipates impinging on blades, while another portion dissipates running up the blades' (Quaranta et al., 2015: p. 3)
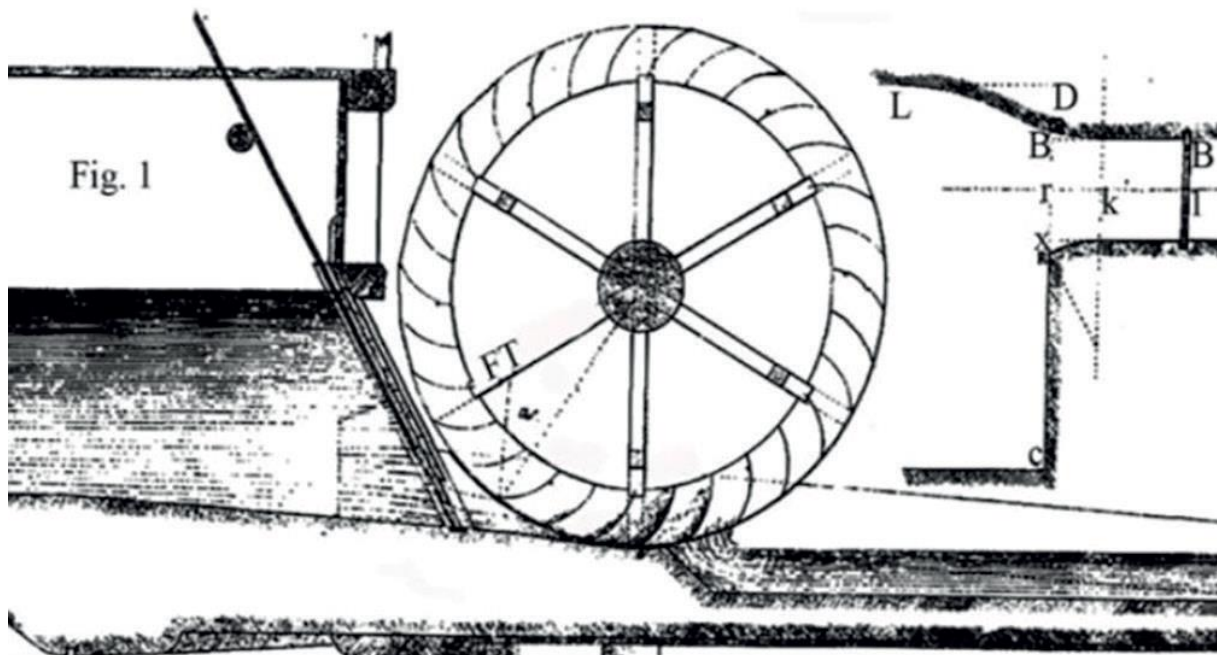

Figure 9. The nineteenth-century Poncelet waterwheel lost half of the water kinetic energy as water tumbled out

Assuming that KE is lost by impact on a flat surface, but not by 'running up the blades', the strategy is to harness the KE in the water by altering the curve of the blade to allow smooth flow. That curved buckets/blades reduce impact losses has been known since Poncelet (1827) designed what is generally considered the most efficient KE wheel. Here very low heads, 0·75 m to 1·7 m (Bozhinova

et al., 2013), were used to speed up the water before entering the wheel. Although using a curved blade to smoothly slow down the water rising up the blade's curve was integral to the Poncelet wheel (Figure 9), the water then tumbled back down, so less than half of the KE was exploited. This process has never been considered for other PE wheels, where simple impact could harness up to half the KE.

4.2 Greater variation in speed

Placing the waterwheel in a river requires handling flows varying considerably from dry to storm conditions. This changes the base assumptions surrounding wheel design and theory. The new design harnesses KE by allowing the water to penetrate further into the wheel, especially important as water speeds increase.

Traditional waterwheels have optimal efficiency at rotational velocity 60% of water entry velocity (Quaranta et al., 2015: p. 3). The ratio can be maintained over the year with median conditions but sudden changes cannot always be catered for. By extending the blades well into the wheel body, the highest anticipated speeds in spate conditions can be absorbed without losses due to splashing, running beyond the ends of the blades or turbulence.

4.3 Change in water depth

The optimal wheel diameter is determined by the total head available, including water depth at entry. Variable flow changes the inlet water depth and speed. As the wheel diameter cannot be changed, variances in water depth were conventionally compensated for by changing the inlet over-weir height, or partially closing sluices. With the new wheel, a 1 m range in the inlet water depth has little effect on efficiency.

During a spate, the water level at the tailrace may be above the lowest part of the wheel. The lower wheel moves in the same direction as water in a river, as the wheel moves slower than the river flood flow, the blades will not have to push the water leaving the wheel against back water. For these reasons the lowest point of the wheel can be set at the 50% downstream river exceedance level. This improves the breast-shot wheel's head compared to over-shot wheels, the lowest point of which must be higher than the 80% exceedance level to prevent 'drowning'.

4.4 Change in wheel speed

Low wheel speeds of around 4 rpm (revolutions/min) are frequently quoted as being optimum. With the ability to harness KE, even lower rotational speeds have advantages and disadvantages for the new wheel.

The slower the wheel turns the greater the KE difference in the water between inlet and outlet – more KE can be harnessed and there is more time to fill the blade space. However, there is also more time for water to leak around the blade edges, greater speed difference across the gearbox, and too slow and the entire system fails, with water coming back down the blade trying to exit into the flume.

4.5 Reduced impact losses

Historically the inlet water for breast-shot wheels was directed to impact the blades. In theory, water impacting a flat surface extracts a maximum 50% of KE to add to the general waterwheel output. When wheel theory was being created (1750 to 1820), what energy was and how energy transfer worked was not fully understood.

The accepted ideas for 'living force' were 'quantity of movement', 'accelerating force', 'retarding force', 'motor force', 'moving force', 'life force' (Carnot, 1803: pp. 25–26). As sound and heat were not considered energy, KE losses were attributed to the loss of 'life force' and later to KE dissipating. 'The theoretical results show that the big power losses are the dissipation of the stream kinetic energy against the blades and the hydraulic losses in the headrace' (Quaranta and Revelli, 2015: p. 315).

The KE that can be captured has long been thought to be 3% of available PE (Müller, 1899: p. 55, Teil 2), confirmed over the centuries by observing existing wheels and laboratory testing. However, existing wheels use lades, which were as level as possible to minimise head loss, and laboratory models mimicked this.

A river's maximum KE is generally greater at 20% to 30% of PE in spate conditions. Water current measurements are scarce, especially those specifically for characterising hydro-kinetic potential. Surface observations for navigational purposes and river discharge data are more common, but the accuracy and stringency of such data are often not sufficient to carry out a reliable resource assessment (Grabbe et al., 2009: p. 113).

4.6 Smooth flow

Simplified models of flow within PE wheels ignore momentum and water oscillation, so do not describe how blade shape affects flow. Simply adapting the Poncelet curve is not optimal, as it is designed for accelerated water velocities, and dumps the water as it reaches the end of the blade. A simplified spiral, the tightness and angle of which are informed by modern hydraulics, and applied mathematics, is a good starting point.

By avoiding impact through smoothly running the water onto the blades, the KE in the water is not reduced and remains available for harnessing. By making the blades as smooth as possible, the turbulence is dimensionally much smaller than the blade, so the water mass can flow as a unit smoothly up and down the curve (Figure 6).

5. Economics

The capital costs of installations at existing weirs with a fall between 2·5 m and 4 m, on rivers with a mean flow between 5 and 3·5 m3/s were calculated using a UK standard price book for detailed bills of quantities drawn up according to the Civil Engineering Standard Method of Measurement (CESMM 4; ICE, 2012). The operating costs were estimated from historical data.

Using the calculated capital and operating costs, net present value calculations using an interest rate of 7·5%, and an electricity sale price equal to the 2017 wholesale price (£45/kWh) showed positive values. Higher flows and/or higher weirs would be extremely profitable.

6. Discussion

A patented waterwheel prototype has been built and extensively tested at Abertay University. By fundamentally changing the blade curve and inclination, the way the water acts within the wheel has altered dramatically. By smoothing the water flow from the flume onto and then along the blade, the water moves in an unbroken wave up and down the blades, a motion believed to be unique to this design.

What others have already shown is that the effective energy transfer in conventional wheels can be significantly improved, as confirmed by the results from Politecnico di Torino (Quaranta, 2017: p. 67). However, greater volume and speed variations can be accommodated in the new wheel while maintaining high levels of efficiency. Test results will be used to determine the possible relationships between the many variables.

Analysis of the prototype tests will aid developing a more accurate theoretical model, which will be used to improve the design process. What is already known is that the new design is an entirely new type of wheel, the first to be designed for modern electricity production and not mechanical tasks.

7. Conclusions

Directing the inlet water to flow smoothly through the wheel allows both PE and KE to be harnessed, with much larger volumes of water per metre width being handled.

Currently the design of the full system is sufficiently developed to be installed and operated profitably on very large numbers of existing weirs. The level of profitability will depend on the water flow regime and weir height. Subsidies may be needed to develop weirs lower than 2 m, unless there is a very substantial water flow, more than 10m3/s, or the wheel is replacing electricity from a diesel generator.

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