Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

BEng. Albert Halenka

Optimizing Pico Hydropower: Enhancing Overshot Waterwheel Performance for Off-Grid Electrification

Maximizing the Potential of Overshot Waterwheel with Adaptive Design

Master's thesis in Hydropower Development
Supervisor: Oddbjørn Bruland
August 2023

NTNU
Norwegian University of
Science and Technology

BEng. Albert Halenka

Optimizing Pico Hydropower: Enhancing Overshot Waterwheel Performance for Off-Grid Electrification

Maximizing the Potential of Overshot Waterwheel with Adaptive Design

Master's thesis in Hydropower Development
Supervisor: Oddbjørn Bruland
August 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

This thesis explores the concept of a pico hydropower unit utilizing an overshot waterwheel capable of variable rotation speed, aiming to provide a suitable energy source for communities without reliable access to electricity. With an estimated 789 million people lacking electricity worldwide, it is reasonable to assume that many of them reside near small water streams. The use of an overshot waterwheel in off-grid operations within developing countries offers advantages in terms of simplicity, cost-effectiveness, and robustness. Although traditional waterwheels have been considered less efficient, limited recent research exists in this area.

The thesis investigates the potential optimization of the waterwheel's efficiency using contemporary technologies. By electronically stabilizing the electricity output, like it is done with solar power plants, the waterwheel can be allowed to operate at its most efficient rotation speed based on the current water discharge. The thesis conducts experiments to measure the performance improvement of the waterwheel when allowed to operate with a non-fixed rotation speed. As expected, this optimization would greatly outweigh any losses in the stabilization process and additional costs.

Additionally, the thesis explores two methods for further improving the waterwheel's efficiency: a telescopic overshot channel and different shapes of the channel's lip. Experimental results reveal that none of the tested channel shapes outperformed a straight perpendicular lip. Furthermore, the investigation demonstrates that adjusting the channel length is unnecessary when the waterwheel operates at a variable rotation speed. However, while operating in synchronized rotation speeds only, telescopic channel seem to offer some improvement in terms of usable flows and increased efficiency.

To validate the proposed concept, a rudimentary prototype of the pico hydropower unit was constructed. The prototype consisted of a waterwheel coupled to an alternator, which was connected to resistors serving as load components. This configuration facilitated the measurement of rotation speed, current, and voltage output across the resistors, allowing for comprehensive data collection. By systematically altering the discharge, channel length, and load on the alternator, approximately 1500 data points were acquired. These data points were then analyzed using various graphs and charts to discern the effects of each element, namely channel length, waterwheel rotation speed, and lip shape, on the performance of the system.

The research is not devoid of limitations, most notably the constraint posed by the torque resistance of the alternator. The insufficient capacity of the alternator prevented a comprehensive exploration of the efficiency curve of the overshot waterwheel with variable rotation speed capability. Consequently, the full potential of this innovative unit remains untapped, highlighting the need for further investigation. Regrettably, within the confines of available time and resources, acquiring an alternator better suited for such analysis proved challenging. It is anticipated and encouraged that future research will build upon these findings, potentially employing modern software and AI tools to reimagine the bucket shapes of overshot waterwheels. This holds the promise of engineering a water engine capable of efficiency levels akin to conventional turbines, yet at a fraction of their cost due to the streamlined design approach.

Sammendrag

Denne avhandlingen utforsker konseptet med en pico vannkraftenhet som bruker et overhengende vannhjul med mulighet for variabel rotasjonshastighet, med mål om å tilby en egnet energikilde for samfunn uten pålitelig tilgang til elektrisitet. Med anslått 789 millioner mennesker uten tilgang til strøm globalt, er det rimelig å anta at mange av dem bor i nærheten av små vannstrømmer. Bruken av et overhengende vannhjul i avsidesliggende områder i utviklingsland har fordeler med hensyn til enkelhet, kostnadseffektivitet og robusthet. Selv om tradisjonelle vannhjul har blitt ansett som mindre effektive, finnes det begrenset nylig forskning på dette området.

Avhandlingen undersøker potensialet for å optimalisere vannhjulets effektivitet ved bruk av moderne teknologi. Ved å elektronisk stabilisere strømutgangen, på samme måte som gjøres med solkraftverk, kan vannhjulet tillates å operere ved sin mest effektive rotasjonshastighet basert på gjeldende vannutslipp. Avhandlingen gjennomfører eksperimenter for å måle ytelsesforbedringen til vannhjulet når det tillates å operere med variabel rotasjonshastighet. Som forventet ville denne optimaliseringen i stor grad veie opp for eventuelle tap i stabiliseringsprosessen og ekstra kostnader.

I tillegg utforsker avhandlingen to metoder for å ytterligere forbedre vannhjulets effektivitet: en teleskopisk overhengende kanal og ulike former for kanalens leppe. Eksperimentelle resultater avslører at ingen av de testede kanalformene overgikk en rett loddrett leppe. Videre viser undersøkelsen at justering av kanallengden er unødvendig når vannhjulet opererer med variabel rotasjonshastighet. Imidlertid, når det bare opererer med synkroniserte rotasjonshastigheter, ser det ut til at teleskopiske kanaler tilbyr en viss forbedring med hensyn til brukbare strømninger og økt effektivitet.

For å validere det foreslåtte konseptet ble det konstruert en enkel prototype av pico vannkraftenheten. Prototypen besto av et vannhjul koblet til en generator, som var koblet til motstander som lastekomponenter. Denne konfigurasjonen muliggjorde måling av rotasjonshastighet, strøm og spenningsutgang over motstandene, noe som tillot omfattende datainnsamling. Ved systematisk å endre vannutslipp, kanallengde og belastning på generatoren, ble det samlet inn omtrent 1500 datapunkter. Disse datapunktene ble deretter analysert ved hjelp av ulike grafer og diagrammer for å identifisere effektene av hvert element, nemlig kanallengde, vannhjulets rotasjonshastighet og leppeform, på systemets ytelse.

Forskningen er ikke uten begrensninger, mest bemerkelsesverdig begrensningen som følge av generatorens dreiemomentkapasitet. Den utilstrekkelige kapasiteten til generatoren forhindret en omfattende utforskning av effektivitetskurven til overhengende vannhjul med mulighet for variabel rotasjonshastighet. Følgelig forblir det innovative enhetens fulle potensial uutforsket, noe som understreker behovet for videre undersøkelse. Dessverre, innenfor rammen av tilgjengelig tid og ressurser, viste det seg utfordrende å skaffe en generator som var bedre egnet for en slik analyse. Det er forventet og oppmuntret at fremtidig forskning vil bygge på disse funnene, potensielt ved å bruke moderne programvare og AI-verktøy for å gjenoppfinne bøtteformene til overhengende vannhjul. Dette har potensial til å utvikle en vannmotor med effektivitetsnivåer som kan sammenlignes med konvensjonelle turbiner, men til en brøkdel av deres kostnad på grunn av en mer strømlinjeformet designmetode.

Acknowledgements

I extend my gratitude to those who have played a pivotal role in the culmination of this thesis:

Professor Oddbjorn Bruland, my thesis supervisor, whose feedback and support have profoundly shaped this work.

NTNU, for embracing me and fostering the pursuit of Hydropower Development, a distinctive program that allowed me to explore unconventional ideas and conduct crucial experiments.

The staff at NTNU's hydrotechnical laboratory, for generously sharing resources, space, , and imparting the vital lesson of self-reliance.

Mr. Alton Bendu, whose belief and guidance prepared the ground for potential pilot project in Sierra Leone, enlightening me about off-grid community needs.

Dr. Emanuele Quaranta, whose doctoral thesis offered inspiration, data, and invaluable insights.

To my fiancée, Soňa, for her unwavering patience and support throughout my studies abroad.

To my mother, whose unshakable encouragement provided solace during challenging times.

To my father, for his technical guidance, the original idea for the unit, and orchestrating the creation of the testing prototype, and its electronical accessories.

Lastly, to the diverse academic community at NTNU, for their engagement, feedback, and the exchange of ideas that enriched this journey.

Funding

I extend my sincere appreciation to TronderEnergi for their invaluable support and commitment to fostering innovative research and sustainable energy solutions. Through the grant scheme they offered, I was granted the opportunity to materialize my aspirations and embark on a journey of exploration and experimentation.

TronderEnergi's generous contribution of 25 000 NOK facilitated the construction of the testing rig, a pivotal element in realizing the concept of the pico waterwheel hydropower unit. This grant not only enabled the practical realization of the idea but also ignited a profound sense of purpose and dedication within me.

The invaluable experience gained from designing, constructing, and testing the pico waterwheel hydropower unit has profoundly shaped my academic and professional trajectory. The encouragement and resources provided by TronderEnergi have fortified my resolve to pursue this innovative avenue beyond the confines of this thesis.

Disclaimer

I, Albert Halenka, hereby declare that I am the sole author of this thesis. I have independently designed the testing rig, conducted all calculations and experiments, and compiled the findings herein. All external information, data, and concepts not originating from my own work have been appropriately cited and referenced.

Throughout the process of crafting this thesis, I have used ChatGPT to ensure grammatical accuracy and readability. This tool has been utilized exclusively for refining language and enhancing comprehension, without altering the underlying content or analysis.

I also wish to acknowledge that I employed ChatGPT as an advanced search tool to acquire additional information relevant to this study. However, it is unquestionably affirmed that all sources consulted through this tool have been diligently acknowledged and referenced within this thesis.

I hold the firm belief that the NTNU, being a forward-looking and progressive institution, embraces the judicious use of emerging technologies such as ChatGPT and other AI tools. The collaborative synergy between human intellect and AI innovation underscores the evolving landscape of academic exploration.

In presenting this thesis, I affirm that the principles of academic honesty, integrity, and transparency have been rigorously upheld, and that the collaborative facets of this endeavor have been conducted with due diligence and adherence to ethical research practices.

Albert Halenka

31.8.2023

Table of Contents

List of Figures xvii

1 Introduction 20

2 Previous research 26

3 Methodology 27

3.1 Aim of the laboratory tests 27

3.1.1 Non-synchronised rotation speed 27

3.1.2 Telescopic channel 28

3.1.3 Adjusted channel's lip 28

3.2 Testing rig description 29

3.3 Measurement instrumentation 31

3.4 Initial Testing and Troubleshooting: 34

3.5 Experimental procedure 34

3.6 Collecting and interpretting data 35

3.6.1 Taking Measurements 35

3.6.2 Data Processing and Interpretation 36

4 Results 37

4.1 Variable speed 37

4.1.1 Observations and data 37

4.1.2 Interpretation of results 38

4.2 Telescopic channel 42

4.2.1 Observations and data 42

4.2.2 Interpretation of results 45

4.3 Adjusted channel's lip 45

4.3.1 Observations and data 45

4.3.2 Interpretation of results 47

4.4 Channel height 50

4.4.1 Observations and data 50

4.4.2 Interpretation of results 51

5 Limitations and sources of error 52

6 Discussion 58

7 Conclusions 61

8 References 62

List of Figures

Figure 1 - Barbegal Mills - a cascade of 16 overshot watermills built by Romans in the 2nd century. Source: Carole Raddato, Museum of Ancient Arles, Arles, France. 22

Figure 2 - Turbine application chart. Bottom left corner is the area of interest. Source: (Emanuele Quaranta, 2018)... 24

Figure 3 - An example of a whirlpool turbine and the amount of concrete and secondary structures needed for its installation. Source: (Wonderful Engineering, 2023). 24

Figure 4 - Breastshot and undershot waterwheels, which may easily be blocked by debris at the point where the water jet enters the wheel. Source: (Boura, 2023). 25

Figure 5 - Wheel buckets made of PVC pipe, used in Ing. Macek's experiment. Source: (Macek, 2016).. 26

Figure 6 - Photo of the assembled prototype 29

Figure 7 – Left side of the prototype with visible pulley system transferring the rotation to the car alternator. First "lightbulb" version of the Load box can be seen in the bottom left corner of the picture.. 30

Figure 8 - Channel and hydropower unit installed in the hydrotechnical laboratory. The original channel's length denoted as "-15", since it was easier to add length extensions than to shorten the channel. 31

Figure 9 - One of the two gauges to measure the depth in channel 32

Figure 10 - View at the laboratory power supply (top left), Load box with one of the lightbulbs engaged (bottom right), and paper with testing sequence of adding load and slowing the wheel down. 33

Figure 11 - Inside of the new load box that utilizes resistors instead of lightbulbs for more linear behavior of the load 34

Figure 12 - Examples of installed extensions. 35

Figure 13 - Typical efficiency curve of an automotive alternator used in the interpretations of results. 36

Figure 14 - Example of data collected for one height and channel setting. 37

Figure 15 - Efficiency curve of the whole prototype unit.. 37

Figure 16 - Result efficiency curve after subtraction of the alternator-induced distortion 38

Figure 17 - Comparison of Efficiency of prototype unit with and without the ability to operate in non-synchronized rotation speeds. 39

Figure 18 - Trendline forecast of efficiency curves.. 40

Figure 19 - Comparison of prototype unit's efficiency curves including forecasted data. 40

Figure 20 - Efficiency using forecasted data without alternator's distortion................. 41

Figure 21 - The effect of channel's length on runaway speed of the wheel 42

Figure 22 - Efficiency of the prototype unit with different channel extensions 43

Figure 23 - Comparison of efficiency at 32 RPM for different channel extensions.......... 44

Figure 24 - Dimension of the two V-notched channel lips used in the tests.................. 46

Figure 25 - Dimension of the three curved channel's lips used in the tests. 46
Figure 26 - Adjusted channel's lip extension used in the laboratory experiment. 47
Figure 27 - Splashes that appeared when using the V-notched channel. They originated from the middle of the jet and splashed beneath the jet outwards. 47
Figure 28 - Comparison of the runaway speed with the best-performing straight channel extension "0", and the three curved channel's lip extensions................................... 48
Figure 29 - Efficiency of the prototype unit in variable RPM with straight "0" extension and the three curved channel's lips 49
Figure 30 - Efficiency of the prototype unit in fixed 32 RPM with straight "0" extension and the three curved channel's lips 49
Figure 31 - Effect of the channel height on the efficiency of the prototype unit. 50
Figure 32 - Effect of the channel height on the rotation speed associated with the highest recorded efficiency.. 51
Figure 33 - Comparison of the provided and final shape of the buckets (on the left), and the wooden form used to bend the heated semi-finished buckets (on the right)........... 52
Figure 34 - Imperfection in the shape of the buckets. Here, the curved edges of buckets are seen. 52
Figure 35 – Dull edges of the buckets. As they were not treated at all, the dull edge was 2 mm thick – same as the material the buckets were made of 53
Figure 36 - Spot welds used to fix the buckets to the wheel, causing minor leaks in between the buckets and wheel's walls... 53
Figure 37 - Pipe system feeding the water to the channel. Only a half of the total length is in this photo, therefore losses through leaks were hardly evadable. 54
Figure 38 - Picture from one of the videos showing the splashes that were almost always present in higher discharges and rotation speeds... 55
Figure 39 - Detailed photo of the diode bridge rectifier of the alternator used in the experimental prototype unit.. 56
Figure 40 - Results from Dr. Quarant's experiment, showing that he also did not have the equipment to assess the parts of the curves that lie in the upper left triangle of the chart area. Source: (Quaranta, 2017). 57
Figure 41 - The whole unit fits into a trunk of a car - ideal for delivering to those communities that have not yet been reached by suitable infrastructure. 59
Figure 42 - Proposed wall to prevent splashes and force water to interact with the wheel, thus increasing efficiency. Souce: (Quaranta, 2017). 60

1 Introduction

Access to reliable electricity is a fundamental aspect of modern life, enabling essential functions ranging from lighting and education to healthcare and economic development. The International Energy Agency (IEA) defines access to electricity as the ability of households and businesses to obtain and use affordable and reliable electricity services for basic and productive needs (International Energy Agency, 2021). This definition emphasizes the importance of both a consistent supply of electricity and reliable infrastructure. The benefits of reliable access to electricity are substantial, contributing to poverty reduction, improved health outcomes, enhanced education opportunities, and economic growth. The World Bank's "Global Tracking Framework" underscores how access to electricity can facilitate health, education, and economic opportunities (World Bank, 2021). The United Nations Development Programme (UNDP) also highlights the role of electricity access in poverty reduction and job creation (UNDP, 2012). Achieving reliable access to electricity for those without it remains a crucial goal, not only for enhancing quality of life but also for fostering sustainable development.

In addition to the direct benefits of electricity access, it's worth considering the sequential impacts on socio-environmental dynamics. Bjorn Lomborg highlights how poverty reduction can lead to increased demand for environmental protection, creating a feedback loop that could make poverty reduction an effective strategy for tackling climate change (Lomborg, 2001). The interplay between poverty alleviation and environmental sustainability underscores the significance of innovative energy solutions that can simultaneously improve lives and minimize ecological footprints.

Sub-Saharan Africa is emblematic of the electricity access challenge. The IEA's estimates from 2021 suggest that approximately 759 million people worldwide lack reliable access to electricity, with 580 million residing in sub-Saharan Africa. Traditional biomass is the primary energy source for many in the region, especially for cooking and heating. Even in urban areas, intermittent power supply is common, and self-managed generators often serve as backup. Although renewable energy sources, including off-grid solar, wind, and hydro power, are making inroads, their adoption remains relatively low due to various factors. The potential for pico hydropower, as an accessible and decentralized solution, offers a promising avenue for addressing this energy disparity.

Sub-Saharan Africa possesses considerable untapped hydropower potential, a critical resource that could transform the region's energy landscape. The International Hydropower Association estimates that Africa's untapped hydropower capacity exceeds 1,750 GW, with approximately 19% suitable for small hydropower installations (IHA, 2023). This immense potential could hold the key to addressing the energy needs of millions without access to electricity. In 2021, the IEA reported that around 580 million people in sub-Saharan Africa lacked electricity access, accounting for 57% of the region's population. The adoption of adaptable and versatile micro and pico hydropower units, like the one examined in this research, offers a promising solution to alleviate this energy disparity. Moreover, the establishment of sub-grids powered by these smaller systems can provide resilience against power outages and grid failures, fostering local energy generation and sustainable development.

In conclusion, providing reliable access to electricity remains a pressing global challenge, particularly in regions such as sub-Saharan Africa. The potential of pico hydropower solutions offers a pathway to address this challenge by harnessing untapped hydropower resources and deploying decentralized energy systems. By embracing such innovations, we can simultaneously enhance the quality of life for underserved communities, foster economic growth, and contribute to sustainable development goals.

The existing circumstances in many off-grid communities suggest a hypothesis that individuals currently lacking access to electricity are unlikely to receive it in the near future through large-scale grid expansion projects. Despite the ongoing efforts to develop substantial grid infrastructure, rural and remote areas, where a significant portion of these individuals reside, often remain underserved. This is due to several factors, including distance from urban centers, economic viability, and the prioritization of more populated regions. Consequently, the gap between the energy-deprived and the electrified persists.

While larger projects may face challenges in extending the grid to these areas, pico hydropower units offer a potential solution that aligns with the needs and conditions of these underserved communities. In many cases, residents in these areas are poor and may not be the primary focus for large energy project developers. Consequently, they might not benefit from grid expansion efforts in the short term. Pico hydropower units, financed through community initiatives or smaller-scale investments, could serve as a rapid and self-reliant approach to meeting local electricity demands. By providing communities with the means to generate their own electricity, these units could catalyze the development of self-sustaining energy systems and alleviate their dependence on centralized grids, offering a practical and accessible solution for addressing electricity demand. While exact data and numbers may vary across regions, the fundamental challenges of grid expansion, economic disparity, and the prioritization of more lucrative markets contribute to the logic behind this hypothesis.

Proposed hydropower unit

The envisioned concept of the proposed pico hydropower units revolves around addressing the immediate and pressing electricity needs of off-grid communities, serving as an interim solution until a major grid infrastructure can be established. This interim period, which could span years, underscores the importance of simplicity in maintenance, robustness, and cost-effectiveness for these units. While the efficiency and installed capacity of these pico hydropower units need not rival that of larger-scale hydropower plants, their strategic placement becomes notably advantageous. The minimal operational prerequisites, demanding only a modest discharge in the range of tens of liters per second and a mere 1-meter head, render the identification of suitable deployment sites considerably more feasible. Settlements typically situated in proximity to water sources, potentially streams, make the proposition of electrification through pico hydropower units far more attainable and practical.

Pareto, positive effect of pico hydro

Undoubtedly, a single pico hydropower unit might not single-handedly suffice to fully power a community comprising, for instance, several thousand individuals. However, this is where the potency of the Pareto principle, the "80/20" rule, becomes apparent. While these units may not cater to the entirety of electricity demand, they can effectively meet approximately 20% of the requirements, which, in turn, could result in an 80% transformational impact on the lives of the local population. The strategic allocation of this limited but significant power output can enable crucial activities such as operating radios for communication, powering lights to extend productive hours, facilitating the use of essential medical appliances like refrigerators or freezers, and even establishing internet connectivity. In this context, the pico hydropower unit emerges not merely as a technical innovation but as a pivotal catalyst in empowering these communities to prioritize and meet their most vital and immediate needs, thereby driving meaningful improvements in their quality of life.

Cascade – scalability and economical accessibility

In the context of the Pareto principle, discussed above, which highlights effective resource allocation, the ongoing need for increased electricity production remains a critical consideration. Let's consider a hypothetical scenario where pico hydropower units are standardized to a unified size to reduce costs. In this situation, if we want to generate more electricity, our option is to use multiple units. Surprisingly, this approach, rather than being a drawback, has distinct advantages. Picture a series of pico hydropower units arranged in a cascade or sequence, similarly to the Barbegal mill in Figure 1 below.

Figure 1 - Barbegal Mills - a cascade of 16 overshot watermills built by Romans in the 2nd century. Source: Carole Raddato, Museum of Ancient Arles, Arles, France.

What's interesting is that this arrangement preserves the benefits of their compact size. Notably, it eliminates the need for extra infrastructure like channels, pipes, or dams, and sidesteps the complexities of heavy machinery and extensive concrete work during installation. More significantly, this design has the potential to minimize environmental impact. It avoids diverting water from the main river course and minimizes disruption to aquatic ecosystems, including fish migration patterns and sediment transport.

Now, let's delve into the economic aspect. This proposed "cascade setup" enhances its appeal from a financial standpoint. This setup makes the units economically feasible for the targeted communities. To illustrate, consider two hypothetical scenarios.

In the first, a community wants to generate electricity from a nearby river by building a small hydropower plant. However, the cost of such a project is substantial, especially for financially challenged communities. Although loans are available from banks for such projects, obtaining them involves a complex process of paperwork and guarantees. But, with some luck, the community secures the loan. They also need to find someone to design and construct the power plant, which can take years before they enjoy consistent electricity access. Additionally, the community must manage loan repayments over a specified period.

Contrast this with the second scenario: a community urgently needs electricity. They have a river nearby, but the funds to build even a small power plant are limited. In this case, they opt to purchase a pico hydropower unit. This unit can be set up by community members themselves, possibly with assistance from a qualified technician. A locally sourced 1-meter-high weir can be constructed at minimal cost by community members. While the unit's electricity output may meet only a fraction of their overall needs, it effectively fulfills essential requirements such as refrigeration for medical supplies, charging critical communication devices, or satellite internet, and providing lighting. All of this is achieved at a fraction of the cost associated with establishing a small hydropower plant. The pivotal difference lies in the absence of a prolonged loan application process and subsequent lengthy repayment commitments. Instead, the community employs its available savings to procure the pico unit, potentially leading to self-financing. While the demand for more electricity persists, the initial pressing needs are promptly met. As financial resources accumulate, a cascade setup emerges as a viable route, either in sequence or adjacent to the initial unit, depending on the river's characteristics.

Choosing the right type of water motor

The core concept of the proposed unit centers on making a thoughtful choice when it comes to the type of turbine used. This decision plays a crucial role in achieving the best performance, ease of maintenance, and technological simplicity.

For pico hydropower applications intended for off-grid communities, an overshot waterwheel presents a strong case compared to other hydraulic machines and turbines. Archimedes screws are well-suited for low heads around 1 meter and are also said to be fish friendly. However, their overall efficiency is known to be around 50-70%, with some designs and optimized setups potentially reaching slightly higher efficiency levels (B. A. Stewart, 2003). However, it's important to note that achieving higher efficiency often requires careful design considerations and proper installation, and they may require more frequent maintenance. Whirlpool turbines are a relatively new technology and lack long-term reliability data. Traditional turbines like Francis, Kaplan, Pelton, Turgo, and Banki offer high efficiency but demand specialized engineering and significant investment in infrastructure, including pipes and dams. They often require diverting water from rivers, which may have environmental impacts, and are generally not as debris-resistant as overshot waterwheels. On the other hand, an overshot waterwheel is simple to construct, offers good debris resistance, and needs only a small weir or dam to create the necessary step. While it may not match the efficiency of some conventional turbines, its robustness, lower cost, and easier maintenance make it an excellent choice for remote, off-grid settings where technical support is minimal. Therefore, after carefully considering the specific conditions, particularly a relatively low head of around 1 meter, it becomes clear that waterwheels are the most suitable option.

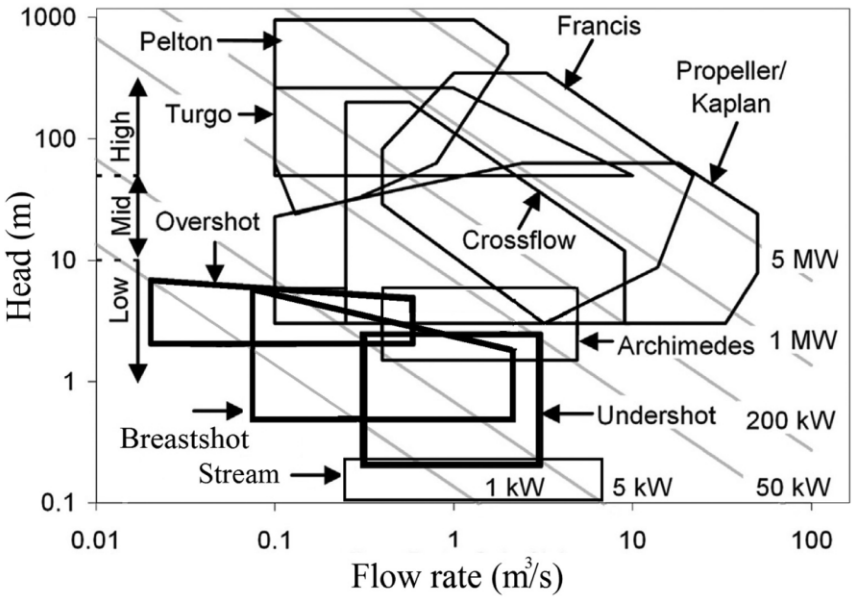

Figure 2 - Turbine application chart. Bottom left corner is the area of interest. Source: (Emanuele Quaranta, 2018)

Figure 3 - An example of a whirlpool turbine and the amount of concrete and secondary structures needed for its installation. Source: (Wonderful Engineering, 2023).

Overshot waterwheel

Specifically, it was opted for an overshot waterwheel, and there are two compelling reasons behind this choice. Firstly, overshot waterwheels can achieve a remarkable efficiency of up to 85%, a fact demonstrated in the research conducted by Dr. Emanuelle Quaranta in their doctoral thesis (2017). Secondly, overshot waterwheels possess a natural ability to withstand challenges posed by debris. Unlike undershot or breastshot designs, where the water enters between the wheel and the channel, thus making them vulnerable to blockages, overshot waterwheels are more resilient in this regard, significantly reducing the risk of debris-related issues. This eliminates the necessity for overshot waterwheels to require secondary structures such as desiltation basins and trash racks.

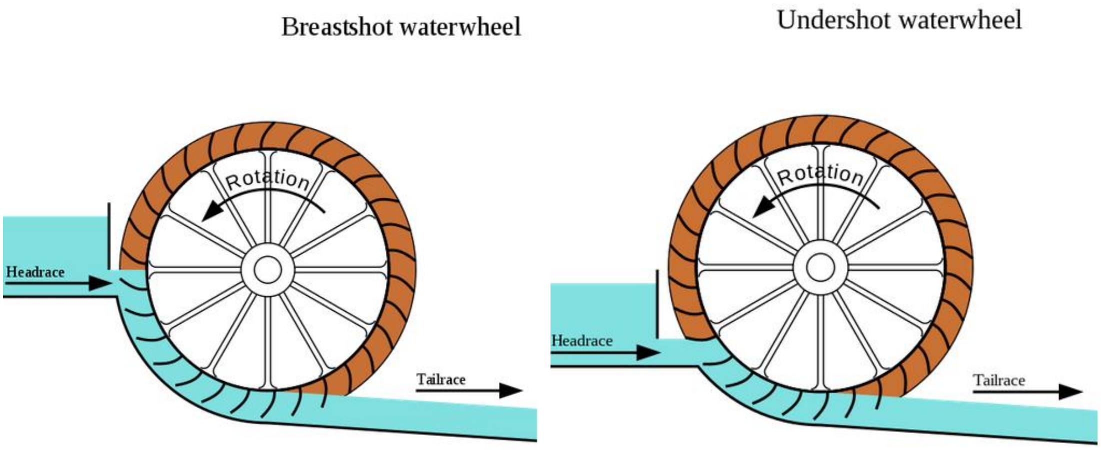

Figure 4 - Breastshot and undershot waterwheels, which may easily be blocked by debris at the point where the water jet enters the wheel. Source: (Boura, 2023).

2 Previous research

Recent years have witnessed limited research on overshot waterwheels, possibly contributing to their perceived obsolescence. This presents a cyclical challenge: the absence of contemporary computational innovations in wheel design might have unveiled efficient solutions, further popularize the wheel and catalyze more research endeavors. Dr. Quaranta's thesis (2017) provides insight, suggesting that while numerous overshot water wheels operated in the past century, only a handful underwent rigorous testing. The majority of these results, unfortunately, were never disseminated in widely-read hydraulic engineering publications. Instead, many are confined to lesser-known reports and articles, such as those by Weidner (1913) and Meerwarth (1935). Some more recent explorations into overshot water wheels include works by Williams and Bromley (2000), and Wahyudi et al. (2013), who investigated a novel configuration aiming at enhanced performance.

A few contemporary endeavors have sought to innovate the overshot waterwheel's design. Notably, the research conducted by Ing. Libor Macek (2016) stands out for its parallel experiments on variable rotation speed and telescopic channels. This line of inquiry was further pursued by researchers like Ing. Zríni (2018). Nonetheless, these studies employed their unique bucket designs and did not emphasize the potential of a hydropower plant operating at varying rotation speeds alongside modifiable water jet entry points through channel adjustments. The rationale for revisiting these experiments is underscored by the commendable efficiency figures achieved by Dr. Quaranta's wheel design, reaching up to 85%, in contrast to Macek’s peak efficiency of 52%. Integrating such an efficient wheel design with features like Macek's telescopic channel and permitting variable rotation speeds might lead to a more consistent efficiency curve. Such an enhancement could render the waterwheel more competitive against traditional turbine models, all the while retaining its intrinsic simplicity, cost-effectiveness, and durability.

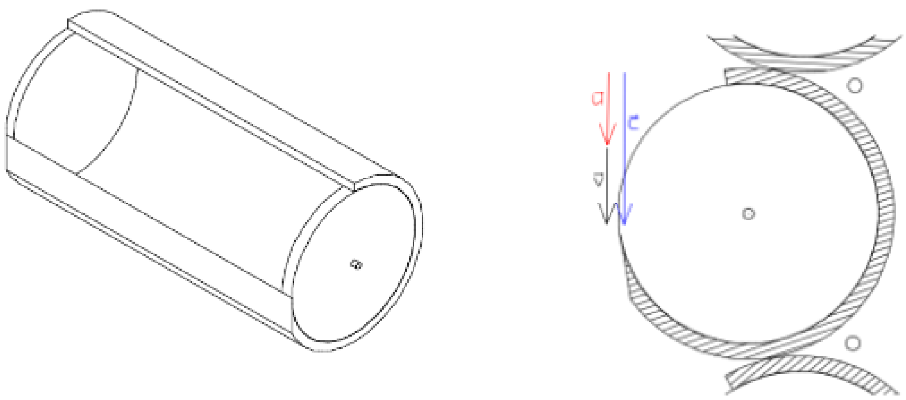

Figure 5 - Wheel buckets made of PVC pipe, used in Ing. Macek's experiment. Source: (Macek, 2016)

3 Methodology

In this study, a comprehensive methodology was developed to evaluate the performance of an undershot water wheel. The primary focus was the creation of a rig that could accurately measure various parameters influencing the wheel's efficiency. Parameters such as discharge, channel position, and rotation speed were meticulously controlled and recorded. Instrumentation and control mechanisms were chosen based not only on their precision and reliability but also with consideration to budget constraints. Despite the rigor of the approach, certain limitations and potential sources of error were identified and documented. The experimental setup, procedures, and potential pitfalls are detailed in the following sections to provide a holistic understanding of the research process and the challenges encountered.

3.1 Aim of the laboratory tests

In a world ardently pivoting towards renewable energy, the revitalization of traditional mechanisms, such as the overshot waterwheel, holds promise, especially for off-grid communities in areas with pronounced seasonal variations. For these regions, like parts of sub-Saharan Africa, where rivers oscillate between robust flows during rainy seasons and diminished volumes in drought periods, adaptability is key. This research delves into three targeted innovations aimed at enhancing both the efficiency and versatility of waterwheels to meet such unique challenges. The first innovation explores variable rotation speeds, harmonizing with water discharge to achieve consistent energy output even during flow variations. The second introduces a telescopic channel, a design leap mirroring modulatory capabilities found in contemporary turbines, to optimize performance under fluctuating water conditions. The culminating idea brings forth a nuanced change to the channel floor, targeting optimal bucket filling by mitigating air entrapment issues. Collectively, these advancements not only elevate the waterwheel's technological profile but also present a potential for off-grid communities, offering them a reliable and adaptable pico hydropower solution tailored to their environmental realities.

3.1.1 Non-synchronised rotation speed

Historically, most hydropower plants have operated with synchronous generators, producing electricity at a frequency consistent with the grid. This meant turbines had to rotate at fixed speeds. However, recent advancements in power electronics and the increasing emphasis on grid flexibility have spurred interest in non-synchronised or variable-speed operation. While not yet mainstream, variable-speed operations are seeing traction in specific scenarios. For instance, pumped storage plants, which traditionally manage electricity demand by storing and releasing water, benefit from variable speeds to fine-tune their output to grid needs. Run-of-the-river plants, without the luxury of large reservoirs, can also capitalize on this feature, adjusting turbine speeds to the available water flow. This adaptability, in fact, introduces a significant advantage:

a broader range of usable discharges. By not being locked into a single operational speed, turbines can harness energy across a wider variety of flow conditions, increasing their efficiency and utility. Size doesn't strictly dictate the feasibility of this technology, but smaller setups, like micro or pico hydropower units, might find a more noticeable percentage increase in performance with variable speeds. Yet, it's essential to note the increased initial costs and complexities tied to this flexibility. Advanced equipment and more intricate control systems are par for the course, although the potential long-term gains in energy capture and reduced equipment stress might well justify the investment. As the energy landscape shifts, it's evident that non-synchronized operations in hydropower are carving a niche, aligning with the global emphasis on renewable energy integration and efficiency.

3.1.2 Telescopic channel

Harnessing the power of flowing water optimally requires a keen understanding of how water interacts with the mechanisms designed to capture its energy. Traditional overshot waterwheels, while being simple and robust, often face challenges in efficiently utilizing varying water velocities. This is because, with fixed channels, the point at which water enters the wheel and its angle of entry change depending on the water's speed, directly influenced by discharge rates. Contrast this with conventional turbines, which benefit from advanced features like guide vanes, stay vanes, and adjustable nozzles. These components allow turbines to modulate water flow, ensuring the highest efficiency across a range of operating conditions. In this context, introducing a telescopic channel to an overshot waterwheel seems not just innovative, but essential. By adjusting the channel in real-time, one can control the water jet's point of entry and its angle, allowing the wheel to capture energy more effectively, irrespective of discharge variations. It levels the playing field, so to speak. With this feature, the overshot waterwheel can be more equitably compared to its technologically advanced counterparts. This adaptation not only promises improved energy capture but also signifies a pivotal step in modernizing the age-old design of waterwheels to cater to contemporary energy needs.

3.1.3 Adjusted channel’s lip

The third and pivotal innovation, conceived during the latter stages of the research, focuses on the meticulous redesign of the channel's profile to bolster the efficiency of the wheel's bucket filling. The heart of this innovation lies in reshaping the channel floor to foster swift air displacement as the water jet fills the buckets. This concept draws inspiration from fluid dynamics principles where trapped air can disrupt smooth flow, potentially affecting energy capture. By facilitating a more unobstructed path for the air to escape, the wheel's buckets are optimally primed to receive and harness the energy of the incoming water.

3.2 Testing rig description

Thanks to the generous grant provided by TronderEnergi, our research was able to design and construct a robust testing rig that faithfully replicates the envisioned hydropower unit. This financial support enabled the creation of a waterwheel with a diameter of 90 cm and a width of 40 cm. Although the ultimate unit is envisioned to have a width of 1 m, the deliberate choice of this dimension allows for seamless scalability. The design of the wheel draws inspiration from the model outlined in Dr. Emanuele Quaranta's thesis, which serves as a foundational reference.

The waterwheel utilized in this study has been carefully crafted with multiple factors in mind to determine its optimal rotation speed. Utilizing a rule of thumb for calculating the optimal speed initially suggested an estimate of 22 RPM. However, adapting the dimensions from Dr. Quaranta's wheel presented an alternative viewpoint, proposing an optimal rotation speed of 38 RPM. Adding to the complexity, an additional guideline stipulates that water wheel buckets should move at half the speed of the water jet, further influencing the calculation. Considering subsequent measurements indicating channel water speeds ranging from 0.5 to 1.24 m/s, the resultant peripheral wheel speed translates to 0.25 to 0.66 m/s—equivalent to 5 to 14 RPM. Given the notable disparities across these findings, a prudent approach was chosen - determining the optimal speed through empirical testing, considering the prototype's unique dynamics and its interaction with the hydraulic environment.

Design discharge determination presented a more straightforward path, as both the scaling of Dr. Quaranta's wheel properties and adherence to established rules of thumb converged on the same outcome: a design discharge of 12 l/s. Nonetheless, a degree of deviation was anticipated due to reservations regarding the faithfulness of the bucket angle replication during the manual crafting process of the wheel utilized in this study.

Figure 6 - Photo of the assembled prototype

Nonetheless, fiscal constraints led to certain concessions in material choices. The wheel's structure is predominantly composed of a duralumin alloy, while the buckets are fashioned from pure aluminum. Due to limitations in available industrial equipment, bucket shaping was accomplished manually - employing heat to shape the sheets in a pottery oven and then molding them over wooden forms. The rig's flanges, axis, and stand are fabricated from steel, providing a balance between manufacturing feasibility and rig stability, fortified by its weight. An innovative design decision involved anchoring the axis to the stand, with bearings interfacing with the wheel's flanges. This provision creates room for potential generator installation within the wheel, envisioning the axis as the generator's stator.

Integrating a pulley system onto one flange, the rig transmits power from the wheel to a 24 V car alternator securely mounted on the steel stand. This setup ensures that the alternator operates at a rotation speed 20 times higher than that of the wheel. The alternator's power supply is established through a laboratory source, while a custom-designed loadbox comprising eight circuits, each with its distinctive resistive load, facilitates adaptable wheel speeds through load adjustments.

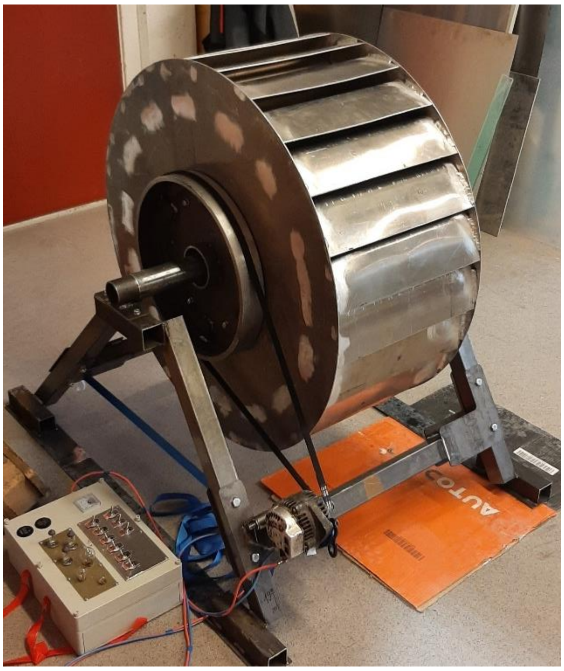

Figure 7 – Left side of the prototype with visible pulley system transferring the rotation to the car alternator. First "lightbulb" version of the Load box can be seen in the bottom left corner of the picture.

In terms of water delivery, the channel ended 15 cm horizontally "before" and 17 mm vertically above the wheel's crest. Water supply to the channel was regulated through a valve-equipped pipe, supplemented with a digital discharge meter. To negate water velocity upon entering the channel, a meshed partition was strategically placed at the pipe-channel intersection. The channel's subsequent slope of 8:100 over a 75 cm stretch came recommended by laboratory staff. To explore the potential of the telescopic channel and the adjusted channel's lip, varying extensions were fitted to the channel's edge during tests.

Figure 8 - Channel and hydropower unit installed in the hydrotechnical laboratory. The original channel's length denoted as "-15", since it was easier to add length extensions than to shorten the channel.

3.3 Measurement instrumentation

To assess the performance of the experimental hydropower rig, a comprehensive instrumentation setup was established. Each component was chosen not only to ensure accuracy, repeatability, and reliability in the collected data, but also to fit within constrained budget. This selection was pivotal in shedding light on correlations between various parameters, furthering our understanding of the system's behavior and potential areas for optimization.

Discharge Control

The hydraulic discharge to the wheel was effectively managed using a valve placed on the feeding pipe. To gauge the exact discharge rate, a digital discharge meter was strategically installed immediately downstream of the valve. This meter provided real-time readings of the discharge, which could be precisely adjusted by manipulating the valve position and observed with minimal delay on the meter's display.

Channel Level Measurement

To infer the velocity of the water within the channel, a dual-scale system was devised. Two measurement scales were delineated along the channel's sides: one positioned immediately post the meshed partition, and another situated at the channel's terminus. By observing the water level in relation to these scales, and factoring in the preset discharge from the valve, water velocity within the channel was ascertained.

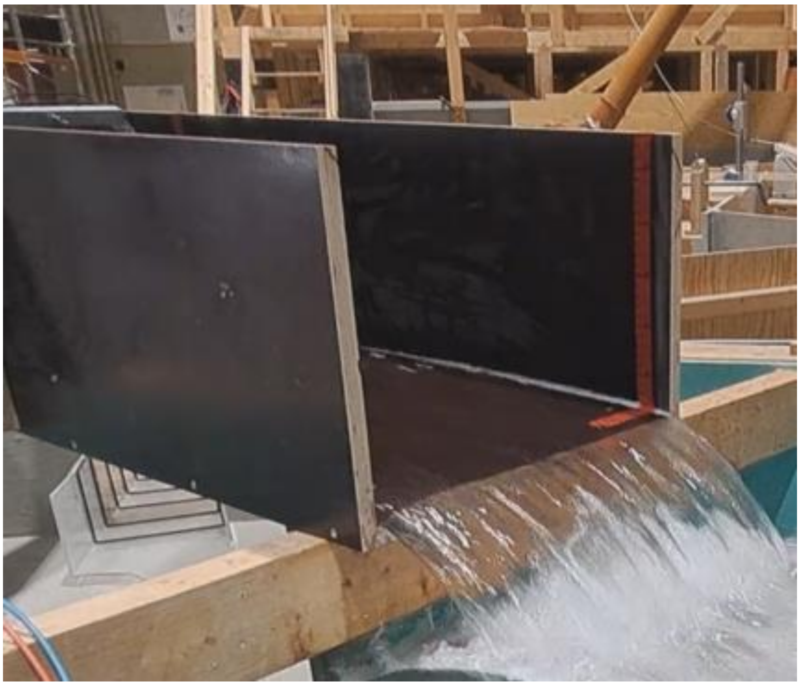

Figure 9 - One of the two gauges to measure the depth in channel

Point of Entry Analysis

Although the point of entry parameter was not directly incorporated into the primary set of calculations, it held relevance in understanding the relationship between efficiency, discharge rate, and the channel's position relative to the wheel. This correlation was explored to gain a holistic view of the system's dynamics.

Rotation Speed Measurement

The rotational speed of the waterwheel was captured using a laser tachometer. This instrument operated by detecting the reflections from a strip of reflective tape affixed to the wheel's exterior. Each reflection was equated to a single rotation, thus providing an accurate readout of the wheel's rotations per minute (RPM).

Alternator Excitation

At the outset of each experiment, the exciting current to the alternator was defined using a laboratory power supply. A consistent value of 2.5 A was selected, as it allowed for a comprehensive exploration of the wheel's performance spectrum. The chosen exciting current directly influenced the torque resistance capacity of the alternator, thus affecting the wheel's operational range.

Output Measurements in the Load-Box

Both voltage and current output from the wheel were monitored via digital meters, each equipped with its dedicated power source. By multiplying the instantaneous readings from these two meters, the power output of the wheel was derived. Considering the minor fluctuations witnessed in both voltage and current readings, an average value was systematically logged for each experimental run.

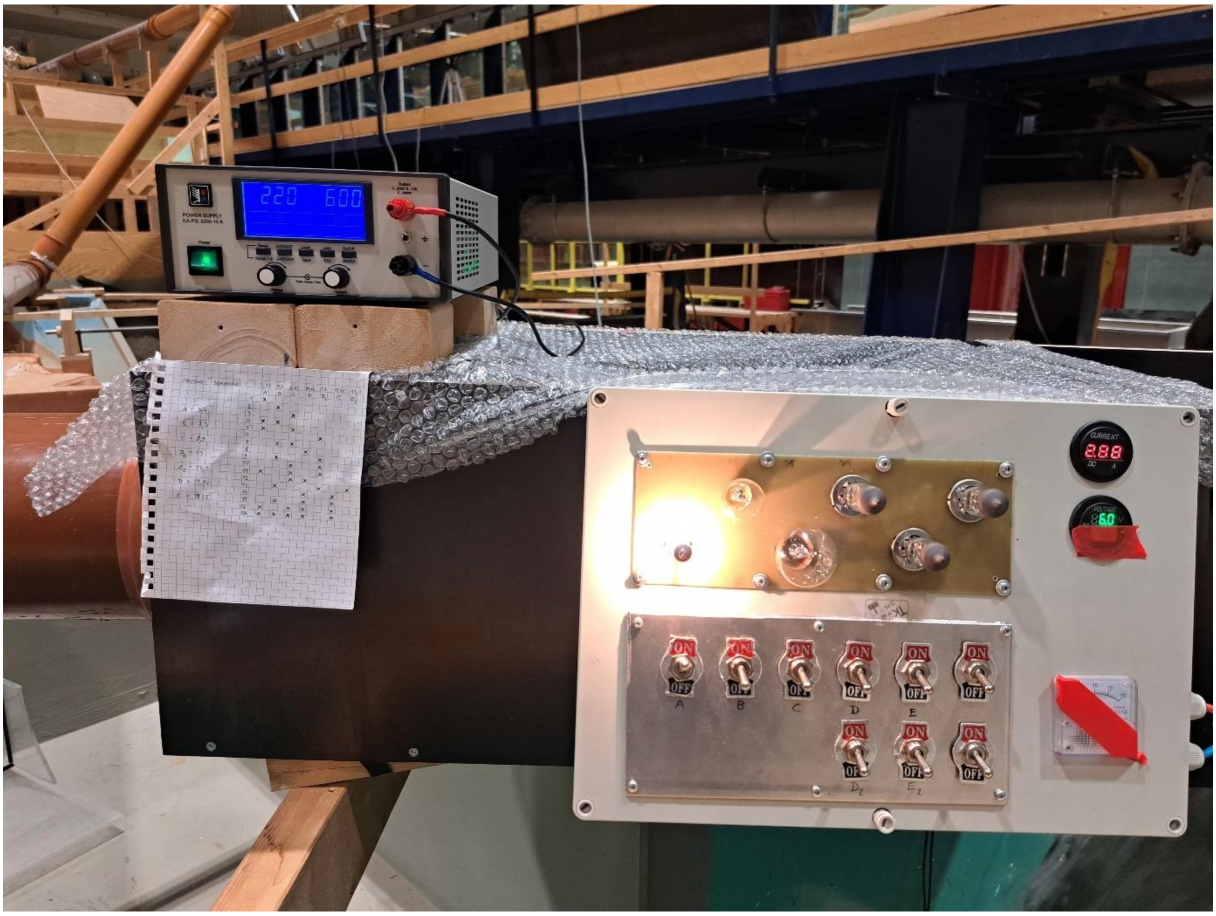

Figure 10 - View at the laboratory power supply (top left), Load box with one of the lightbulbs engaged (bottom right), and paper with testing sequence of adding load and slowing the wheel down.

3.4 Initial Testing and Troubleshooting:

During the preliminary phase of experimentation, several challenges stemming from a lack of expertise in electrical engineering were encountered. The initial version of the testing rig faced obstacles in delivering accurate results. Notably, the use of light bulbs as a load in the load box instead of resistors led to inconsistent measurements. This was due to the non-linear load behavior of light bulbs and their restricted range of resistance. Additionally, utilizing a 12 V alternator was found to be inadequate, primarily because of its limited torque resistance capacity. To further compound these issues, the chosen voltmeter consumed a portion of the generated power, introducing measurement discrepancies and reducing its functionality below 5 V. To rectify these setbacks, several modifications were instituted: the transition to a 24 V alternator, the inclusion of both a voltmeter and an amperemeter with independent power sources, and the substitution of resistors in place of light bulbs for a broader and more consistent range of load resistances.

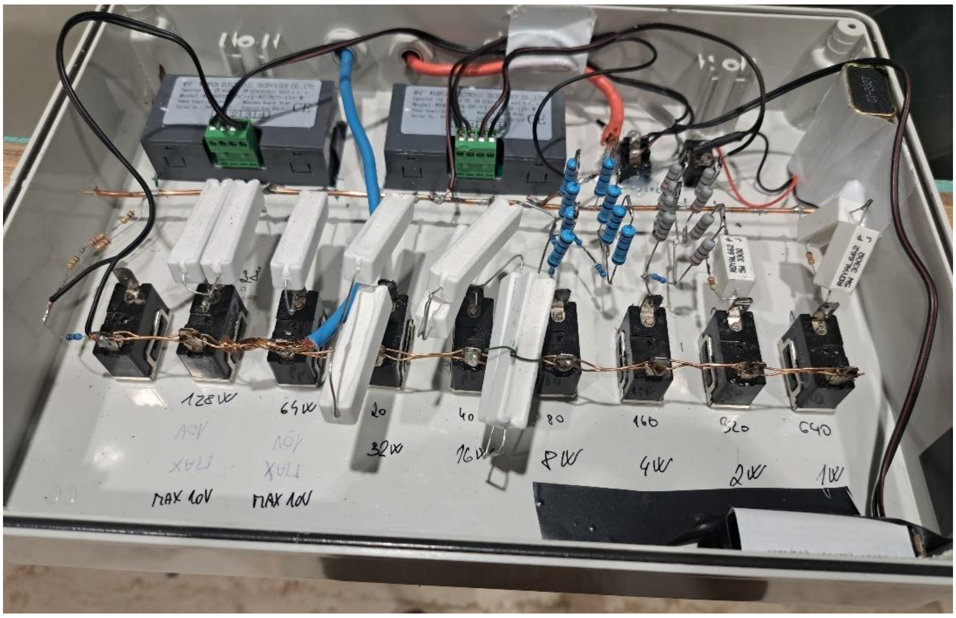

Figure 11 - Inside of the new load box that utilizes resistors instead of lightbulbs for more linear behavior of the load

3.5 Experimental procedure

The experimental process was approached strategically, working sequentially based on the ease of modifying each variable. It was essential to prioritize certain aspects over others, given the varying levels of complexity involved in altering each parameter.

Starting with the vertical positioning of the channel: two primary elevations were explored. The first had the channel's edge positioned 87 mm above the crest of the waterwheel, while the second, a more proximate setting, had the edge just 7 mm above. We then progressed to examine different channel extensions. Beginning with the inherent length of the channel, which concluded 15 cm prior to reaching the wheel's crest, we tested a series of extensions. Each subsequent extension added an additional 5 cm, with the most extended piece reaching 10 cm beyond the wheel's crest.

Figure 12 - Examples of installed extensions.

From there, we delved into evaluating the influence of varied channel lip designs. A total of five distinct shapes were explored, three of which showcased rounded cut-outs, with the remaining two presenting V-shaped notches. With regards to water discharge, tests were conducted in a spectrum ranging from 1 to 40 l/s. However, certain exceptions were made. For instance, if a noticeable decrease in performance was observed with increasing discharge or if the discharge level was insufficient to yield a stable power output, adjustments were made.

Lastly, we tackled rotation speeds. The evaluation commenced from the minimal load, progressing up to the maximum available load. Of course, there were certain limitations, primarily revolving around ensuring the applied load still enabled measurable voltage and current readings, given our instrument specifications.

Throughout this exhaustive testing phase, we also employed video recording for an in-depth analysis. This proved invaluable, especially in assessing how the water interacted with the wheel's buckets. Slow-motion footage was instrumental in capturing the nuances of the water jet's trajectory and any subsequent splashes or disturbances.

3.6 Collecting and interpretting data

3.6.1 Taking Measurements

For each test, once the appropriate extension or channel lip was fitted, the entirety of evaluations for discharges and achievable rotation speeds — dictated by the properties of the load box — spanned between 40 to 60 minutes. Adjusting the discharge necessitated a brief walk of roughly 30 meters to the pipeline, and the response time between manipulating the valve and the subsequent reflection of changes on the discharge meter introduced additional time delays. However, the bulk of operational tasks were carried out proximate to the wheel. At this locus, the load box, equipped with a voltmeter and ampere meter, stood ready. Here, a systematic procedure was followed: load adjustments were made, rotation speed was gauged, pertinent data was meticulously documented into an Excel spreadsheet, and, for comprehensive documentation, video recordings of the operations were captured. The option of automation was entertained but later shelved due to the technical expertise it demanded.

3.6.2 Data Processing and Interpretation

Owing to the intricate web of limitations and inefficiencies, the recorded performance of the entire apparatus invariably appeared slightly muted compared to the wheel's innate efficiency. Since the instruments in use, specifically the voltmeter and ampere meter, measured the collective efficiency of the entire rig rather than the wheel in isolation, arriving at a precise figure became an intricate task. The approach adopted to navigate this intricacy was to substract the presumed efficiency of the alternator, based on a generic efficiency curve matched to its rotation speed. Such an approach, though somewhat heuristic, is expected to shed light on the efficacy of the waterwheel and channel modifications in enhancing the hydropower unit's output.

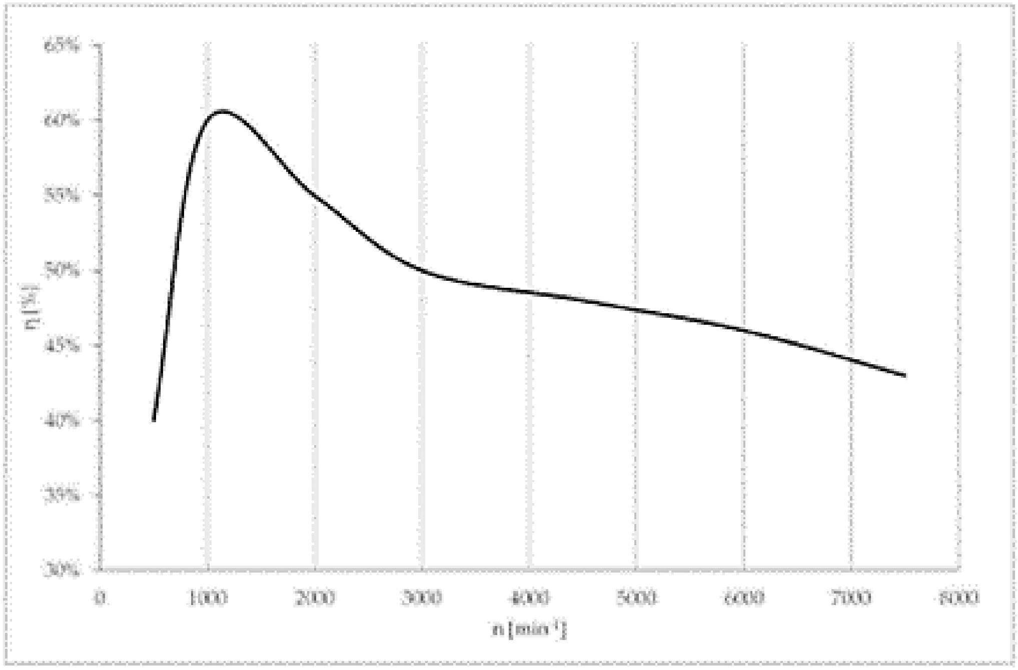

Figure 13 - Typical efficiency curve of an automotive alternator used in the interpretations of results.

4 Results

4.1 Variable speed

4.1.1 Observations and data

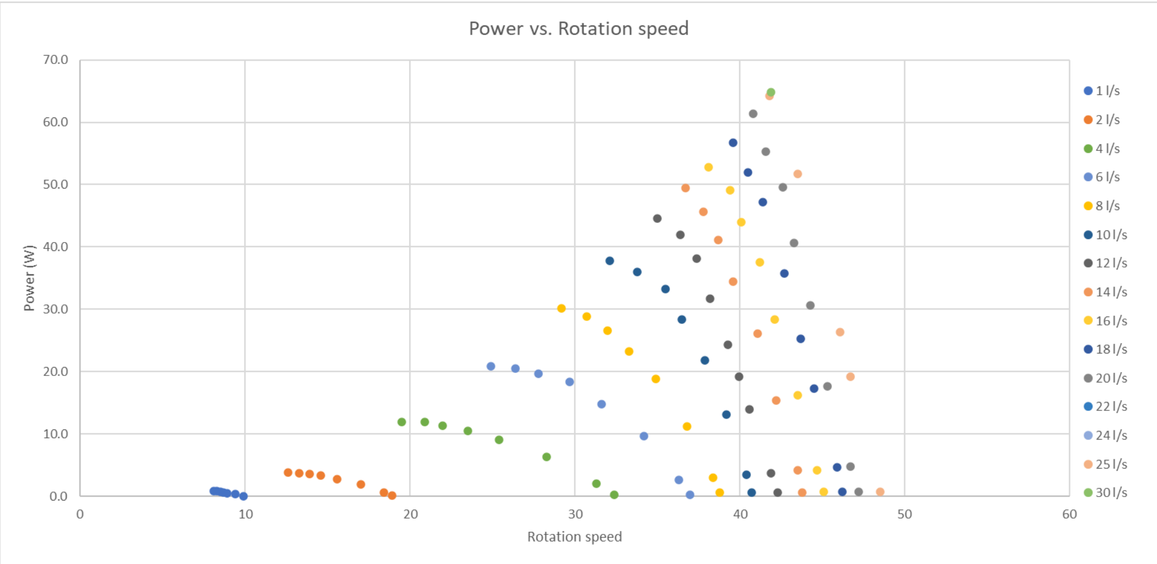

Figure 14 - Example of data collected for one height and channel setting.

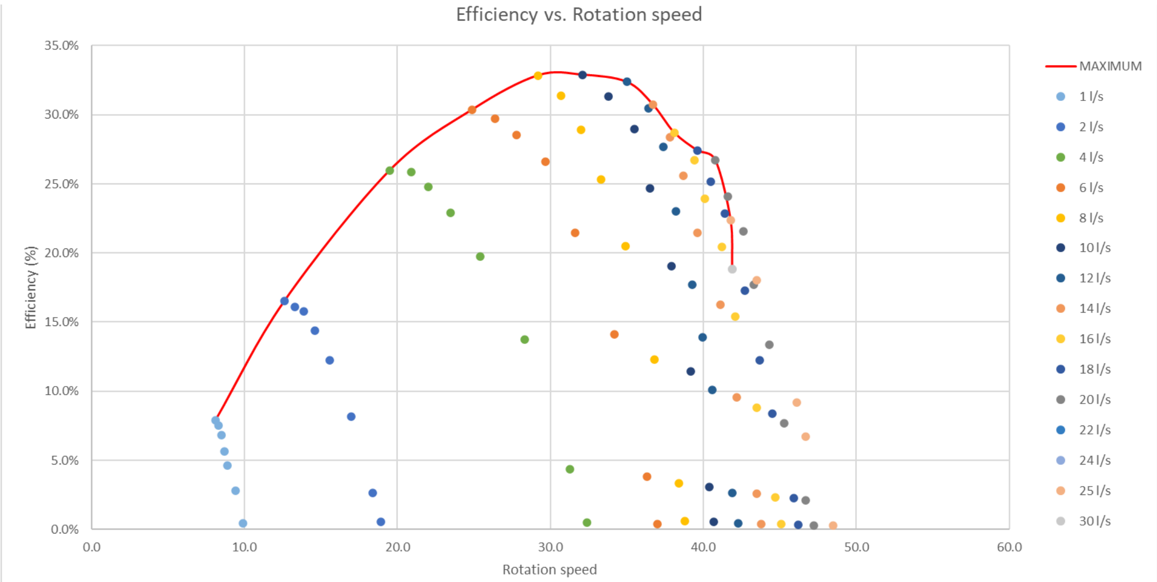

Figure 15 - Efficiency curve of the whole prototype unit

Figure 14 displays a chart comparing the power output of the laboratory prototype in relation to its rotation speed, while Figure 15Figure 15 - Efficiency curve of the whole prototype unit presents a graph of the prototype's efficiency against rotation speed. Both graphs feature data collected with a 27 mm high channel that terminates directly above the wheel's crest and utilizes a straight channel lip. Importantly, Figure 14 illustrates the power output of the entire testing prototype, including distortions introduced by the alternator.

In Figure 15, the highest efficiency observed for this particular setting was 33%, achieved at discharge rates of 8 and 10 l/s and rotation speeds ranging between 29 and 32 RPM. This represents some of the highest unit efficiencies recorded across all various settings tested.

Missing parts of curves

A noticeable gap in the data exists within the upper-left triangular region of the chart in Figure 14, emphasizing the alternator's inability to generate sufficient torque resistance, especially when all loads are engaged. This limitation becomes more pronounced at higher discharge rates. Without the alternator's capability to adequately slow down the wheel, it is challenging to map out the complete power output curve, consequently hampering the identification of the maximum potential power output for a hydropower unit designed to operate at variable RPMs for any given discharge.

4.1.2 Interpretation of results

In order to glean a more accurate understanding of the wheel's performance, it was essential to account for the influence of the alternator, a significant source of system inefficiency. The alternator's efficiency curve was assumed to align with the one presented in Figure 13. By adjusting for this, a 'clean' efficiency curve for the wheel alone could be approximated, as illustrated in Figure 16 below.

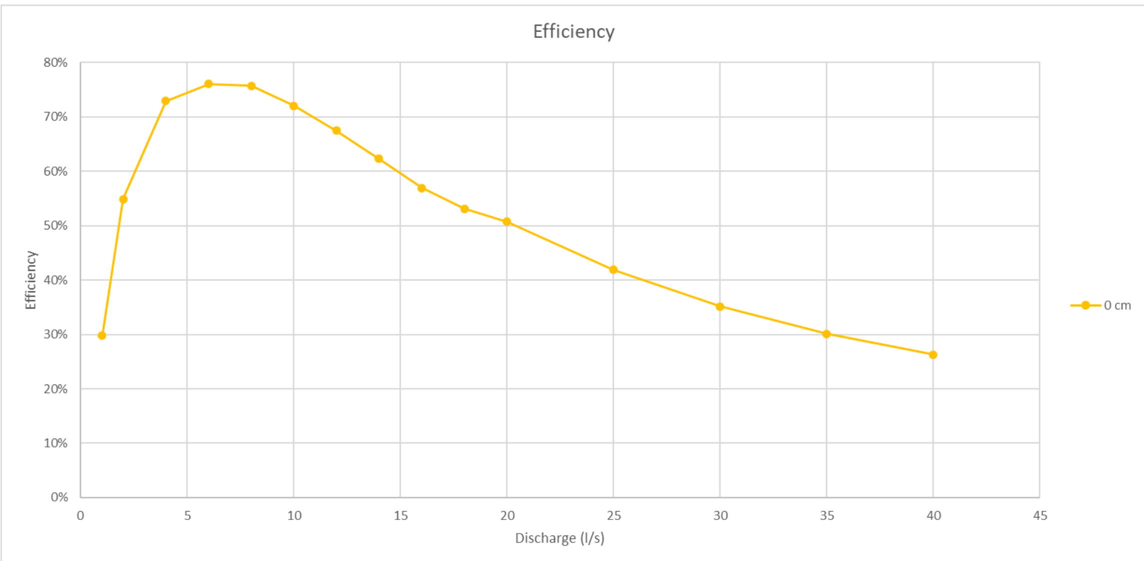

Figure 16 - Result efficiency curve after subtraction of the alternator-induced distortion

When juxtaposed with Dr. Quaranta's wheel, which reached an apex of 85% efficiency, the wheel in this study was found to lag by approximately 10%. This shortfall is largely congruent with expectations, given the myriad of limitations and inefficiencies inherent in the experimental setup.

Notably, the efficiency curve revealed a sharp increase at its onset. This characteristic is particularly advantageous for the specific application scenarios targeted in this thesis, which often feature highly variable flow rates. Additionally, when compared to conventional turbines, this steep onset is relatively more pronounced, offering a unique advantage in efficiency across varying flow conditions.

Of interest is the observation that the efficiency curve in Figure 16 does experience a decline after reaching its peak. A closer inspection reveals that this drop corresponds with the insufficient torque resistance offered by the alternator. Given these constraints, it is reasonable to anticipate that the true performance of an overshot waterwheel capable of variable rotation speeds may actually exceed what has been documented in this thesis. The limitations imposed by the alternator, therefore, hint at untapped potential that could be more fully realized under optimized conditions.

While it is acknowledged that the full efficiency curve could not be completely mapped out due to the limitations of the alternator, it's still informative to compare the performance of a variable RPM system with a hypothetical fixed RPM system. The latter would operate at the RPM level that yielded the highest efficiency during the design discharge. Even with the incomplete data, it is clear that the variable RPM system exhibits superior performance across a broader range of discharge conditions. This versatility could prove valuable in real-world applications where water flow can fluctuate. Thus, while the result appears clearly in favor of the variable RPM system, comparing the two efficiency curves side by side emphasizes the distinct advantages of a more adaptable approach.

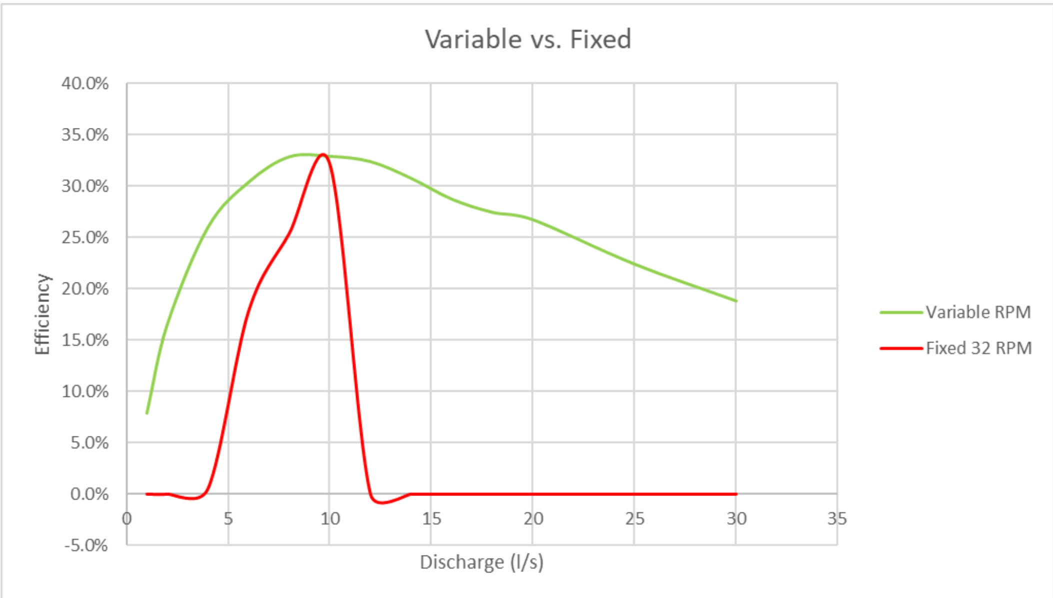

Figure 17 - Comparison of Efficiency of prototype unit with and without the ability to operate in non-synchronized rotation speeds.

To further elucidate the potential benefits of a variable RPM system, a supplementary comparison was conducted using trendline-estimated data to fill in the missing portions of the efficiency curves. While this method involves a degree of speculation, it serves to strengthen the argument for a variable RPM system. It should be noted, however, that for discharges exceeding 16 l/s, the trendline estimates proved to be evidently inaccurate, forecasting maximum efficiencies exceeding 100%. Consequently, the comparison chart was restricted to discharges up to 16 l/s, bearing in mind that even within this range, the estimations may still border on speculation.

Figure 18 - Trendline forecast of efficiency curves.

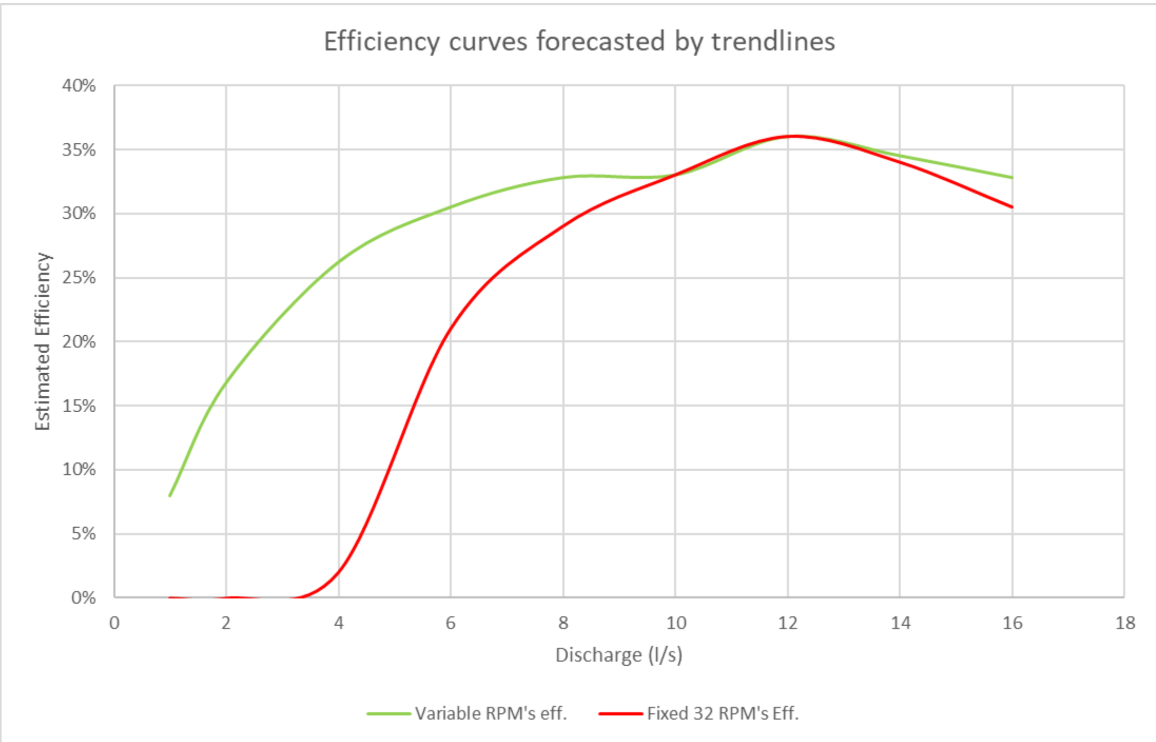

Figure 19 - Comparison of prototype unit's efficiency curves including forecasted data.

In the preceding comparisons, the focus was on the performance of the entire unit, accounting for efficiency distortions introduced by the alternator. To focus solely on the wheel's behavior in variable versus fixed rotation speeds, trendline-forecasted data were utilized, omitting the alternator's distortion but including other minor losses, which are considered negligible for this analysis. While the method does incorporate a degree of speculative inference, the resulting graphs offer valuable insights into the wheel's performance under these different operational conditions.

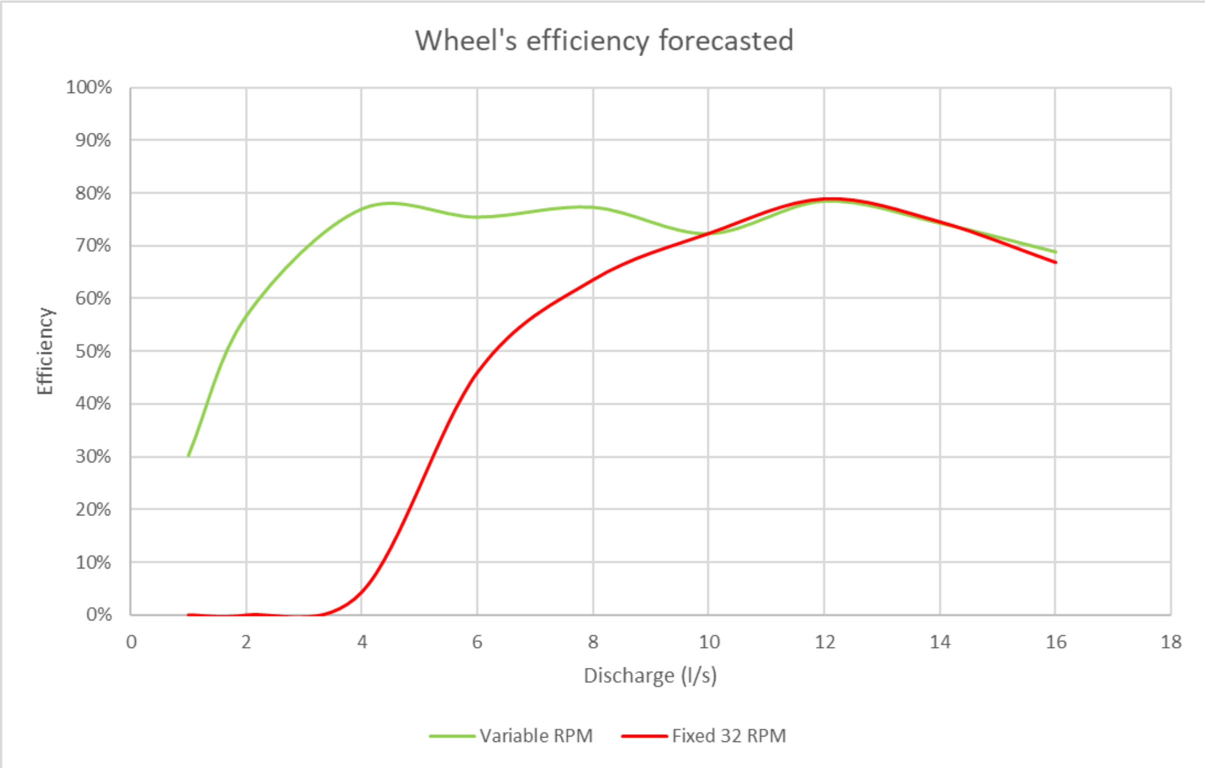

Figure 20 - Efficiency using forecasted data without alternator's distortion.

A noteworthy distinction of the waterwheel, in comparison to systems with enclosed pipe configurations, lies in its capacity for what can be termed "overclocking." Remarkably, even though the design discharge was set at 12 l/s, the rig demonstrated the ability to accommodate a discharge as high as 60 l/s – 500% of design discharge - while still yielding a steadily increasing power output. The potential capacity of the wheel to handle even greater discharges remains a subject of interest; however, caution prevailed in pushing the boundaries further. While the wheel could have potentially withstood more, the limitations of the resistors became apparent as they were already subjected to voltages exceeding their design specifications. The prospect of continuing experiments at such elevated discharges posed a risk of damaging the Load box, a scenario that could have prolonged the already time-sensitive testing phase.

4.2 Telescopic channel

4.2.1 Observations and data

Runaway Speed Analysis

The concept of runaway speed refers to the maximum speed the wheel can achieve when it is not loaded by the alternator. This is an important parameter as it impacts the system's safety and operational capacity. With the telescopic channel engaged, a marked change in runaway speed was observed. Recorded differences in runaway speeds for various telescopic channel positions are illustrated in Figure 21. In the context of runaway speeds, it was observed that longer channel settings led to higher runaway speeds in low discharges. Conversely, in high discharges, shorter channel settings were more effective, yielding higher runaway speeds for the unloaded wheel. Interestingly, the channel length that ended 15 cm (-15) before the crest of the wheel did not yield the highest runaway speeds in any of the tested discharges, including minimal ones. This renders it a less useful position within the potential range of a hypothetical telescopic channel.

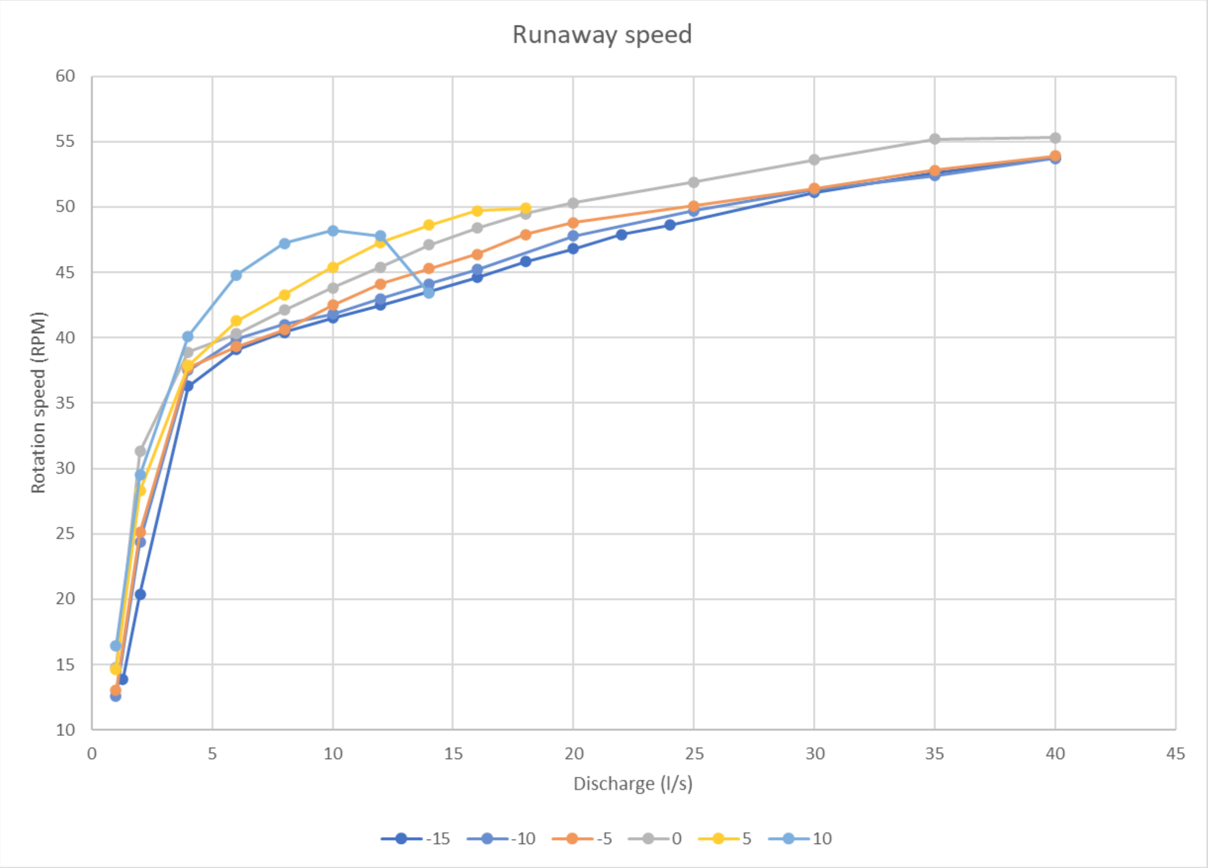

Figure 21 - The effect of channel's length on runaway speed of the wheel

Effects on Performance Across Different Discharges

Following the runaway speed analysis, the effects of the telescopic channel on performance across various discharges were assessed. A rotation speed of 32 RPM was selected for this part of the study, based on prior observations that indicated the prototype unit reached its peak efficiencies at this specific speed. While the runaway speed data might suggest that regulating the channel length would have an impact on the overall performance of the unit, further examination challenges this idea. In Figure 22, performance curves for different channel lengths are displayed. Although limited by the insufficient torque resistance of the alternator, the available data points, as well as forecasted efficiency curves, indicate that a telescopic channel may not influence the performance in a meaningful way, as the highest efficiency at a rotation speed of 32 RPM consistently occurred with a 0 cm channel extension, that is, when the channel ended directly above the crest of the wheel.

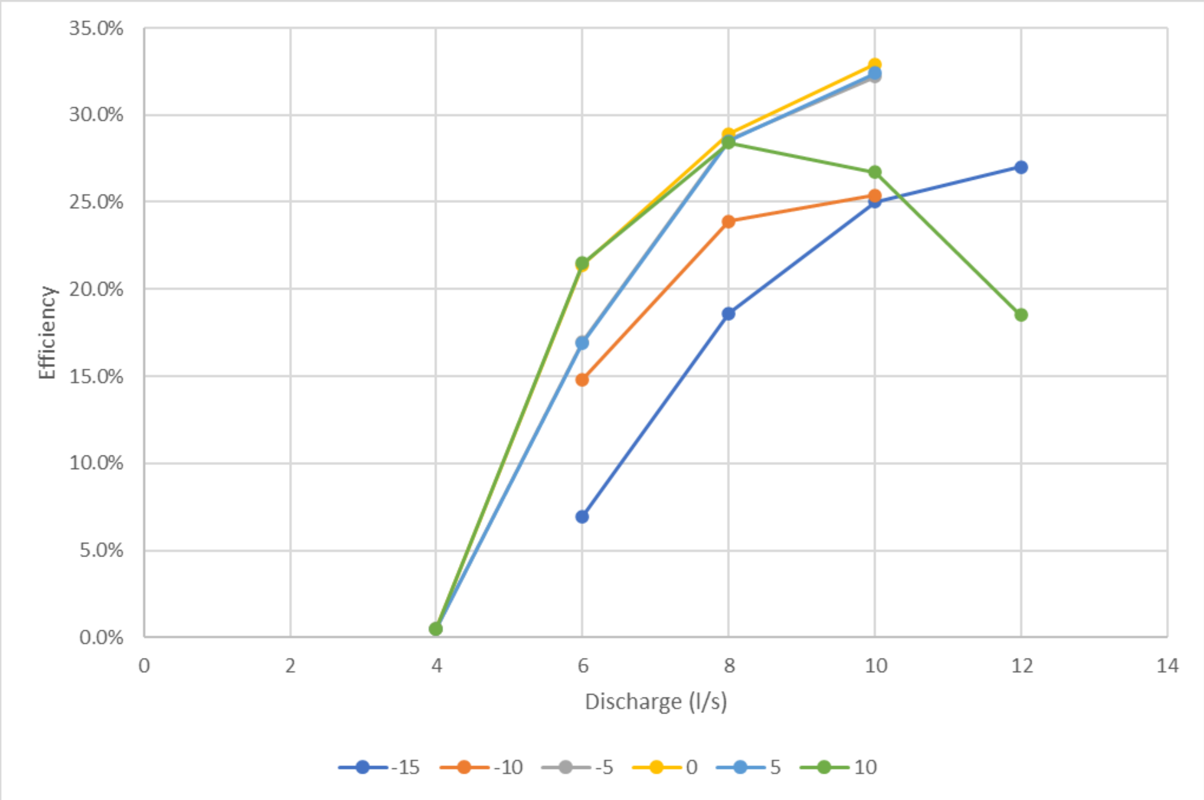

Figure 22 - Efficiency of the prototype unit with different channel extensions

Interestingly, while the results of the tests with variable rotation speed capability indicate that the telescopic channel has no substantial impact on the unit's performance, a distinct advantage emerges when considering scenarios where the unit operates solely in synchronized rotation speed. In cases where the unit's rotation speed is fixed, the telescopic channel appears to offer benefits by accommodating a wider range of flow rates. This phenomenon can be attributed to the alteration of the ratio between potential and kinetic energy transferred to the waterwheel. The telescopic channel's longer length allows for a delayed impact of the water jet on the wheel's buckets, leading to a decreased filling ratio and thus reduced potential energy. However, the increased velocity of the water jet resulting from the longer channel distance contributes to higher kinetic energy. These combined effects influence the wheel's overall performance. Notably, the results from the telescopic channel tests reveal variations in achieved rotation speeds for the same discharges, as evidenced in Figure 23 below. This underscores the telescopic channel's potential advantage for waterwheels operating under synchronized rotation speed conditions. In essence, the telescopic channel's suitability seems to align with scenarios where the wheel's rotation speed is controlled and maintained at a specific value.

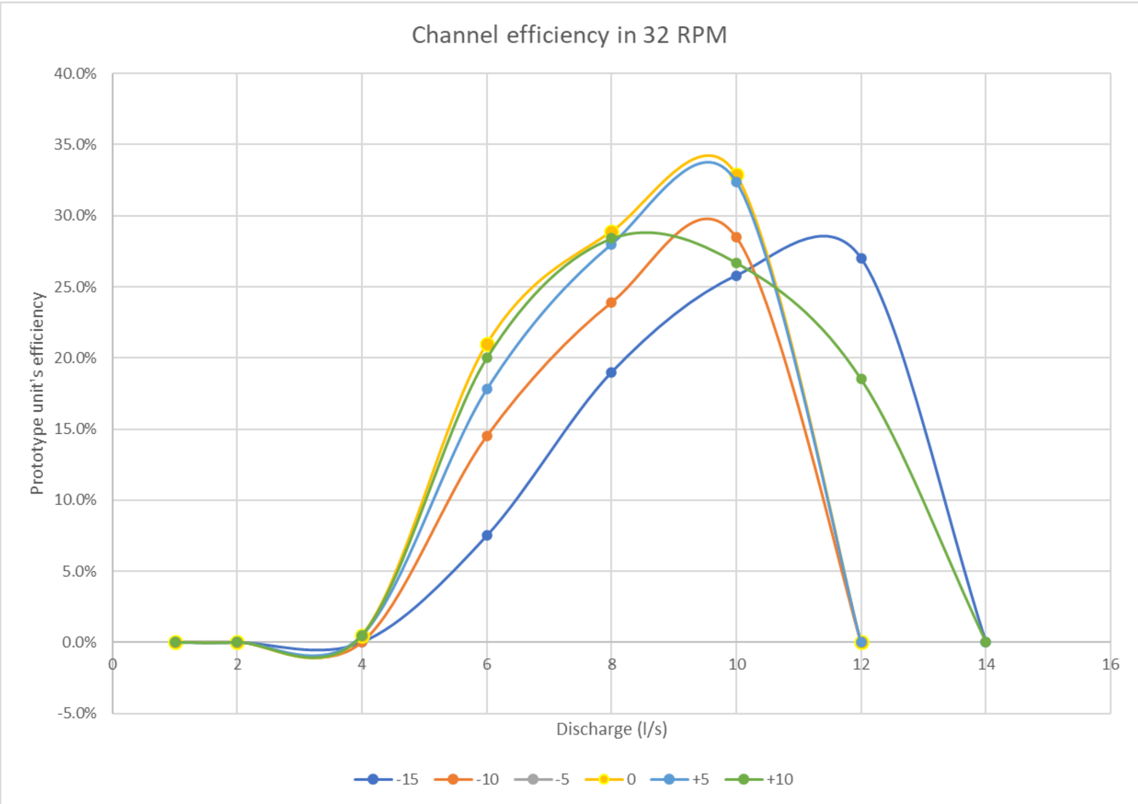

Figure 23 - Comparison of efficiency at 32 RPM for different channel extensions.

Furthermore, when analyzing the impact of different telescopic channel extensions, it is noteworthy that the channel extensions labeled as "+10" and "+5" did not yield discernibly improved results compared to the baseline configuration labeled as "0." This observation implies that, within the scope of this particular case, the telescopic channel's beneficial effect is predominantly achieved within the channel positions of "0" and "-15". This limitation emphasizes that, for this specific unit and operational context, the optimal channel extension range for enhancing performance lies within these positions, reinforcing the significance of synchronicity between waterwheel rotation speed and telescopic channel configuration.

4.2.2 Interpretation of results

The interpretation of the results obtained from the tests involving the telescopic channel offers valuable insights into its effects on the overshot waterwheel's performance. Notably, the measurement of runaway speeds of the wheel provides an indication of how different channel lengths impact its behavior. Shorter channels demonstrate a tendency to accelerate the wheel more rapidly at higher discharges, whereas longer channels lead to higher runaway speeds at lower discharges.

Interestingly, the tests reveal that the incorporation of a telescopic channel in a unit with variable rotation speed capability does not yield an increase in either efficiency or the range of usable discharges. However, when examining tests conducted at a fixed rotation speed of 32 RPM, it becomes apparent that the telescopic channel enables the wheel to operate across a wider range of flow rates with heightened efficiency.

An intriguing possible explanation for these findings lies in the way channel length influences the interplay between the kinetic and potential energy of the flowing water as it interacts with the wheel. In the context of overshot waterwheels, the water entering the buckets contributes to both the kinetic and potential energy driving the wheel's rotation. Longer channels reduce the number of buckets filled, consequently decreasing the potential energy transferred to the wheel. Simultaneously, an extended channel increases the fall distance of the water jet, elevating its velocity and thus augmenting the kinetic energy transferred to the wheel. Although the overall sum of these energies remains constant, yielding no discernible impact on a wheel with variable rotation speed capability, it does exert an effect on a wheel operating at a fixed RPM. The fixed RPM wheel, constrained by a set rotation speed, benefits from the telescopic channel's capacity to alter the balance between potential (torque) and kinetic (rotation speed) energies, ultimately influencing its efficiency and performance characteristics.

The results from our tests confirm the conclusions drawn by Ing. Zríni in his work, which, although centered on determining an optimal channel position, provided a foundational understanding of the potential benefits of a telescopic channel for a fixed-rotation-speed overshot waterwheel.

4.3 Adjusted channel’s lip

4.3.1 Observations and data

Two distinct V-shaped notches, designated as "-10+5" and "-10+10," were investigated to assess their impact on the performance of the wheel. Dimensions for these notches are illustrated in Figure 24. Initial tests were conducted with the channel elevated 87 mm above the wheel. Interestingly, neither of these randomly selected shapes demonstrated superior performance compared to a straight end of the channel. The highest efficiency recorded for these adjusted lip shapes was marginally above 28%, as opposed to the efficiencies of around 33% achieved with a straight lip.

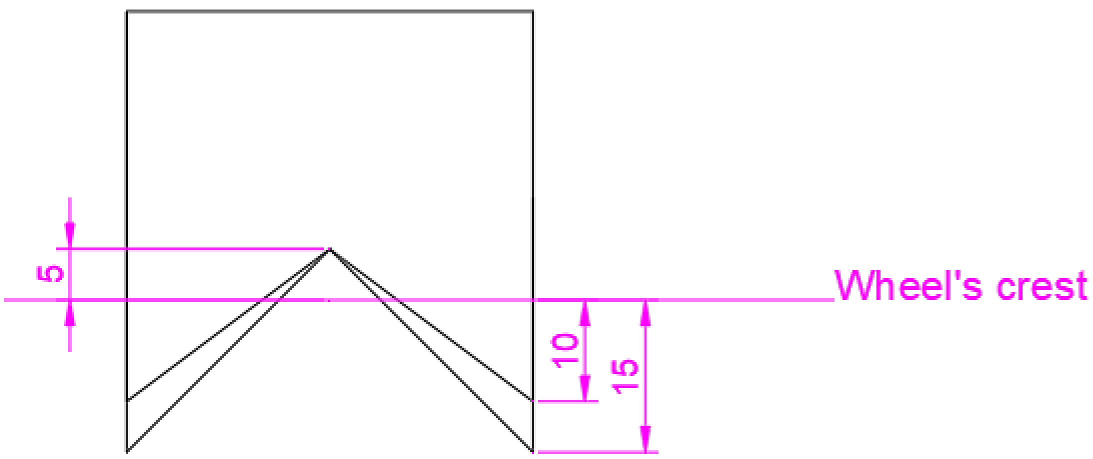

Figure 24 - Dimension of the two V-notched channel lips used in the tests

The underlying theory for implementing the V-shaped notches was to optimize air escape from the wheel's buckets. The expectation was that the V-shaped waterjet would initially strike the center of the bucket, thereby forcing any trapped air towards the sides. As the water gradually filled the bucket from the center outward, the air would be progressively pushed to the sides, where it would eventually escape. This contrasts with a conventional straight-lip channel, where the waterjet engages the entire width of the bucket simultaneously, leaving limited space for the air to evacuate. Despite these considerations, the V-notch designs did not yield the anticipated improvements in efficiency. The primary reason appears to be the additional splashes generated by the V-shaped notches. Particularly, the central part of the notch produced a splash that diverged from the intended water jet trajectory, as evidenced in Figure 9. Moreover, side splashes were observed to bypass the bucket entirely, flowing down the outer side of the wheel without contributing to its rotational energy.

After the inconclusive results with the V-notches, alternative designs were explored to eliminate the splashing in the center of the wheel. Three curved notches were chosen for this purpose, the dimensions of which are specified in Figure 27. Despite the elimination of the center splash—unlike the V-notches—the efficiency of these designs also failed to exceed that of a straight-edged channel. A comparison of efficiencies between all the tested channel lip shapes and a straight-edged channel is provided in Figure 28.

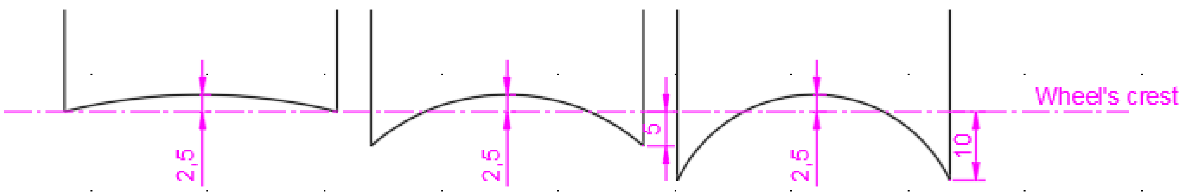

Figure 25 - Dimension of the three curved channel's lips used in the tests.

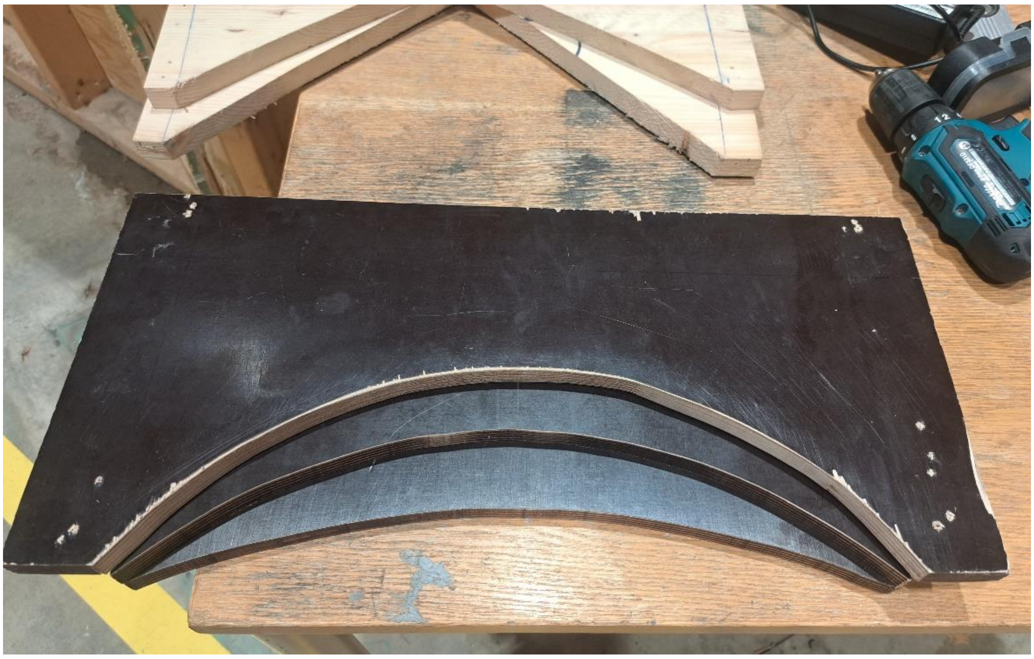

Figure 26 - Adjusted channel's lip extension used in the laboratory experiment.

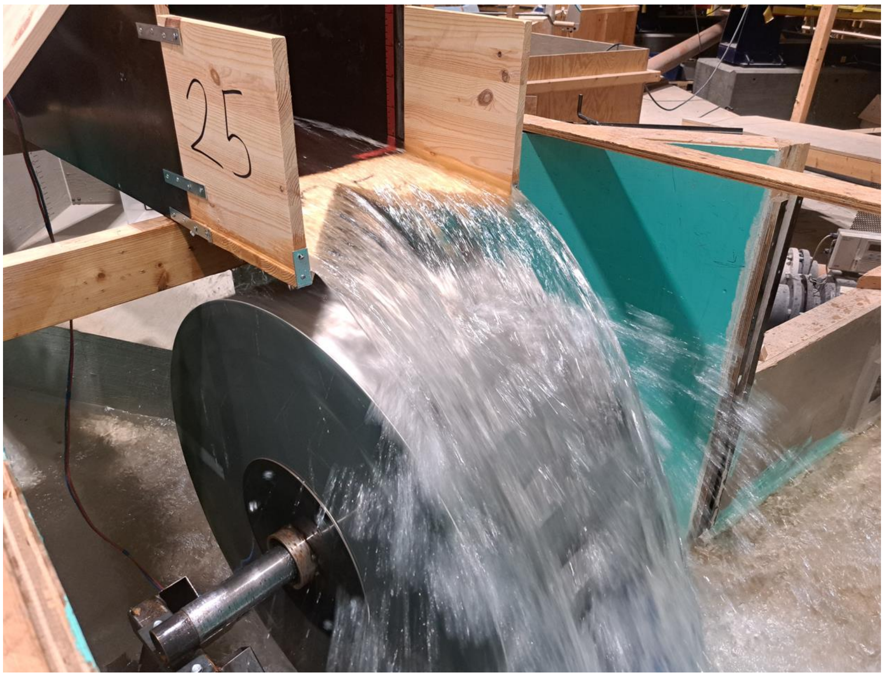

Figure 27 - Splashes that appeared when using the V-notched channel. They originated from the middle of the jet and splashed beneath the jet outwards.

4.3.2 Interpretation of results

While the original rationale for introducing notches, whether V-shaped or curved, was to facilitate the efficient movement of water into the buckets, the actual results did not support this hypothesis. The V-notches seemed to create additional energy losses due to splashing, while the curved notches, although mitigating this issue, also failed to provide a noticeable efficiency gain. This suggests that the interplay between water flow and bucket design is more complex than initially anticipated, and that the simplistic geometric changes to the channel's lip did not significantly influence the system's performance. Further studies are required to understand this complex dynamic, possibly involving fluid dynamics simulations to predict the behavior of different channel lip designs.

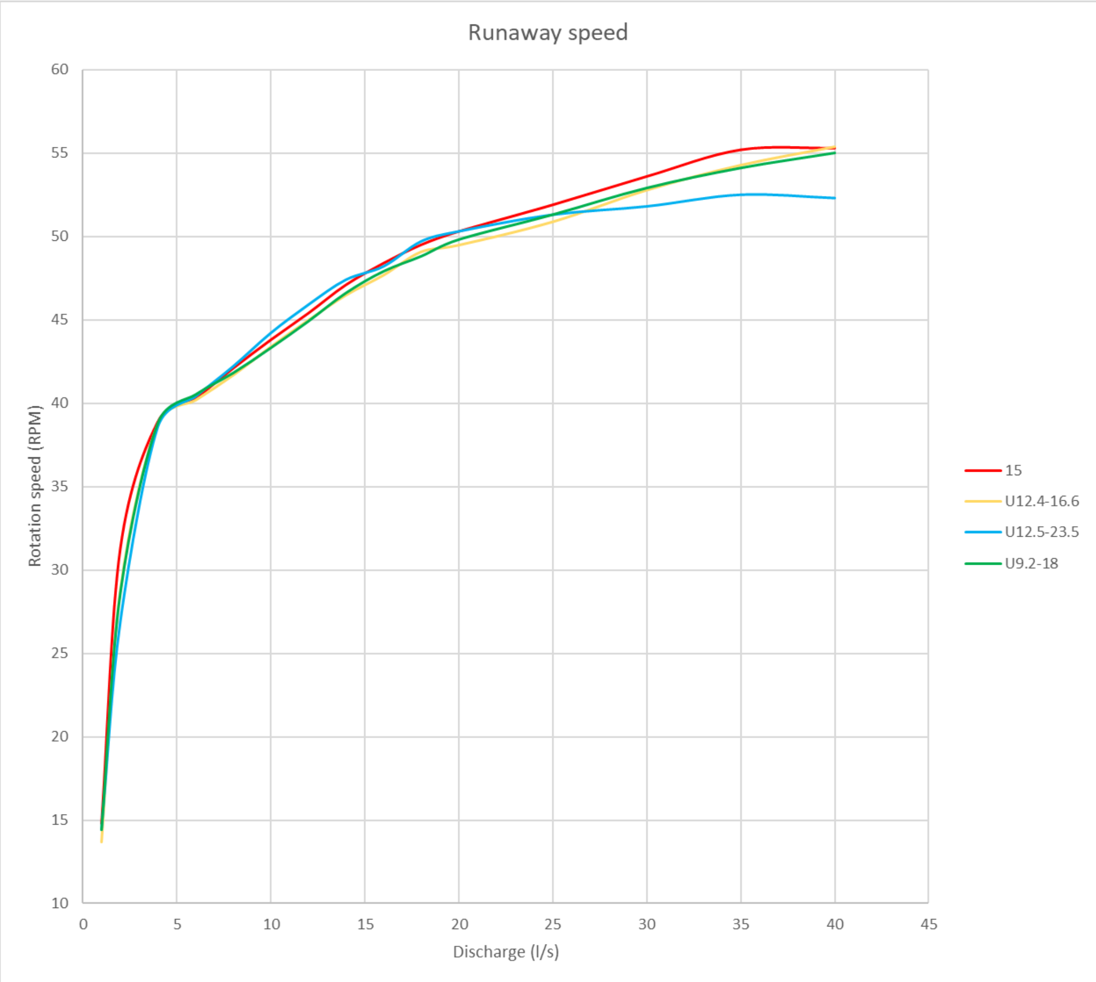

Figure 28 - Comparison of the runaway speed with the best-performing straight channel extension "0", and the three curved channel's lip extensions

The evaluation of the adjusted channel lips' impact on the unit's performance is presented in Figure 29 and Figure 30. Figure 29 offers a comparative analysis of the maximum recorded efficiency across different lip configurations, while Figure 30 provides efficiency curves at a constant rotation speed of 32 RPM. Though efficiencies with adjusted lips occasionally exceeded those associated with a "0" length channel featuring a straight end, the observed improvements are marginal. Such incremental gains are likely attributable to experimental errors and inaccuracies. Given these inconclusive results, further investigation is warranted to assess the efficiency of various channel lip shapes more comprehensively.

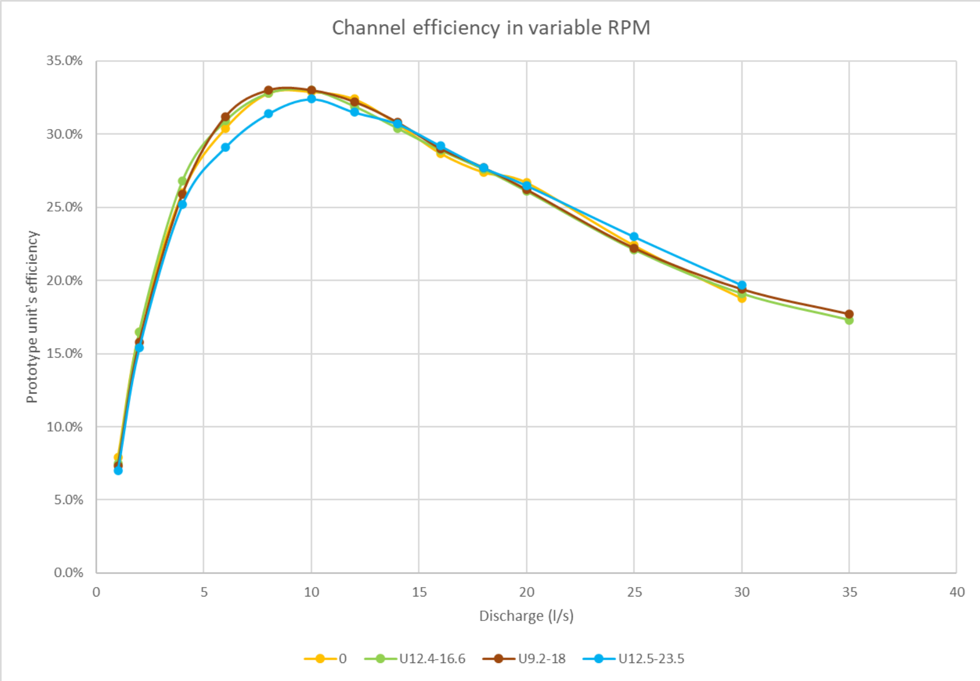

Figure 29 - Efficiency of the prototype unit in variable RPM with straight "0" extension and the three curved channel's lips

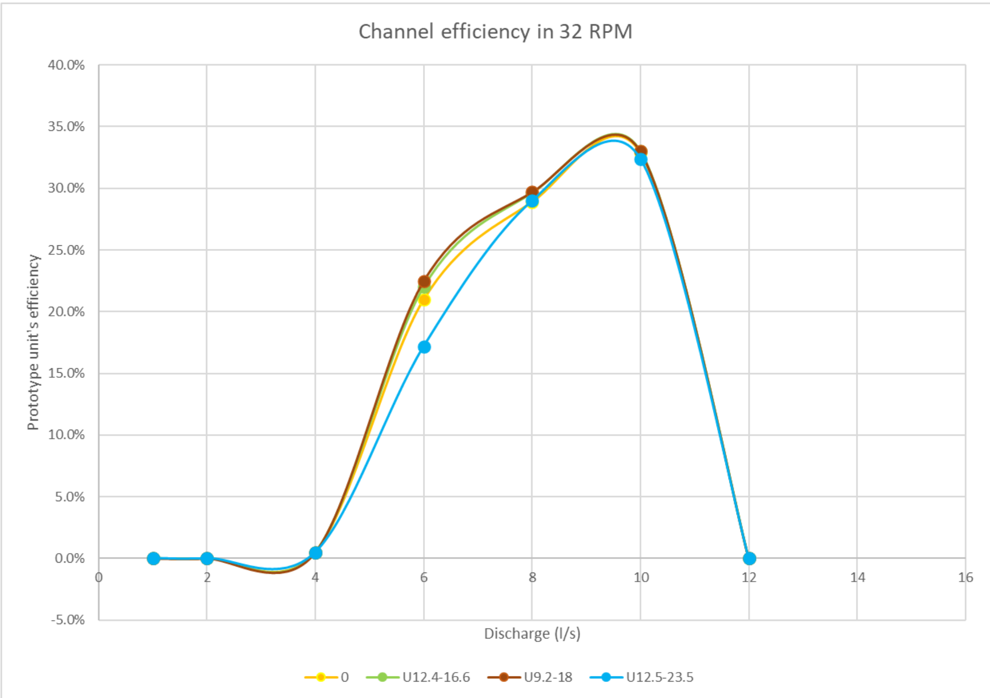

Figure 30 - Efficiency of the prototype unit in fixed 32 RPM with straight "0" extension and the three curved channel's lips

4.4 Channel height

4.4.1 Observations and data

Two channel heights were tested due to the constraints imposed by the design of the testing rig. The channel heights were set with a vertical distance of either 107 mm or 87 mm between the bottom of the channel and the crest of the wheel. The hypothesis was that a lower channel height would result in higher efficiency because, with a greater distance between the channel and the wheel, a smaller portion of the available hydraulic head would contribute to wheel rotation.

Additionally, the change in channel height was anticipated to alter the point at which the water jet makes contact with the wheel's buckets. Given that the water possesses forward momentum as it exits the channel, it was expected that the point of contact would shift accordingly. This phenomenon was thought to be similar to the effect observed with telescopic channels, which also modify the point at which the water jet enters the buckets.

The comparative performance of the two channel heights is illustrated in Figure 31 and Figure 32. It is observed that the smaller vertical distance of 87 mm between the channel and the wheel yielded slightly better results in both variable and fixed rotation speeds at 32 RPM. An anomaly appears at around 17 l/s, where the larger 107 mm height unexpectedly shows superior performance. This is likely attributable to an experimental error, as no rationale for this anomaly could be identified during the testing phase or through subsequent video analysis.

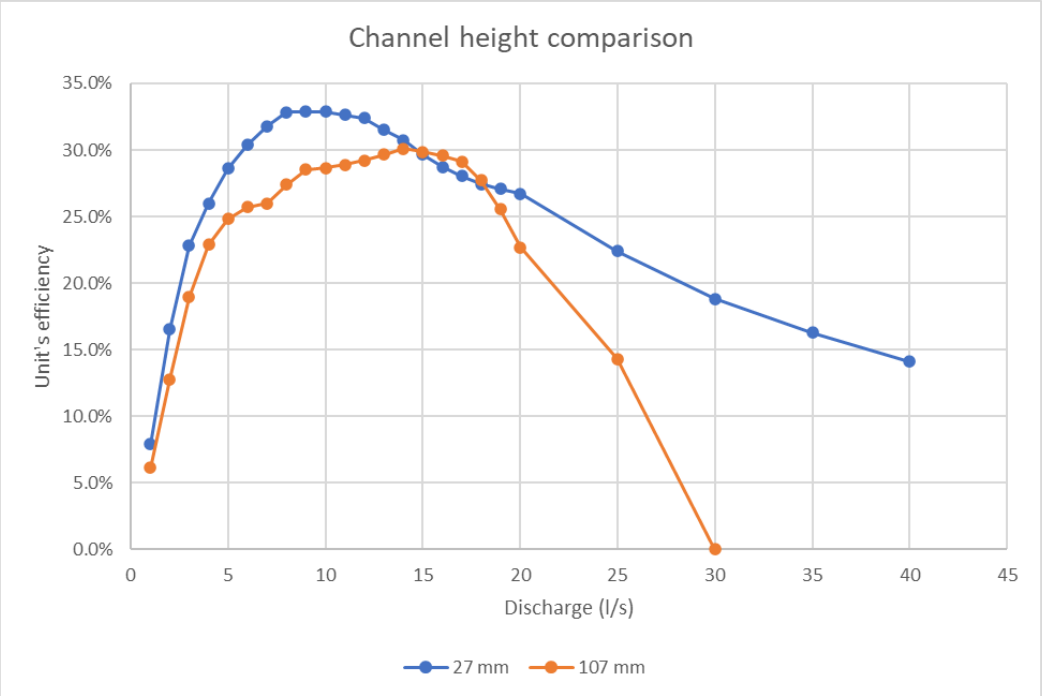

Figure 31 - Effect of the channel height on the efficiency of the prototype unit.

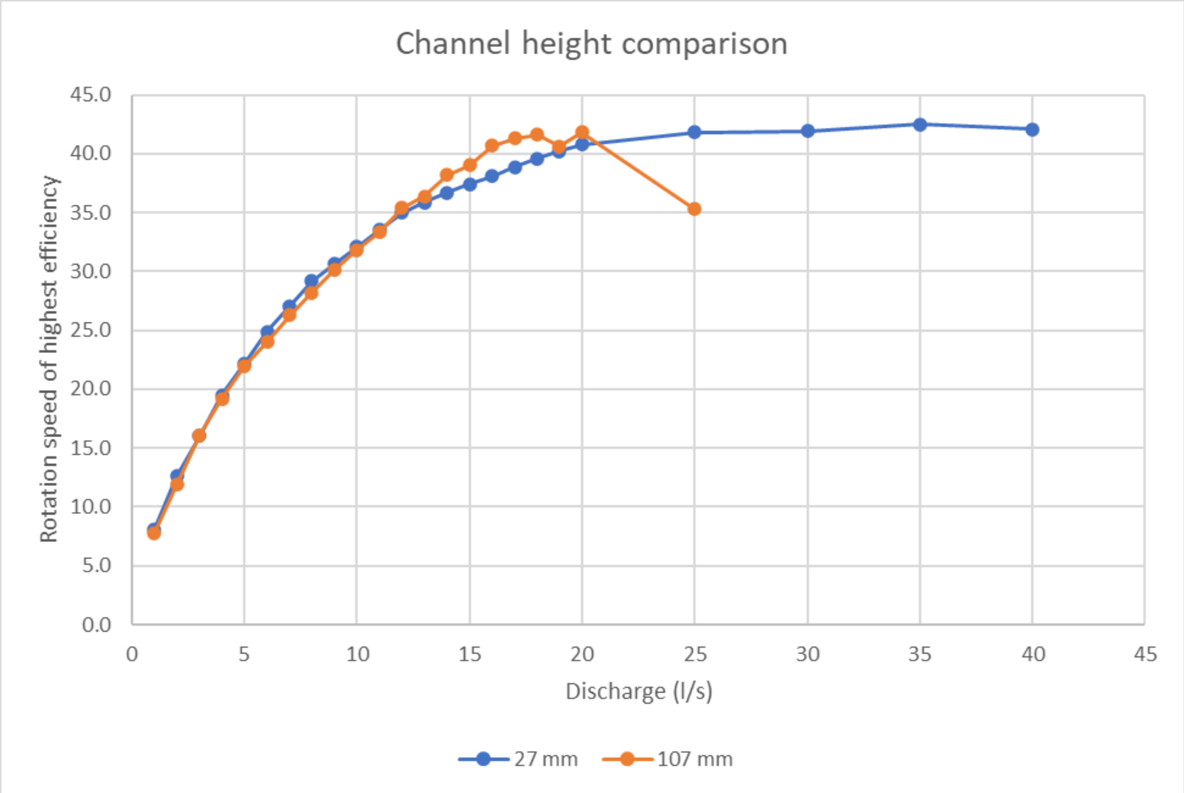

Figure 32 - Effect of the channel height on the rotation speed associated with the highest recorded efficiency.

4.4.2 Interpretation of results

In drawing conclusions from the limited data on channel heights, several caveats must be acknowledged. Due to the time constraints in the laboratory and the complexity involved in altering the channel height, only two heights could be tested. Nonetheless, the available data appears to support the theoretical expectation that a smaller vertical distance between the channel and the wheel would result in better efficiency for the hydropower unit.

While further research could explore how varying the channel's height and length could affect not only the point of water entry into the buckets but also the angle of entry, the incremental gains in efficiency are hypothesized to be marginal. Such alterations could introduce technological complexity into the pico waterwheel unit design, which may not justify the potential efficiency gains. Therefore, minimizing the vertical gap between the channel and the wheel, which is less technologically challenging, seems to offer a more straightforward avenue for enhancing performance.

5 Limitations and sources of error

In the quest to model and test the efficiency and adaptability of the waterwheel, certain limitations and error sources were encountered, some of which were inherent to the design and construction process:

Bucket asymmetry

While the primary curvature of the buckets was achieved using an industrial process to ensure precision, the intricate final shape demanded a more nuanced approach. As a result, the buckets underwent a manual shaping process, involving heating in a pottery oven followed by molding over a home-made wooden template. This process, though cost-effective, did introduce minor asymmetrical deviations between the buckets.

Figure 33 - Comparison of the provided and final shape of the buckets (on the left), and the wooden form used to bend the heated semi-finished buckets (on the right).

Figure 34 - Imperfection in the shape of the buckets. Here, the curved edges of buckets are seen.

Bucket edge dullness

The industrial cutting technique used for the semi-finished J-shaped parts rendered the edges of the buckets slightly dull. Consequently, when the water jet contacted these edges, some unintended splashes occurred, diverting water from its intended trajectory, or causing minor water loss from the wheel. These irregularities, although small, may have influenced the efficiency measurements.

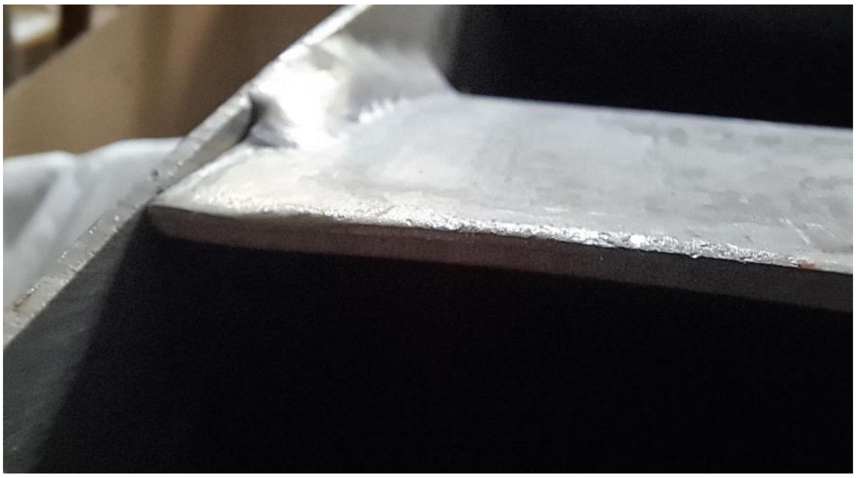

Figure 35 – Dull edges of the buckets. As they were not treated at all, the dull edge was 2 mm thick – same as the material the buckets were made of

Bucket welding gaps

The welding approach taken for the bucket attachment process was primarily budget and time-constrained. Rather than welding the entirety of the bucket's interface with the wheel, spot welding at strategic points was employed. This decision did lead to some water leakage from one bucket to another during operations. While these leaks were minimal, they may have had subtle effects on the wheel's performance.

Figure 36 - Spot welds used to fix the buckets to the wheel, causing minor leaks in between the buckets and wheel's walls

Pulley system energy losses

The power transmission from the wheel to the alternator, facilitated by the pulley and belt system, inevitably led to energy losses. Factors such as belt friction and pulley dynamics played a role. While these losses weren't quantified within this research scope, industry standards suggest they can range from 1-3% for well-maintained systems (Maitra, 2010).

Losses in bearings

Bearings, both in the waterwheel's fixed-axis system and within the alternator, inherently introduce energy losses due to friction. The specific grade, type, and maintenance state of the bearings can determine the extent of these losses. Typically, well-lubricated and maintained bearings can have efficiency losses ranging from 0.1-1% (Hamrock, 2004).

Discharge fluctuation

Digital discharge meter readings indicated that the discharge fluctuated by approximately 0.05 l/s. Attaining a more stable discharge was not feasible given the equipment and conditions. Consequently, for the purpose of result calculations, the discharge was considered constant throughout.

Water losses in pipes and channel

Despite the implementation of a relatively tight system, there were minor leaks detected both in the pipework and from the channel itself. These leaks equated to a few drops per second, and given their miniscule nature in the context of the overall water flow, they were deemed negligible and were thus excluded from the performance calculations.

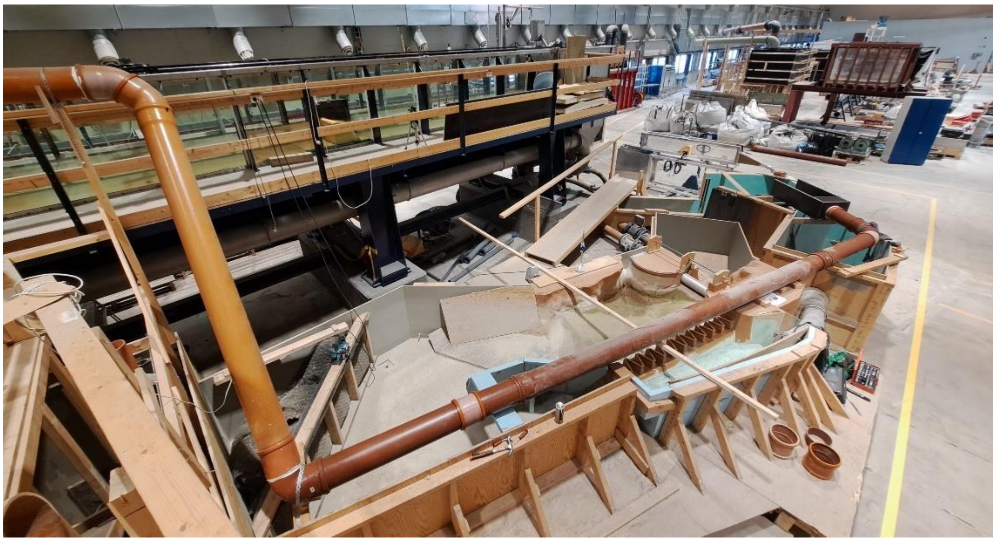

Figure 37 - Pipe system feeding the water to the channel. Only a half of the total length is in this photo, therefore losses through leaks were hardly evadable.

Water losses at the wheel

The most significant water losses occurred due to the channel's inner width mirroring the wheel's width. This design resulted in the water jet expanding slightly upon exiting the channel and before making contact with the wheel. As a result, a portion of the water merely grazed the wheel's surface, failing to contribute to its motion.

Further, during tests with low discharge and a shorter channel, the water jet would often strike the wheel prior to reaching the crest. This premature contact resulted in water flowing backward due to gravity, instead of efficiently filling the wheel's buckets. Additionally, splashes were observed in various combinations of rotation speed and discharge. This phenomenon was thoroughly documented via video recordings for subsequent analysis and better understanding.

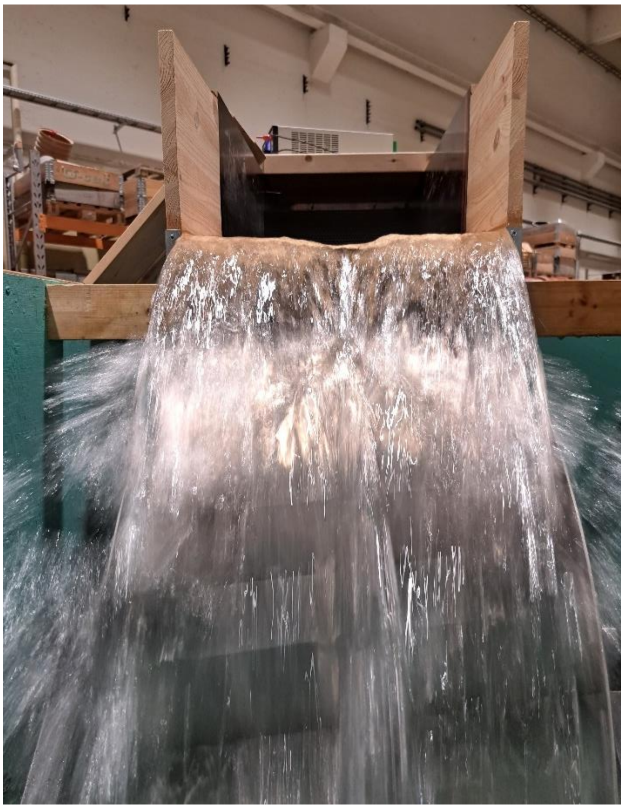

Figure 38 - Picture from one of the videos showing the splashes that were almost always present in higher discharges and rotation speeds.

Electrical losses in alternator

In the realm of electrical generation, every component has its nuances and associated inefficiencies, and car alternators are no exception. These devices, crucial in automobile electrical systems, are not immune to losses, particularly when repurposed for different applications like this hydropower experiment.

The losses within the alternator are of several kinds, out of which Heat induced losses and Switching and reverse recovery losses are so small, that they can be neglected in this thesis. Forward Voltage Drop represents a more considerable loss, clocking in at approximately 0.7 V for each diode in the rectifier. It's a direct consequence of the diode's intrinsic properties and becomes especially significant at higher current outputs.

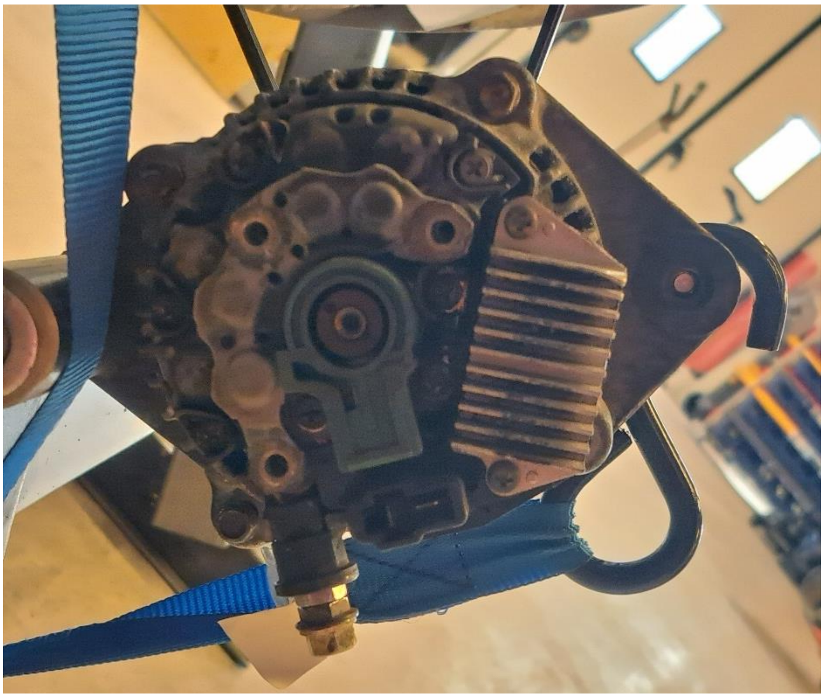

Figure 39 - Detailed photo of the diode bridge rectifier of the alternator used in the experimental prototype unit.

Perhaps the most crucial aspect to consider is the efficiency curve of the alternator itself. Alternators, especially those found in cars, are built to operate efficiently across a wide range of engine speeds. However, they are not designed for optimal performance in a hydropower setup like ours. Typically, a car engine's RPM ranges from 500 to 10,000. When considering the pulley system's ratio, the alternator spins almost twice as fast. This expansive operational range means the alternator is not particularly optimized for any specific RPM, contrasting with a generator purpose-built for a hydropower unit (which was operating in 6 to 60 RPM). To compensate for this distortion in data, we utilized a typical efficiency curve to adjust the results according to the alternator's performance at various speeds.

It's vital to understand that while car alternators can be repurposed for experiments like ours, their inherent design and efficiency curves may not perfectly align with the requirements of a dedicated hydropower system. This distinction is crucial for interpretation and application of our test results.

Alternator's torque resistance

Every mechanical and electrical device has its operating thresholds, and car alternators are no different. While typically designed to handle a broad range of operations in an automobile setting, when repurposed for hydropower applications, certain limitations became evident. One of the significant constraints in this context is the alternator's torque resistance.

The torque resistance of an alternator defines the maximum opposing force it can exert against the driving source—in our case, the rotating water wheel. For our experiment, it became clear that the alternator's torque resistance was insufficient to effectively slow down the wheel, especially at higher water discharges. Even when the full load of all resistors was engaged, the decelerating effect on the wheel was insufficient.

This limitation had a particular impact on the research objectives. We aimed to investigate the wheel's performance characteristics in the upper left triangle of the performance chart from Dr. Quaranta's thesis (in Figure 40 below). Yet, due to the constraints of our chosen alternator, we were unable to obtain meaningful data from this specific operational zone. It underscores the importance of component matching in system design, especially when deviating from the original intent of the equipment.

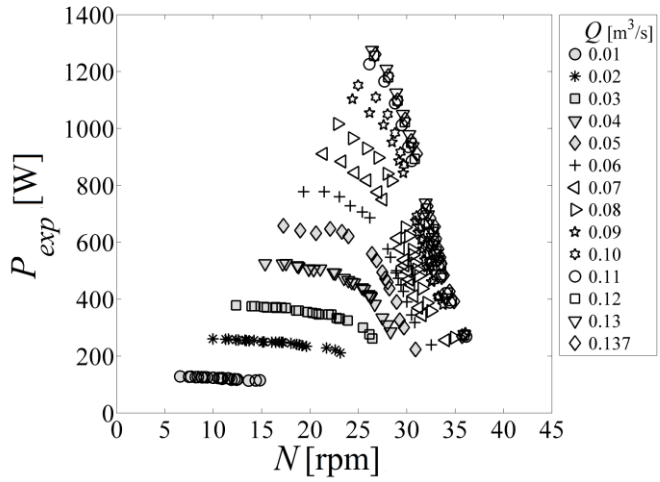

Figure 40 - Results from Dr. Quarant's experiment, showing that he also did not have the equipment to assess the parts of the curves that lie in the upper left triangle of the chart area. Source: (Quaranta, 2017).

Performance reading

The method for reading voltage and current could be noted as a further constraint on the study's accuracy. Due to fluctuations in the measurements, the recorded values represent an average of the minimum and maximum values observed over approximately a 5-second span. This approach may introduce some level of imprecision into the data and potentially affect the reliability of the performance metrics reported.

6 Discussion

Variable Speed Operations and Efficiency

The potential performance of a hydropower unit capable of variable rotation speeds has been explored, even though the prototype itself lacked the ability to adapt its rotation speed. Instead, this study aimed to assess the viability of such a unit. Notably, the prototype simulated modulating rotation speed based on varying discharges. The efficiency curve's steep onset underscores the concept's potential to maintain high efficiencies across diverse flow conditions. While the alternator's limitations prevented complete efficiency curve mapping, trendline-estimated data suggests untapped potential within a variable RPM system. A comparison with a hypothetical fixed RPM system highlights the adaptable approach's advantages, particularly in fluctuating flow scenarios. The concept's adaptability aligns with off-grid communities' dynamic energy needs, making the overshot waterwheel a promising solution.

Telescopic Channel and Channel Lip Design

The investigation into the telescopic channel's impact revealed a significant distinction in its effects based on the unit's rotation capabilities. For a wheel capable of variable rotation speed, the telescopic channel demonstrated no discernible influence. In contrast, units operating at fixed rotation speeds exhibited a favorable response to the telescopic channel. This discrepancy likely originates from the interplay between the system's dynamic equilibrium and the intricate balance between the kinetic and potential energy of the water jet. Further exploration of this phenomenon necessitates the employment of advanced fluid dynamics simulations to elucidate the underlying mechanisms and optimize the telescopic channel's potential benefits. While V-shaped notches held theoretical promise, their practical implementation introduced challenges, including splashes and deviations from anticipated water trajectories, which in turn dampened their efficiency. Nonetheless, the ongoing endeavor to enhance efficiency through adjusted channel lip shapes retains its allure, primarily due to the technical simplicity that these modifications offer.

Channel Height and Efficiency

The correlation between channel height and efficiency has offered intriguing insights. While data leans toward supporting the idea that a smaller channel height corresponds to heightened efficiency, this inference remains cautious due to the limited range of channel heights explored. Nevertheless, the investigation reinforces the notion that minimizing the vertical gap could offer a pragmatic route to efficiency enhancement without introducing undue complexity.

Suitability for Underserved communities

After analyzing the test results, it is affirmed that an overshot waterwheel unit akin to the one subjected to examination within this thesis stands as a viable proposition for pico hydropower, aptly addressing the electrification needs of off-grid communities in developing nations. The unit has demonstrated a significant potential to yield substantial power output with commendable efficiency levels. The findings substantiate that this unit possesses the capacity to generate electricity across a range spanning from 8% to 500% of its design discharge, with a corresponding escalation in power output. This remarkable versatility renders the unit well-suited for regions characterized by pronounced fluctuations in water flow, such as sub-Saharan Africa, which experiences alternating seasons of drought and rainfall. From an economic perspective, though no formal cost estimation has been undertaken, an evaluation of the unit's technological intricacy suggests a cost profile that could be on par with that of a comparably powerful solar system. Furthermore, the unit's inherent portability and straightforward assembly are evident, as evidenced by its journey from its origin in Czechia to Trondheim, transported conveniently in the confines of an automobile trunk, back and forth between these locations for enhancements and testing, and eventually returned to Czechia for storage in preparation for further research endeavors.

Figure 41 - The whole unit fits into a trunk of a car - ideal for delivering to those communities that have not yet been reached by suitable infrastructure.

Potential for Further Research

As the outcomes of this study are reflected upon, the potential for further research becomes apparent. Advanced fluid dynamics simulations hold promise in unraveling the intricate interplay between water flow and wheel behavior, yielding insights for design refinements. Exploration into bucket geometry and materials, along with devising mechanisms for more efficient air escape, presents fertile ground for optimization. Integration of AI-driven simulations to assess various bucket shapes and channel designs could revolutionize design methodologies, addressing the paucity of computer-aided research in overshot waterwheels.

Prototype Enhancement

While the research endeavor has illuminated several promising directions for the advancement of overshot waterwheel technology, further investigation remains paramount to unlock its full potential. Notably, the alternator's torque resistance capacity emerges as a critical factor in the accurate exploration of the prototype's efficiency curve. The observed limitation in the alternator's capacity hindered the ability to comprehensively map the efficiency curve across different rotation speeds and discharge rates. As far as current knowledge extends, the complete efficiency curve of overshot waterwheels has not been thoroughly explored. Hence, enhancing the alternator's torque resistance, thereby enabling the full range of operational conditions to be tested, is pivotal to providing a robust foundation for future design iterations. This step would not only advance the understanding of overshot waterwheel behavior but also contribute to the broader knowledge base of hydropower technology operating in variable rotation speeds.

Adaptation for Different Contexts

An avenue worth exploring involves adapting the proposed design for on-grid or off-grid use in developed regions, where increased complexity is feasible. In such contexts, the design could encompass advanced features, such as anti-splash walls inspired by Dr. Quaranta's work. Enhanced debris sensitivity could be addressed through the integration of economically accessible mechanisms like trash racks. This adaptation could leverage the overshot waterwheel's advantages while accommodating available infrastructure and resources.

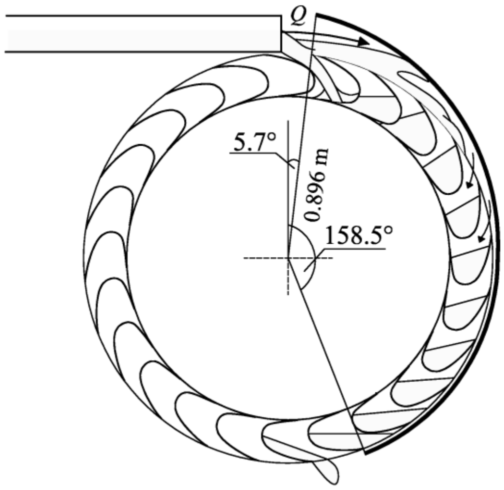

Figure 42 - Proposed wall to prevent splashes and force water to interact with the wheel, thus increasing efficiency. Souce: (Quaranta, 2017).

7 Conclusions

In conclusion, this study embarked on a journey to evaluate the feasibility of employing overshot waterwheels in the design of adaptable pico hydropower units for off-grid communities. Through meticulous exploration of various parameters and innovations, the research has yielded valuable insights into the potential of overshot waterwheel technology. The findings underscore the adaptability and versatility of overshot waterwheels, showcasing their potential to harness energy across a range of flow conditions and discharge rates. The prototype testing unveiled the complexities of real-world implementation, revealing both advantages and limitations that warrant further attention.

The investigation into overshot waterwheels as a solution for pico hydropower units illuminated their potential suitability for small-scale energy generation. Factors such as head, discharge, technical complexity, debris resistance, efficiency, usable discharge range and environmental impact were considered, all of which indicated the promising attributes of overshot waterwheels. The analysis considered the intricacies of water flow dynamics, bucket design, and channel configuration, suggesting that further exploration into these facets could lead to refinements in performance.

Looking forward, the research paves the way for enhanced overshot waterwheel designs tailored to specific contexts, whether off-grid communities or broader applications in developed regions. The significance of advancing this technology lies not only in its potential to provide reliable electricity to underserved areas but also in its alignment with the global emphasis on renewable energy integration and efficiency.

In sum, this study contributes to the comprehensive understanding of overshot waterwheels' potential in pico hydropower applications. As future endeavors build upon these insights, the vision of sustainable and adaptable energy solutions for off-grid communities draws closer to realization.

8 References

B. A. Stewart, T. A. (2003). *Encyklopedia of Water Science.* New York: Marcel Dekker Inc.

Boura, M. (2023). *Wikipedia - Water wheel*. Načteno z Wikipedia: https://en.wikipedia.org/wiki/Water_wheel

Emanuele Quaranta, R. R. (2018). Gravity water wheels as a micro hydropower energy source: A review based on historic data, design methods, efficiencies and modern optimizations. *Renewable and Sustainable Energy Reviews, volume 97*.

Hamrock, B. J. (2004). *Fundamentals of machine elements. .* McGraw-Hill.

International Energy Agency. (2021). Energy Access Outlook 2021. Paris.

International Hydropower Association. (2023). *What is Hydropower?* Načteno z hydropower.org: https://www.hydropower.org/what-is-hydropower

Jirků, I. F. (2021). Optimalizace nátoku na vodní kolo a jeho vliv na účinnost. *Water Wheel Inflow part optimization - Master's Thesis*. Brno: VUT Brno.

Lomborg, B. (2001). *The Skeptical Environmentalist.* Cambridge: Cambridge University Press.

Macek, I. L. (2016). Návrh vodní mikroelektrárny pro malé spády a malé průtoky. *Master's Thesis*. Brno: VUT Brno.

Maitra, S. (2010). *Handbook of gear design.* Tata McGraw-Hill Education.

Meerwarth, K. (1935). Experimental and theoretical investigation of an overshot water wheel. *PhD thesis*. Germany: Technical University of Stuttgart.

Müller, G. a. (2004). Performance characteristics of water wheels. *Journal of Hydraulic Research, 42(5)*, stránky 451-460.

Quaranta, E. (June 2017). Investigation and optimization of the performance of gravity, PhD thesis. Politecnico di Torino, Porto Institutional Repository.

United Nations Development Programme. (2012). Sustainable Energy For All: A Framework for Action. New York.

United Nations Industrial Development Organization (UNIDO). (2020). Global overview of small hydropower. Načteno z https://www.unido.org/sites/default/files/files/2020-08/Global_overview.pdf

Wahyudi, B. a. (2013). Increasing Efficiency of Overshot Waterwheel with Overflow Keeper Double Nozzle. *Applied mechanics and materials 330*, stránky 209-213.

Weidner, C. (1913). Test of a Steel Overshot Water Wheel. *Engng. News*, stránky 39-41.

Williams, A. a. (2000). New ideas for old technology-experiments with an overshot waterwheel and implications for the drive system. *International Conference of Gearing, transmission and mechanical system.*

Wonderful Engineering. (2023). Načteno z Wonderfulengineering.com: https://wonderfulengineering.com/the-simple-whirlpool-turbine-can-power-upto-60-homes/

World Bank. (2021). Global Tracking Framework.

Zríni, I. M. (2018). Experimentální ověření paramterů vodní turbíny. *Master's Thesis*. Brno: VUT Brno.

NTNU

Norwegian University of
Science and Technology