# ENERGY EXTRACTION EFFICIENCY OF IN-STREAM MULTISTAGE MICRO-HYDRO TURBINE

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**ABSTRACT:** *This paper describes the techniques for estimating the kinetic energy extraction efficiency of a multistage micro-hydro turbine with five blades. The broad objective of this study was to measure the overall energy extraction efficiency of the said turbine system. This experiment was conducted in a closed-loop water channel, and the velocity range was from 0.5 m/s to 1.1 m/s. The estimated overall energy efficiency of this turbine ranged from 12.8 percent to 25 percent. However, the most energy-inefficient component here appeared to be the turbine's blades, whose value was 84 percent. Indeed, energy inefficiency of the blades contributed to a reduction in the overall energy efficiency. This study concludes that in-stream multistage micro-hydro turbines are a useful mechanical device for generating low-cost green energy from water. However, the energy extraction efficiency of micro-hydro turbines depend on the interaction between the turbine blades and water flux; these two variables can be manipulated to increase the energy extraction efficiency. The goals for future studies are to find out the causes of energy extraction inefficiency and to increase the efficiency so that such turbines can become economically sustainable.*

**Keywords:** Multi Stage; Energy Efficiency; Hydro Turbine; Energy Transfer

## 1.0 INTRODUCTION AND BACKGROUND

This paper discusses the techniques of efficient energy extraction by a multistage micro-hydro turbine (MMHT). This is an extension of the research that has been published earlier by Shahidul *et al*. [1]. The aforementioned research was on a laboratory-scale MMHT. Energy security and environmental sustainability have always been highlighted in all countries for their smooth economic growth. Both developing and developed economies are struggling to increase the energy utilisation efficiency and productivity in the harnessing of renewable energy. For example, between 2000 and 2012, the renewable energy production capacity in the USA has increased by about 100 percent. The USA alone produced more than 163 gigawatts per year, which was about 12% of total electricity usage of that country [2]. Likewise, in Malaysia, various projects concerning energy extraction from in-stream water have been undertaken.

JARIMAS, which was conducted from 2010-2012 in collaboration with JKR Malaysia and Universiti Malaysia Sarawak (UNIMAS), was one such project. This research was conducted on a single-stage blade micro-hydro turbine (SMHT). Similar researches have been conducted at the operations research laboratory of UNIMAS using MHT and MMHT[3]. Hydrovolt Inc [4] and Verdant Power [5] have conducted similar nature of researches on MHT. All these projects have been conducted to characterise the energy extraction behaviour and model the blades of MHT. There are not many reports on the energy extraction efficiency of MHT or MMHT in the published journals. This scenario demanded a research to model the energy extraction efficiency of MHT and MMHT. In order to address this issue and fill the research gap, we have conducted a research on energy extraction from in-stream water via MMHT.

## 2.0 LITERATURE REVIEW

The literature review in this paper was aimed to study the latest researches on MHT and MMHT in order to gather information and knowledge on energy extraction efficiency. The published scientific journals have also been studied in order to obtain relevant theories and equations for estimating the energy parameters.

### 2.1 Multistage Blade Micro-Hydro Turbine

Traditionally, MHT has been designed with one set of blades, and it has been reported that when water flux left the turbine system, the water velocity remained significantly high. A five-stage MMHT designed by Shahidul *et al*. in order to utilize unused Kinetic energy[1]. The fundamentals of multi stage Turbine is in Figure 1.

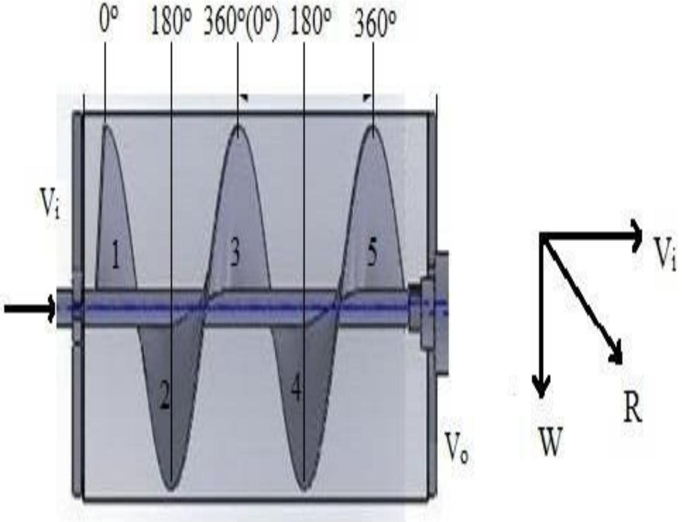

**Fig. 1: Multistage blade micro-hydro turbine [1]**

During the operation of MHT at in-stream water bodies, the water flux interacts with the blades, and a part of the kinetic energy transfer to the turbine shaft occurs through the blades. Traditionally, MHT has been designed with one set of blades, and it has been reported that when water flux left the turbine system, the water velocity remained significantly high. It meant that the velocity drop across the blades was not much. This operating behaviour was responsible for the low energy efficiency of MHT [1,6]. It was then suggested that additional blades in the turbine shaft could increase the interaction between water flux and blade, which would facilitate higher energy extraction levels by the turbine. The MMHT designed by Shahidul et al.[1] is shown in Figure 1, while the area of the turbine blades is presented in Eq 1.

$$\text{Blade area (A)} = \sum_1^5 A_i \qquad \text{(Eq.1)}$$

Here, $A$ is the total blade area of the MMHT while $I$ = 1, 2, 3, 4, and 5. Fig. 1 and Eq. 1 indicate that the energy extraction can be maximised by increasing the interaction between the blade surface and water flux. It also indicates that if the blades surface increase and split in different stages, it could provide better kinetic energy extraction from water flux[1].

### 2.2 Energy Extraction Efficiency of Micro-Hydro Turbines

The energy extraction efficiency of micro-hydro turbines depend on the interaction between the turbine blades and water stream, or between the turbine blades and in-stream water flux. Shahidul *et al*. stated that the velocity drop across blades is a measure of energy extraction efficacy of MHT[1]. Arena, Gatt and Kadhim stated that the energy efficiency of cross-flow MHT increases with the increasing of water head and water velocities [6,2]. Solemslie stated that the Pelton Wheel is an impulse turbine that harnesses only kinetic energy from water flow, and that its energy extraction efficiency could be as high as $77.75\% \pm 0.24\%$ at a 70 m head [7]. Gudukeya reported that the efficiency of micro-hydro turbines would be 60 percent at best [8]. Nasir stated that when a water jet of penstock hit the turbine's buckets, the runner started to rotate, hence converting the kinetic energy of water to shaft power. He also stated that the energy efficiency depended on the pressure of the nozzle [9].

Muller stated that the Breastshot-type MHT was suitable to extract energy from water at a water head of 1.5 to 2.5 m. He added that this MHT was also efficient in extracting energy at a water flow rate of 0.35 to 0.65 $m^3/s$ per meter width of blade. Muller also reported that the maximum energy extraction efficiency of this type of MHT was 87.3 percent [10,11].

Capecchi and Kyaw et al. stated that the Undershot Water Wheel MHT could be used for harnessing both kinetic and potential energy from a low water velocity and low water head. They found that the range of energy extraction efficiency of this type of MHT was 33 percent to 50 percent [12,13]. Archimedes screw-type MHT is known for its ability to harness kinetic energy from low velocity in-stream water [11,12]. According to Brada and Saroinsong, the energy extraction efficiency range of Archimedes screw-type MHT was from 79 percent to 89 percent at a water velocity of 0.5m/s [14,15].

### 2.3 Energy Efficiency of Various Turbine Systems

Steam turbines are commonly used for converting fossil fuels to electricity. The reported thermal efficiency of these turbines ranges from 30 percent to 37 percent, though their efficiency depends on many operating and environmental factors [16,17]. The energy efficiency of gas turbines are almost the same as steam turbines. The lowest reported efficiency of these turbines was 35.32 percent at an ambient temperature of 31°C, while the highest was 42.89 percent at 27°C. However, the energy efficiency of gas turbines may range from 34-58 percent [16, 17].

### 2.4 Overall Energy Efficiency of Micro-Hydro Turbine

The kinetic energy of water flux rotates the blades of MHT and produces shaft power. The shaft power is picked up by generators and is later transformed into electrical energy [18]. Konota performed an analysis to test the efficiency of a hydroelectric power plant, whereby the reported efficiency of this turbine was 93.4 percent [19]. According to Tani, the maximum efficiency of the conversion of mechanical to electrical power by large-scale hydro power plants can be as high as 95 percent [20].

### 2.5 Theoretical Framework of Energy Extraction

This section focuses on the conceptual model of energy extraction, which models the energy extraction efficiency and overall energy efficiency of MHT and generators.

#### 2.5.1 Conceptual Model of Energy Extraction

In-flowing water contains kinetic energy, whose magnitude depends on the in-stream water velocity. The conceptual model of energy extraction by MMHT and energy conversion to mechanical and electrical energy is shown in Fig.2[1].

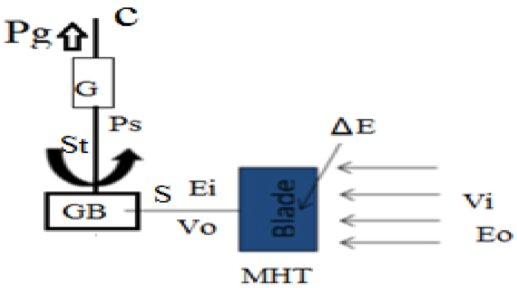

**Fig. 2: Conceptual Model of Energy Extraction by MMHT**

The figure demonstrates that the inlet water at velocity (Vi) is passed over the surface of the turbine blade. At the exit point, the water velocity is Vo. The difference between Vi - Vo is known as velocity drop across the turbine blades. The velocity drop across the MMHT blades is a measure of energy extraction. Practically, Vo is less than Vi (Vo < Vi), and the difference between inlet velocity and outlet velocity is a determinant of the energy extraction efficiency of MMHT [1, 21]. The energy available in flowing water can be represented by Eq. 2:

$$\mathrm{E} = \frac{\rho C A v^3}{2} \qquad \text{(Eq.2)}$$

Here, E is the energy, A is the blade area in contact with flowing water, C is the power coefficient, V is the water velocity (in m/s) at the inlet point, and ρ is the water density ($kg/m^3$) at normal atmospheric conditions. This equation indicates that blade area is a dominant factor in energy extraction. Another important factor that highly associated with energy extortion is the decline in water velocity ($Vi - V_0$) across the turbine blades.

#### 2.5.2 Energy Extraction Efficiency of Turbine Blade

The energy extraction with respect to the velocity drop across the turbines can be estimated by using Eq.3 [1]:

$$\Delta E = Ei - Eo \qquad \text{(Eq.3 ) or}$$

If E is replaced with Eq. 2, then

$$\Delta E = \frac{\rho CA(Vi^3 - Vo^3)}{2} \qquad \text{(Eq.4)}$$

Here, ΔE is the difference between Eo, and Ei. The energy extraction efficiency of turbine blades ( ŋ ) can be estimated from Eq. 5:

$$\eta_b = \frac{Ei-Eo}{Ei}100 \quad \text{or}$$

$$\eta_b = \frac{(Vi^3-Vo^3)}{Vi^3}100 \quad \text{(Eq. 5)}$$

### 2.5.3 Shaft Power Measurement

The energy available at the turbine shaft is known as shaft power (Ps), or torque (Td**),** which can be estimated using Newton's law. Td is the mechanical energy required to stop the rotation of the shaft (St). Ps can be estimated from Eq.6 [21]:

$$Ps = T_d x\omega \text{ (Nm/s)} \quad \text{(Eq.6)}$$

$\omega = 2\pi n$. Rotation of shaft can be measured by a tachometer.

A brake pad and gravity weight mechanism could be used to measure the work required to stop the rotation of the shaft. Td can be measured by Eq.7 [21]:

$$Td = mgL \text{ Nm} \quad \text{(Eq. 7)}$$

Here, mg is the weight of the weight hung with a steel wire from the brake pad. L is the length of the steel wire; and n is the rotation of the turbine shaft in RPM.

### 2.5.4 Energy Transfer Efficiency from MHT to Shaft

Fig.1 demonstrates that Ei amount of energy is available at the turbine; and this Ei is transferred through a gearbox (GB) to the generator shaft, which is denoted as Ps. Ps is available at the shaft of the generator ('St'). The efficiency of energy transfer (ηs) can be estimated from Eq.8:

$$\eta s = \frac{(Ei-Ps)}{Ei} \quad \text{(Eq. 8)}$$

### 2.5.5 Energy Conversion Efficiency of Generator

Ps will be converted to electrical power ($P_g$), the latter of which will be available at the outlet point of generator "C". The energy transfer efficiency of generator can be estimated by Eq.9:

$$\eta g = \frac{(Ps-Pg)}{Ps} \quad \text{(Eq. 9)}$$

### 2.5.6 The Overall Energy Efficiency

The overall energy efficiency of MMHT is a product of the energy efficiency components of the system, and can be estimated by Eq. 10 [21]:

$$\eta_o = \eta_B .\ \eta_s . \eta_G \quad \text{(Eq.10)}$$

### 2.6 Objectives

The broad objective of this study is to measure the overall energy extraction efficiency of the MMHT system. The specific objects of this study are as follows:

2.6.1 To measure the energy extraction efficiency of turbine blades ($\eta_B$)

2.6.2 To measure the efficiency of energy transfer from turbine to generator (ηs and $\eta_g$)

2.6.3 To measure the overall energy extraction efficiency of the turbine and generator system ($\eta_o$)

### 2.6.1 Scope of Study

In order to achieve the research goals given the limited resources, the scope of study is as outlined below:

The experiment setup in Figure 3 will be used to measure the energy extraction as well as conversion to mechanical and electrical energy. Three aspects will be measured to determine the overall efficiency: (1) in-stream energy extraction by the MMHT blades and its transfer to the MMHT shaft, (2) energy transfer from the MHHT shaft to the generator shaft through an energy transfer belt, as well as (3) mechanical energy, or shaft power, conversion to electrical energy through a generator. The novelty of this study is that it develops a technique to evaluate the overall energy efficiency of MMHT in a low-velocity in-stream water flow setting.

**Table 2: Shaft Energies at Various Water velocities**

| Water Velocity Vi m/s | Turbine shaft's Rotation (RPM) | Torque of Generator shaft Td (Nm)* | Shaft Power Ps (W=Nm/s)** |
|---|---|---|---|
| 0.5 | 45 | 0.44 | 2.1 |
| 0.65 | 67 | 1.0 | 7.1 |
| 0.8 | 100 | 1.13 | 11.9 |
| 1.1 | 120 | 1.18 | 18.5 |

**Nm –the unit of torque: Newton meter, ** (Nm)/s-Shaft power Ps - Watt or Newton meter per second*

## 3.0 RESEARCH METHODOLOGY

The study on the energy extraction efficiency of multistage MHT begins with the literature review in order to obtain the latest research findings on the topic. The building of a conceptual model of MMHT operations relating to energy extraction was the second stage of this research. The designing and development of a laboratory-scale turbine was the third stage of this research. The final stage involved the conduction of an experiment to collect data and estimate the energy extraction efficiency.

### 3.1 Scope of Study and Research Design

The energy extraction efficiency is evaluated in three stages: (1) energy transfer from in-stream water to turbine blades, (2) energy transfer from MHT to generator shaft through a gearbox, and (3) energy transfer from shaft to generator.

A five-blade laboratory-scale MMHT is designed and developed to conduct a study on the energy extraction efficiency. The selected inlet water velocity range was from 0.3 m/s to 1.1 m/s. To achieve the research objectives, we measured the inlet (Vi) and outlet (Vo) water velocity as well as the shaft speed (in RPM) of generator. Finally, the collected data is used to estimate the energy extraction efficiency.

### 3.2 Experiment Setup and Data Collection

The layout and machinery setup of the experiment are shown in Fig.3. The main equipment used here are a closed-loop water channel, a variable-speed water pump, a water flow piping system, a five-blade (5 stages) horizontal-type cross-flow turbine, an energy transfer pulley, and an alternator.

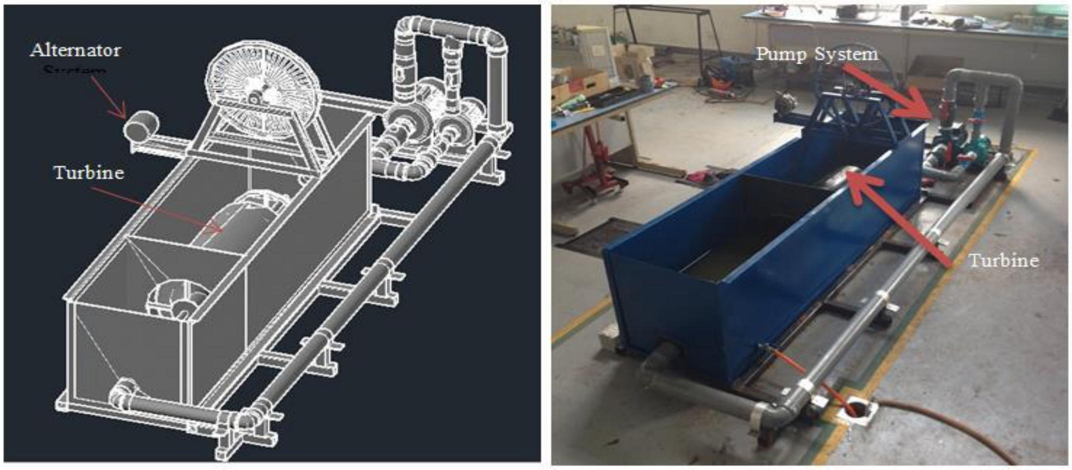

**Fig. 3: Picture of Experiment Setup**

Two centrifugal pumps are used to maintain water flow within the closed-loop water channel. The water flow rate and water velocity are regulate by a frequency inverter. Two velocity meters are used to measure the inlet and outlet water velocity. A one-hand-drive tachometer is also used to measure the shaft speed (in RPM).

The total operating time of the MMHT is 300 hours on different working days. Five sets data for water velocities of 0.3, 0.5, 0.7, 0.9, and 1.1 m/s are gathered from the experiment. In order to reduce the estimation error of the collected data and to achieve higher data quality, statistical techniques in the SPSS software are used. The data, which falls within three standard deviations (3σ) of the normal distribution, is used to estimate the energy extraction efficiency.

## 4.0 RESULTS OF EXPERIMENT

This section is designed to analyses the data gathered from experiment with the aim of estimating the overall energy efficiency of MMHT. This section is mainly divided into three parts in order to achieve the research objectives stated in section 2.6.

### 4.1 Energy Extraction Efficiency of Turbine Blades

This section presents the results of the data analysis of the energy extraction by the turbine's blades. In order to achieve research objective number one, Eq. 4 is applied for estimation, the results of which are listed in Table 4.1.

The energy extraction efficiency of the blades is denoted as $\eta_B$. The estimation results are listed in Table 4.1(a) in column 4; rows 2, 3, 4, and 5. The results indicate that the energy extraction efficiency increases with water velocity, and that the highest energy extraction efficiency is achieved at a water velocity of 1.1 m/s.

**Table 4.1a: Energy Extraction Efficiency of MMHT**

| **Energy Extraction parameters Of Turbine blade** | **Inlet velocity Vi m/s** | **Outlet Velocity Vo m/s** | **Energy Extraction Efficacy of turbine blades [$\eta_B$ (%) ]** |
|---|---|---|---|
| **Energy Extraction efficiency by turbine blades** $\eta_b = \frac{(Vi^3 - Vo^3)}{Vi^3} 100$ | 0.5 | 0.42 | 16 |
| | 0.65 | 0.51 | 23 |
| | 0.80 | 0.60 | 25 |
| | 1.1 | 0.78 | 29 |
| **Table 4.1b:** Energy Transfer Efficiency by MMHT | | | |
| **Energy transfer parameters from Turbine blade to Generator Shaft** | Energy at Turbine Outlet Ei | Energy at Generator Shaft Ps | Energy Transfer Efficiency $\eta s$ (%) |
| **Energy transfer efficiency from MMHT to Turbine shaft** $\eta s = \frac{(Ei - Ps)}{Ei} 100$ | 2.35 | 2.1 | 89 |
| | 7.95 | 7.1 | 89.4 |
| | 13.22 | 11.9 | 90 |
| | 20.32 | 18.5 | 91 |

**Table 4.1c:** Energy Conversation Efficiency by Generator

| **Energy transfer parameters from Turbine blade to Generator Shaft** | Energy at Generator Shaft Ps | Electrical energy at generator outlet Pg | Energy Conversion Efficiency from generator Shaft to Electricity (ηg) |
|---|---|---|---|
| **Energy conversion efficiency from generator Shaft to Electricity** $\eta g = \frac{(Ps-Pg)}{Ps}100$ | 2.1 | 1.89 | 0.9 |
| | 7.1 | 6.461 | 0.91 |
| | 11.9 | 10.948 | 0.92 |
| | 18.5 | 17.575 | 0.95 |

## 4.2 Energy Efficiency of Shaft and Generator

This section estimates the energy efficiency of the shaft and generator in order to achieve objective number two of this research (as mentioned in section 2.6.2). Here, we have estimated the shaft power (Ps) using Eq. 5, the results of which are listed in Table 4.2.

The estimations show that Ps increases with the increase in the in-stream water velocity. To achieving objective number two, Eq. 7 and Eq. 8 are applied, the results of which are listed in Table 4.1b and Table 4.1c.

Tables 4.1.b demonstrates that the efficiency of energy transfer from turbine to shaft (ηs) depends on the energy extraction efficiency of the turbine blades ($\eta_B$), the values of which are listed in columns 7, 8, 9, and 10. The highest efficiency of energy transfer from MMHT to shaft is 91 percent. The energy conversion efficiency from mechanical (Ps) to electrical energy ($\eta_g$) increases with the energy efficiency of the shaft (ηs), the values of which are listed in column 11, 12, 13, 14, and 15 of Table 4.1c. However, the results show that 95 percent is the highest estimated energy efficiency of the generator.

## 4.3 Overall Energy Extraction Efficacy

This section describes the data analysis related to the overall energy efficiency of the MMHT system. The overall energy efficiency of the MMHT is a product of the energy efficiency of the components of the system, which is demonstrated by Eq. 9 and denoted as $\eta_O$. The estimation results of Eq. 9 are listed in Table 4.3.

**Table 4.3: Overall Energy Extraction Efficacy**

| Water Velocity Vi m/s | Energy extraction inefficiency at Turbine Blade | Energy Transfer inefficiency at Generator Shaft | Energy Conversion Inefficiency at Generator | Overall Energy Efficiency ($\eta_O$) |
|---|---|---|---|---|
| 0.5 | 84 | 11 | 10 | 12.8 |
| 0.65 | 77 | 10.6 | 9 | 18.5 |
| 0.8 | 75 | 10 | 8 | 20.7 |
| 1.1 | 71 | 9 | 5 | 25 |

The estimation results demonstrate that the overall energy efficiency of the MMHT system increases with an increase in the in-stream water velocity. The estimated overall energy efficiency ranges from 12.8 percent to 25 percent, which is significantly low. However, the components with the highest energy inefficiency in the MMHT system appeared to be the turbine's blades, which had an inefficiency of about 84 percent. Indeed, the energy inefficiency of the blades contribute to the reduction in the overall energy efficiency of the MMHT.

## 5. DISCUSSION AND CONCLUSION

This study has estimated the energy extraction efficiency of a multistage micro-hydro turbine at low water velocity. The results of the experiment have been shown in Tables 4.1(a, b, c), 4.2, and 4.3. The lowest energy extraction efficiency of the blades was 16 percent at an inlet water velocity of 0.5 m/s, with an overall energy efficiency of 12.8 percent. Conversely, the maximum energy extraction of the blades was 29 percent at an inlet water velocity of 1.1 m/s, with an overall energy efficiency of 25 percent.

These findings have also demonstrated that the turbine rotation and energy extraction depend on the decline in water velocity across the turbine blades, as described in Table 4.2. The MMHT attained a turbine speed of 45 RPM at a water velocity 0.5 m/s, which was insignificantly low. At this speed, the energy extraction was also at a minimum of 16 percent. Table 4.2 also demonstrates that at a water velocity of 1.1 m/s, the turbine speed became 120 RPM. In this case, there was a significantly higher velocity drop across the turbine blades and increased energy extraction.

### 5.1 Practical Implications of Research Findings to Society and Economy

In-stream MMHT is a useful mechanical device, which can be used for extracting low-cost green energy from water. In addition, the model reported in this paper will be greatly useful in the quest to increase the energy extraction efficiency. The results of this experiment will help policy-makers commercialise MMHT in order to achieve economic and environmental sustainability for the society. The developed turbines will be commercially feasible for producing electricity for use in the manufacturing SMEs, agricultural projects, and residences adjacent to rivers, hence boosting the economy.

### 5.2 Conclusion and Directions for Further Studies

Thepproach used in this study is potentially effective for extracting energy from in-stream water. Undoubtedly, green energy will contribute to an increase in the environmental sustainability, so societies will benefit from the usage of MMHT. However, the findings of this study suggest that MMHT can increase the energy extraction efficiency at a lower water velocity, although its energy efficiency is significantly low. This study concludes that the developed model and the findings will provide useful information for future researches, which aim to increase the energy extraction efficiency. Future researches should be conducted along the lines of characterizing the energy extraction at a water velocity of more than 1.1 m/s, apart from developing a MMHT of more than five stages of blades to characterize the energy extraction efficiency.

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