A review of hydrokinetic turbines and enhancement techniques for canal installations: Technology, applicability and potential

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Abstract
The hydrokinetic industry has advanced beyond its initial testing phase with full-scale projects being introduced, constructed and tested globally. However primary hurdles such as reducing the cost of these systems, optimizing individual systems and arrays and balancing energy extraction with environmental impact still requires attention prior to achieving commercial success. The present study addresses the advances and limitations of near-zero head hydrokinetic technologies and the possibility of increased potential and applicability when enhancement techniques within the design, implementation and operational phases are considered. Its goal is threefold: to review small-scale state-of-the-art near-zero hydrokinetic-current-energy-conversion-technologies, to assess barriers including gaps in knowledge, information and data as well as assess time and resource limitations of water-infrastructure owners and operators. A case study summarizes the design and implementation of the first permanent modern hydrokinetic installation in South Africa where improved outputs were obtained through optimization during each design and operation phase. An economic analysis validates a competitive levelized cost of energy and further emphasizes the broad potential that is relatively unexplored within existing water-infrastructure.

Highlights
- Relatively unexplored potential within water infrastructure exists for zero-head technologies.
- Careful selection of an optimal hydrokinetic installation site is a critical challenge.
- Hydrokinetic development phase enhancement measures allow an optimized system.
- Standards development is a critical need to advance hydrokinetic project development.
- Lack of awareness of hydrokinetic resource potential is a large development barrier.

Keywords
Hydrokinetic energy conversion; low head hydropower; Hydrokinetic technology; Hydrokinetic applicability; Hydrokinetic turbine

Word count: 9507

Nomenclature

ε	Blockage coefficient
η_1	Gearbox efficiency
η_2	Generator efficiency
η_3	Transmission efficiency
η_{el}	Electrical efficiency
η_{hyd}	Hydraulic efficiency
η_{mech}	Mechanical efficiency
ρ	Density
τ	Instantaneous torque

A	Turbine swept area
AEP	Annual Energy Production
CEC	Current energy conversion
CFD	Computational Fluid Dynamics
C_p	power coefficient
D	Turbine diameter
DoE	Department of Energy
E	Device efficiency
E_s	Specific energy
ESHA	European Small Hydropower Association
ft	Feet
G	Safety performance function
GA	Genetic Algorithm
GW	Gigawatt
H	Turbine blade height
HK	Hydrokinetic
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
kg	Kilogram
kW	Kilowatt
LCOE	Levelized cost of Energy
m	Metres
MEC	Marine energy conversion
MW	Megawatt
N	Newton
P	Power output
P_{HK}	Power density
$P_{Extracted}$	Extracted power
$P_{dissipated}$	Extracted power including dissipated power
R	South African Rand
Re	Reynolds Number
REC	River current energy conversion
RM	Reference model
RPM	Revolutions per minute
s	Second
SA	South Africa
SHP	Smart Hydropower
TAG	US Technical Group
TC	Technical Committee
TSR	Tip speed ratios
USD	US Dollars
V	Fluid velocity
W	Watt
Wh	Watt Hour

Contents

1 Introduction

In recent years renewable energy sources have increasingly contributed to global energy production with a total supplement of around 2 179 GW (approximately 34% of global installed power capacity) of which hydropower is the largest contributor of approximately 1 151 GW (approximately 18% of global installed power capacity) [1] [2]. Considering the climate change crisis and ever increasing global electricity demand, there is a pressing need to rapidly accelerate this trend and transition to a renewable energy dominant portfolio that significantly reduces carbon emissions within the next decade [3]. This can be achieved largely through the rapid expansion of utility-scale renewable energy projects and markets using mature and cost-effective renewable energy conversion technologies, e.g., solar, hydro and wind turbines [4]. Efforts are also needed to accelerate the development of new renewable energy industries and markets using next generation energy conversion technologies with the ability to extract untapped renewable energy reserves, including low-head (potential) hydropower and hydrokinetic (HK) power in water currents and waves. Studies on the opportunities for energy development such as those in water conduits [5] create a forefront to accelerate development by allowing insights into available opportunities.

Ideally a renewable energy conversion technology should have a minimum cost per annual average energy production as well as minimal and mitigatable environmental impacts with a maximum power output. Hydropower generation through the use of water conveyance systems can be a valuable global renewable energy asset, but relatively little of this potential has been accurately assessed or developed globally. This renewable energy resource can be harvested from existing water-infrastructure without the need to construct new dams or diversions, significantly reducing construction costs and the need to develop additional capital-intensive centralized generation systems. By avoiding water impoundment, environmental impacts are minimized, further reducing the short- and long-term economic impact of environmental externalities. Furthermore, innovative technologies have been developed, including low-head hydro technologies that efficiently generate at low heads of approximately 3 m (9 ft), and near-zero head HK also referred to current energy conversion (CEC) devices, technologies that generate with no local potential energy head requirement. Projects with the potential to generate at least 1 000 MWh annually (~100 kW installed capacity) can achieve competitive levelized costs of energy (LCOE) of approximately $0.07 to $0.08 per kWh [6] and additional renewable-energy-development incentives can further reduce project development costs. Smaller projects can also be viable investment opportunities in alternative energy markets where electricity costs from conventional sources such as diesel generation are high.

For electricity demand located near flowing water, micro-hydro systems such as HK schemes may in many cases be the most economical and reliable option for generating electric power [7].

The European Small Hydropower Association (ESHA) [8] defines low head hydropower as electricity generation devices conveying sustainable volumes of water at relatively low-pressure heads (up to 30 m). More specifically HK energy falls within the “zero-head” class. Conditions forming the scenario for low- to zero-head installations typically lie at various hydraulic structures in irrigation canals, rivers, low height dams, gauging weirs, outflow structures etc. Additionally, HK turbines can be installed along sections of canals, where sufficient flow volumes, velocities and reliability of flow exists [9]. These HK opportunities allow new areas of application and hold the key to possibly discovering new potential in previously unexplored territories such as flat long river/canal sections where conventional hydropower in the form of available potential energy does not exist.

2 Hydrokinetic technology

HK systems are a class of “zero-head” hydropower whereby energy is extracted from the kinetic energy of flowing water, similar to wind turbines, rather than the potential energy of falling water. These systems can be installed in free-flowing rivers or streams [10]. By harnessing this form of energy, HK energy production avoids many of the challenges faced with the more traditional forms of hydropower such as high civil works costs and the need for an acceptable and exploitable potential energy head. HK technologies are one of the oldest forms of hydropower, however the evolution of these systems may be divided into period, from the traditional period from which the waterwheel concept was derived, to the recent empirical period characterized by modernised pilot plants and experimentation. Currently the technological evolution is in its growth period with several HK development initiatives materializing within river, tidal and wave energy systems [11].

HK turbines are relatively simple designs with no reservoir or spillway requirements. Initial testing have indicated the environmental impact is minimal and the simplicity of these devices allow for low cost installation and maintenance. Due to this simplicity these systems may hold value in rural or remote areas [10]. The basic working of a HK device can be seen in Figure 1.

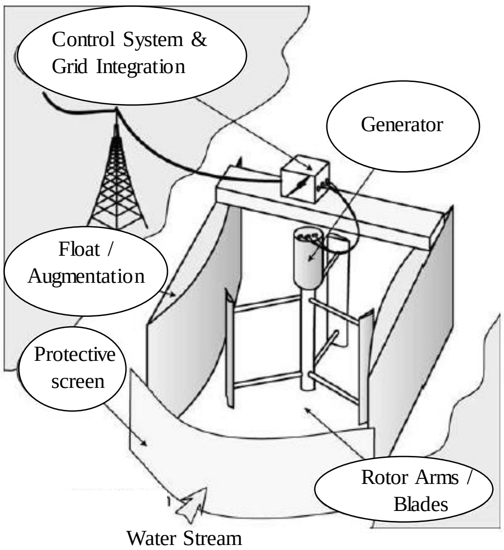


Figure 1. Basic working of inland HK turbines [12] (Used with the permission of MJ Khan)

The applicability of HK technology within rivers, tidal and ocean currents and man-made channels enables installation at sites which do not hold possibilities for other technologies. The major types of CEC systems are shown in Figure 2. The turbine category employed can be characterized by its rotational axis orientation with regard to the water flow direction. The first being an axial flow (horizontal axis) turbine whereby the rotor is placed perpendicular to the direction of the current to ensure power conversion efficiency. The second, cross flow (vertical axis) turbine-type classifies a device with rotational axis perpendicular to the current direction. This turbine rotation is not dependent on flow direction and can operate in any orientation perpendicular to the flow. Both types can be deployed in rivers and canals. Additional consideration during design work may be required to maximize the energy generated [13]. General characteristics and comparisons between the two common CEC systems are listed in Table 1. In addition, numerous HK turbines of varying configurations are emerging, these may divert slightly from the classifications in Figure 2. This may result in further classification defined by the principle of lift or hydraulic drag force (driving force acting on the blades [14]).

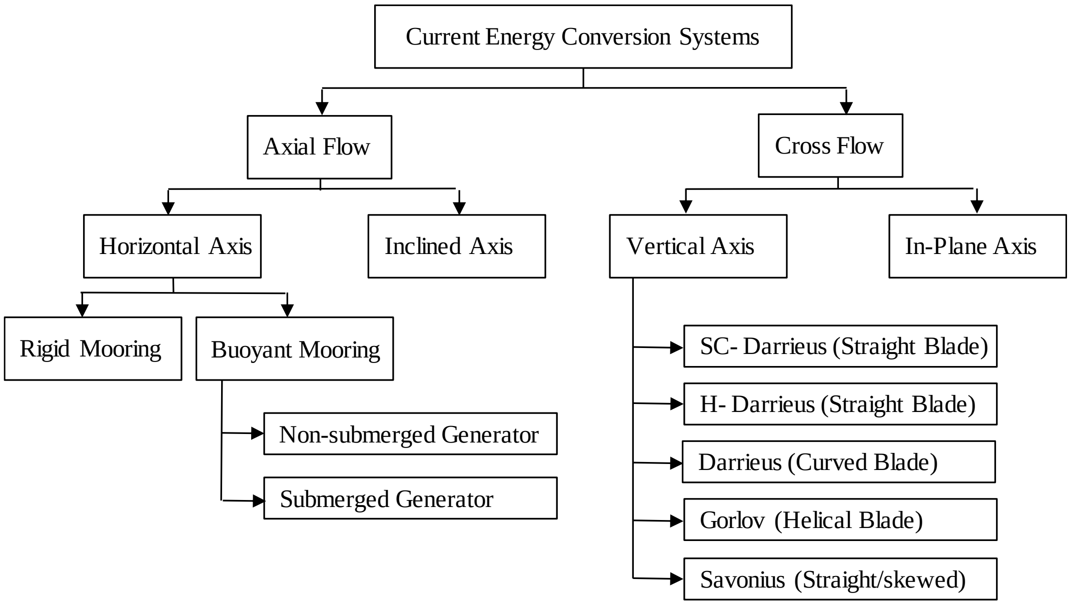


Figure 2. Hydrokinetic turbine classification [15] (Used with the permission of MJ Khan)

Table 1. Current energy conversion turbine characteristics comparison [16]

General characteristics	**Horizontal axis turbine**	**Vertical axis turbine**
Minimum operating current velocity	0.5 m/s	1 m/s - need higher velocity to self-start
Operating tip speed ratio (TSR)	Faster (TSR up to 4.5)	Slower (TSR below 3)
Coefficient of power C_p	46%	35%
Water to wire efficiency	25% (calculated) due to less efficient transmission and generator	26% (claimed) due to efficient transmission and generator
Debris resistant	Poor	Good
Torque ripple	Smoother	Pulsating
Rotor simplicity	Fairly complex	Simple
Material quantity and cost	Less	More
Weight	Less	More
Pontoon	Smaller due compactness	Larger
Mechanical power transmission	Complex	Simple

For HK devices the power available is determined per swept area and may be termed the HK power density (P_{HK}, (W/m^2)) which is a function of fluid velocity, density and device efficiency as shown in equation 1 [17]:

$$P_{HK} = E \times \frac{\rho}{2} \times V^3 \quad (1)$$

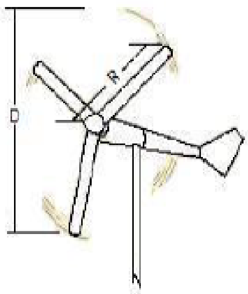
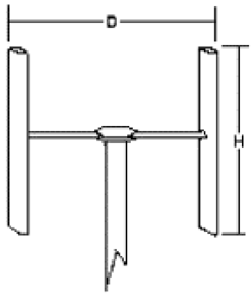
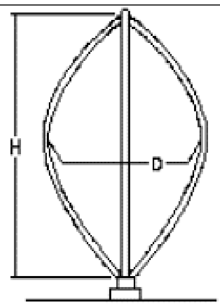
The equation may be explained in a similar to determine power output (P (Watts) [18]:

$$P = \frac{\rho}{2} \times A \times V^3 \times C_p \quad (2)$$

Where V defines Fluid velocity (m/s) ρ the fluid density (kg/m^3) A the HK turbine swept area (in m^2) with the manufacturer specified device efficiency (E (%)) and power coefficient (C_p) of a specific HK turbine taken into account.

The swept area is determined based on the turbine configuration as shown in Table 2 (common turbine types). Where *D* and *H* define the turbine blade diameter and turbine blade height respectively.

Table 2. Swept area calculation for relevant blade configurations [19] (Used with the permission of P. Gipe)

Rotor blade	Conventional rotor	H-Darrieus Rotor	Darrieus Rotor
Arrangement			
Swept area	$A = \pi \times \frac{D^2}{4}$	$A = D \times H$	$A = 0.65 \times D \times H$

Power performance tests are conducted to determine the mechanical power coefficient, C_p, over a range of tip speed ratios (TSR). The power output achieved from instantaneous torque (τ in (N.m)) and angular velocity (ω in $(\mathrm{rad/s})$) measurements is compared to the HK power density (available power) to obtain the power coefficient (C_p) as in equation 3 [20]:

$$C_P = \frac{\tau \times \omega}{P_{HK}} \tag{3}$$

The turbine power performance (power coefficient) is dependent on the Chord Reynold number and the blockage ratio (projected area of rotor to flow section area). Thus scaled model performance tests are needed to establish that power performance is Reynolds independent and to quantify power coefficients accurate at full scale installations. Large blockage ratios during performance tests can significantly increase power coefficients, therefore, these should be avoided if possible. If not, power coefficients should be adjusted accordingly [21].

Once the power performance of a HK turbine is fully characterized, the annual energy production (AEP, (kWh)) can be calculated for a given site following standards by the International Electrotechnical Commission (IEC) [22]. Combining the predicted mechanical power performance characteristics (equation 2, for a specific velocity V_i) , revised as $P = \frac{\rho}{2} \times A \times {V_i}^3 \times C_p\,(V_i)$ in kW with a current frequency histogram $p(V_i)$ for the project site:

$$AEP = 0.95\left(\frac{8766}{1000}\right)\eta_1\eta_2\eta_3\frac{1}{2}\rho A\sum_{i=1}^{n} C_p(V_i)\cdot u_i^3\cdot p(V_i) \tag{4}$$

Where $C_p(V_i)$ is the power coefficient which accounts for the on-site conversion of HK power to mechanical power; $p(V_i)$ the probability of a given current speed occurring during the year for the site (obtained from the current speed frequency histogram) and V_i a given current speed in m/s. A is the swept area in square meters, ρ is the density of water in kg/m^3, 8766 is the number of hours in a Julian year (365.25 days) and 1000 is the number of Watts (W) per kW. The assumed operational availability in this formulation is 95%.

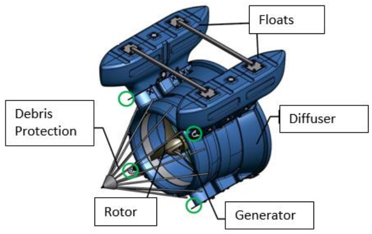
Specific values for gearbox and generator efficiencies, η_1 and η_2, for whichever HK device is used should be determined by the manufacturers. Typical values for η_1 range from 0.92 (92%) to 0.96 (96%), values of 0.96 (96%) are typical for wind turbine gearboxes [23]. Values for η_2, range from 0.90 (90%) for the small generators e.g., that used in the Reference model (RM) 2 crossflow turbine [24] [25], and for large permanent magnet generators may range up to 0.98 (98%) e.g., that used in the RM1 axial flow turbine [24] [25]. Transmission efficiency, η_3, is approximately equal to 0.98 (98%) and accounts for the heat loss in the conductor (*Joule effect*) [26].

Assessments of the hydrodynamic effects of a HK turbine deployment specifically the upstream damming and the downstream flow disturbance (wake) are of great importance[27] [28] [29]. For the application of HK devices in open channels the flow properties such as the flow regime, flow state and the bulk flow properties (Froude number, Reynolds number etc.) which characterize a specific section are of important consideration. For Reynolds values above 4 000 inertia forces dominate over viscous forces which result in unstable and turbulent flow. Canals with fast moving (turbulent) flow are most ideal for HK deployment (Re values well over 10^5) [13]. The Froude value dictates sub- or super-critical flow types. Where the Froude number is below 1 it indicates the wave celerity or speed of propagation of a small surface wave is greater than the bulk velocity, meaning gravitational forces dominate (over inertia). Most man-made structures are designed for subcritical flow to reduce scour [13] thereby contradicting infrastructure design for HK potential. The extent of hydrodynamic effects of HK installations must be considered in all installations and should be noted that as the HK system extracts power from the flowing water (even during a stopped configuration) the flow velocity may be impacted thus affecting water elevation (damming effect), sediment transport and other properties of importance [17].

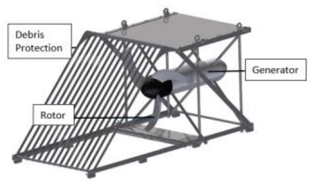
2.1 CEC turbine availability

Numerous small-scale modular HK units are available on the market, summarized in Table 3, most of which derive optimum outputs at velocities between 2.5 - 3 m/s. A number of these turbines make use of enhancement techniques: Turbines (1) and (3) incorporate confinement and diffuser mechanisms, whereas (4) makes use of cross-sectional alteration. However, most of these enhancement techniques are designed to function at a specified range of application and are usually less effective in slow flow or lower velocity scenarios.

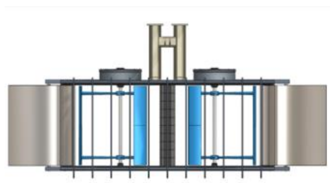
Table 3. Commercially available turbine units (used with the permission from all suppliers)



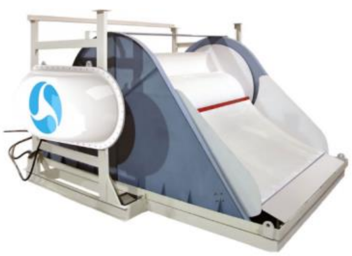
1) Smart Duofloat [30]
Axial flow- Submerged generator
At V=2.8 m/s P=5 kW (1 m diam)



2) Smart Freestream [30]
Axial flow- Submerged generator
At V=3.1 m/s P=5 kW (1 m diam)

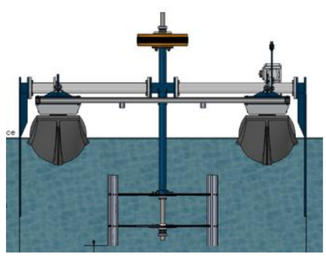


3) Hydroquest River 1.4 [31]
Cross flow- Darrieus
At V=3.1 m/s P=40 kW



4) Waterotor Energy Tech [32]

5) Guinard Energies [33]



6) EnviroGen Series [34]

Cross flow- Savonius At V=0.89 m/s P=1.1 kW	Axial flow- Custom Power output range P= 130-3500 W Min V=1 m/s	Cross flow- H-Darrieus At V=3 m/s P=5 kW
		
7) ORPC RivGen [35] Cross flow- Custom AT V=2.3 m/s P=15 kW	8) HeliosAltas [36] Cross flow- Custom Power output range P=100-500 W Min V=1.8 m/s	9) Instream energy system [37] Cross flow- H-Darrieus At V=3 m/s P=25 kW

2.2 CEC installation examples

A number of small-scale HK turbines within inland water-conveyance systems have been installed throughout the world and a summary of applications are included in Table 4. Many of the applications ([16] [38] [21]) were short-term testing installations, which make evaluation of long-term functioning of these units difficult to predict, although these applications do provide insights on attainable power outputs. The Smart Hydropower [39] projects were mostly installed to provide decentralized energy solutions whilst the Nile HK project [16] was the only reported permanent installation which indicated operation for an extended period of time. Projects such as these may provide insights into further improvement and optimization of installations such as the Yakima project [21] where the effects of HK turbine on hydrodynamics and canal operations, including flow recovery in the wake and backwater effects were reported and evaluated.

Table 4. Examples of HK installations (used with the permission of Smart hydropower, MJ Khan, H van Els, B Gunawan and New Energy Corp)

Description and reference	Range: rotor diameter, velocity, output	Purpose	Picture
Horizontal Axis turbine in the Nile River [16] [40]	unknown	Pumping irrigation water to Egypt, Sudan and Somalia.	
Horizontal Axis HK ducted Turbine Brazil [41]	0.8 m diameter V=2 m/s P=1 kW	Demonstration purposes by the University of Brasilia.	
EnCurrent Floating Barge Kinetic turbine, Manitoba, Canada. [38]	1.5 m Diameter V= >2 m/s P=5 kW	The turbine was in place for less than a year, removed prior to river icing.	

Description and reference	Range: rotor diameter, velocity, output	Purpose	Picture
Smart Irrigation Project in Neiva, Colombia [30]	1 m Diameter. V=1.7 m/s P=1.1 kW	Duofloat, Powering off-grid irrigation pumps. Operation 5 years to present.	
Smart Monofloat grid-connected project Roseheim, Germany [30]	1 m Diameter. V = 0.7-3.5 m/s P = 2 kW at 2.1 m/s	Monofloat turbine. Power produced feeds into national grid compensated by the German feed-in-tariff policy. Operating since July 2013.	
Instream- Yakima Hydrokinetic project, Roza Canal, USA [21]	3 m Diameter (1.5 m height) P = 10.9 kW V = 2.5 m/s	H-Darrieus turbine installed in 2013 for a 3-year testing period in the Roza canal.	

Small-scale hydropower, and in particular HK energy systems hold great potential in not only off-grid rural areas where localized electricity sources are required [10], but also in developed countries where most large-scale potential has been exploited and large civil works such as dam construction is not feasible [42]. The Applegate Group and Colorado State University [43] identified the extent of typical structures with small-scale hydropower potential on canal systems such as diversion structures, chutes, vertical drops and pipelines and estimated a great state-wide potential for Colorado, USA. In Pakistan (a water stressed country) the small-scale system potential was investigated and in a single region more than 290 micro hydro run-of-river schemes (of around 3-50 kW capacity) have been installed, accumulating to the capacity of around 3.5 MW [44]. This highlights the reachable capabilities of small-scale hydropower schemes and further emphasizes the need to improve HK technologies and the availability of these systems which could allow a change in characterizing potential and thus a greater range of potential sites for small-scale hydropower installations.

In terms of HK resource assessment, few assessments of potential within existing canals and rivers have been completed to broadcast this potential worldwide ([7] [9] [43]). These assessments vary in methodology, and combine low-head hydro technologies with HK turbines. Therefore, access to realistic estimates of potential installed capacity and exclusively HK turbine projects is not easily obtainable and resource assessments among other critical needs are needed first.

3 Development phases in hydrokinetic implementation

HK devices may be placed in natural streams, tides, ocean currents, artificial waterways and similar sites where sufficient velocities and cross-sectional parameters are available. Although the structural requirements are minimal, low efficiency, cavitation [45], high installation costs and unpredictable maintenance remain the largest challenges in advancing this technology [14]. To further develop HK potential, subsequent improvement is required on not installation and operation phases and is a crucial element to increasing the economic feasibility of site specific HK projects. Optimization and enhancement techniques are utilized during the design, installation and operational phases of a HK development process as indicated in Figure 3. Knowledge of the site characteristics are of great importance and act as inputs in all stages of development [46]. During the various phases, elements described in the subsequent sections may be evaluated and utilized to develop an efficient system with the highest possible output.

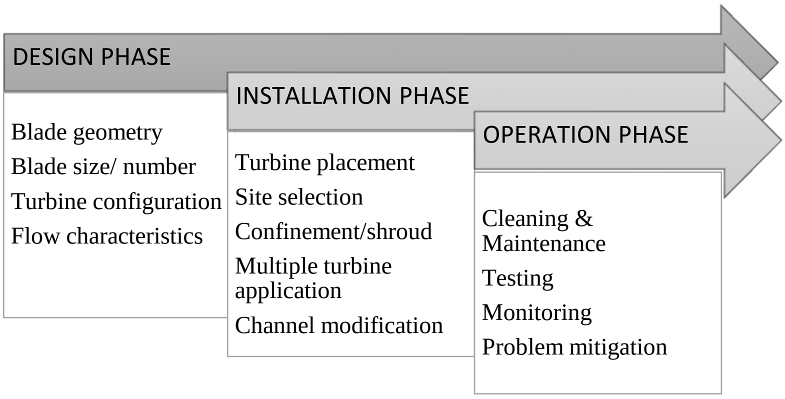


Figure 3. Development phases and optimization options

3.1 Design phase optimization

According to Kumar & Sarkar [47] the basic principle of HK design and important components for consideration are summarized in the process flow diagram depicted in Figure 4. The design process is initialized by optimization of the electrical, mechanical and hydrodynamic components which is followed by consideration of enhancement techniques and a subsequent economic analysis on the components and possible improvements thereof. The process allows an optimized design based on assumptions on operational conditions and ensures all aspects of importance are considered during the design process.

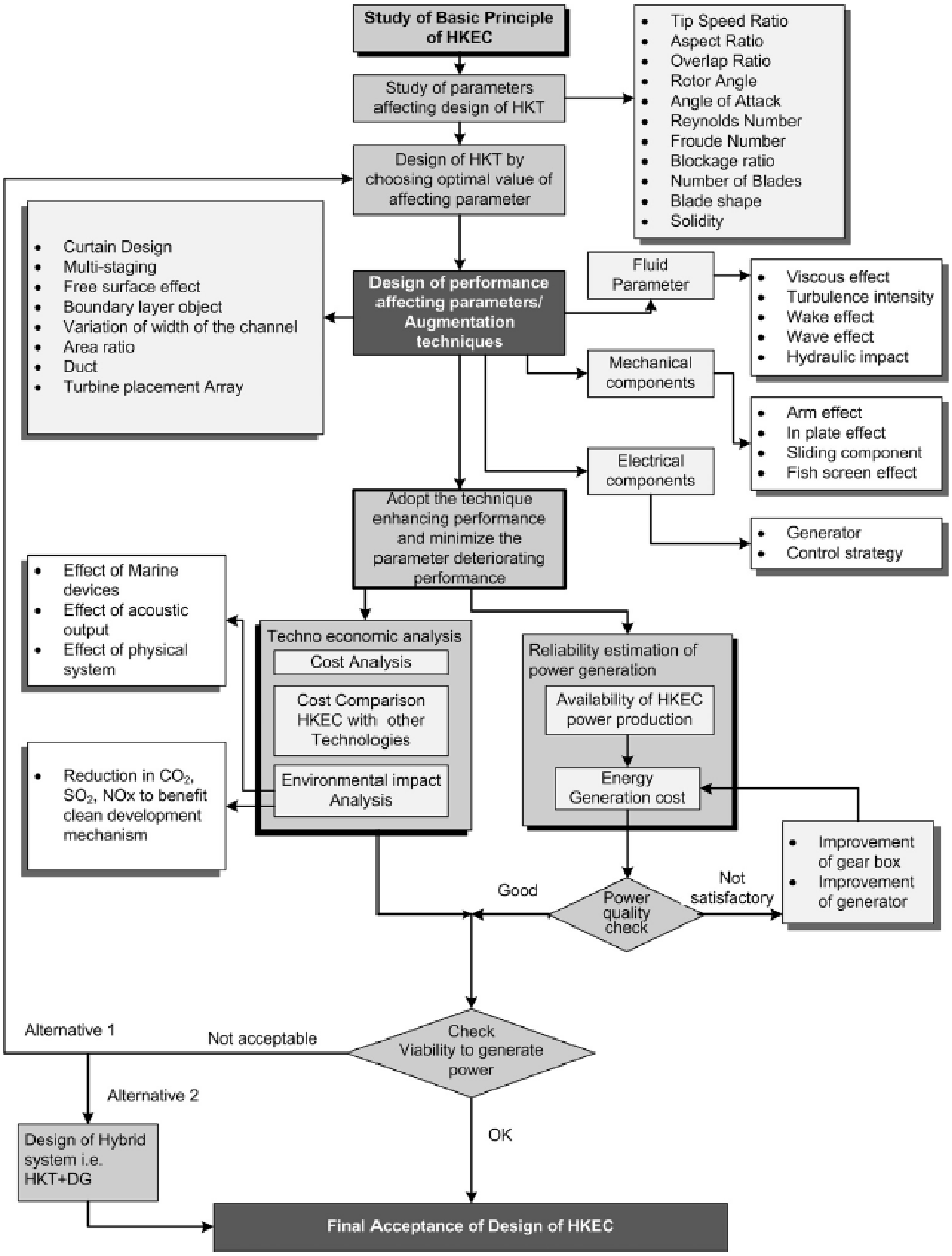


Figure 4. Process of design and implementation of hydrokinetic energy conversion systems [47] (Used with the permission of D Kumar)

The design success is largely based on mechanical operation, Sale et al. [48] define 15 mechanical optimization variables for HK turbines related to the turbine configuration such as chord, twist and percentage thickness distributions of the components such as blade hub, tip etc. all relating to the blade geometry. Multiple studies have analysed the various effects of these variables [49]. These aspects are considered during the design stages of the turbine and prove difficult and not economical to alter post-manufacturing to suit a specific site.

Computational design optimization tools such as the Rotor Optimization Algorithm as tested by Sale et al. [48] may be used for HK designs. The algorithm incorporates 15 defined variables at 5 control points, namely the blade hub, blade tip, and even spaced points in between after which a Genetic Algorithm (GA) enforces constraints and bounds to converge on the most structurally and hydrodynamically feasible blade shapes.

Optimizing a rotor for maximum hydrodynamic efficiency does not necessarily result in a turbine with the highest annual energy production, this is rather related to maximizing the turbine efficiency (increasing approach angle/velocity) [48] to approach the Betz limit. The Betz limit is used in HK design as a "goal factor" and basis for efficiency calculations. This allows a practical upper limit on the highest attainable efficiency. An example of this may be seen in Figure 5 where the rated speed for the turbine is selected by minimizing the area (Area1) between the Betz limit and the power curve to maximize the turbine efficiency. This is then proposed as the operational point [48]. The process allows prediction of the desired flow speed when installed to obtain the highest possible efficiency. Mathematical models have been incorporated into an optimization design approach as developed by Shinomiya et al [50] which was designed to optimize the blades of a horizontal axis turbine considering the cavitation effect.

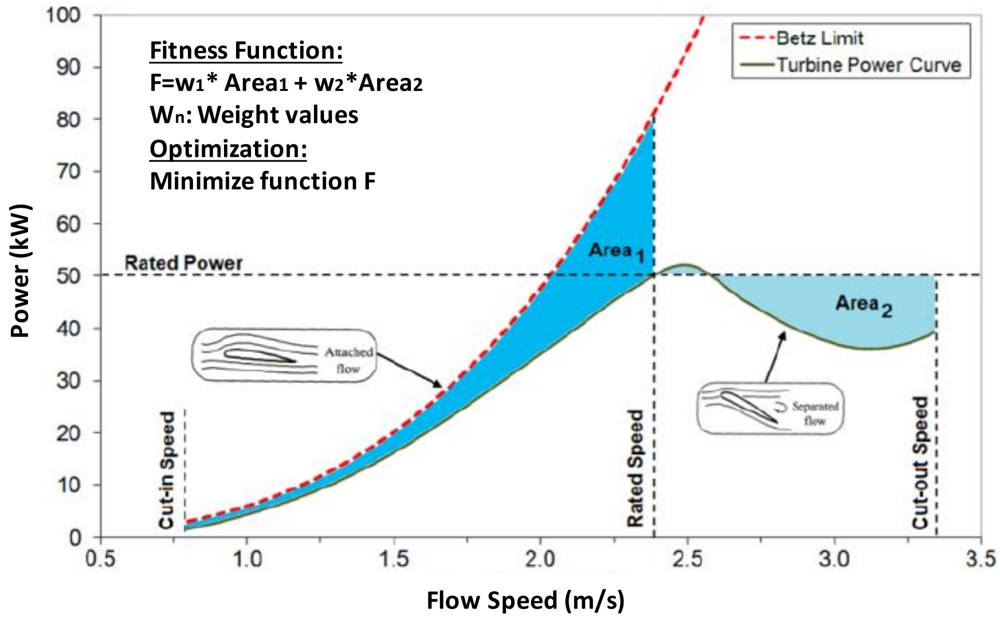


Figure 5. Example power curve for a HK turbine [48] (Used with the permission of D Sale)

An alternative to the design of a specific unit (fitted to a specific range of operation) is allowed through the use of techniques such as varying the pitch of the blades (in axial turbines) or allowing the blades to stall (stalling the turbine as the rated flow velocity is reached and exceeded) [51], however this may require each blade to have its own mechanism thus adding a large complexity and cost factor. Additionally, Computational Fluid Dynamics (CFD) modelling simulations may be performed to study the hydrodynamic performance of the HK turbine [49]. The HarpOpt rotor design code process defined in [51] may be used to create an optimized rotor for a specific current or optimize the system to function at a specific RPM. Cross-sectional velocity mapping is recommended for accurate assessment of the approach velocity (and thus turbine performance and loading) which is site specific, additional to determining flow steadiness and numerical model boundary conditions [13]. A detailed procedure of this process is described in [13]. The International Electrotechnical Commission (IEC) standards TC 114 [52] for river resource assessments also aim to assist in performance reliability with the goal of ensuring reliability and safety standards.

The electro-mechanical equipment selection and matching to the water-energy conversion system is of great importance. These may be similar to wind turbine generation, where advances in research provide information on efficient system operation [14].

3.2 Further turbine performance enhancement methods

The production of HK energy directly links to the available velocity of the water. Higher velocities (within the operational range) produce exponentially higher power outputs, due to the exponential behaviour of a HK power curve (typical example can be seen in Figure 5), this directly influences economic viability. Enhancement techniques are in many cases considered as a means to increase the power density of the turbine [53]. Additionally, the placement of the turbine within the flow area, specifically in array applications, may be investigated (high and low flow velocity zones) to optimize the output and predict the flow effects of the HK unit as indicated in Figure 6, this velocity zone distribution is similar over the plan view [54].

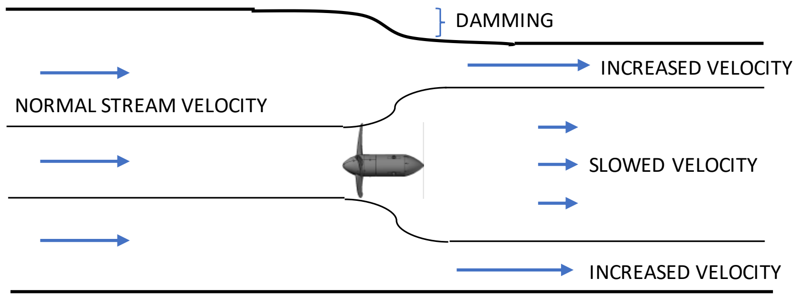


Figure 6. Control volume schematic (Side view) [54] (Used with the permission of AH Birjandi)

Numerous physical and numerical modelling tests have been conducted on possible enhancement techniques [55] [53] [56] [57]. These results can, to an extent, be used as a basis for performance enhancement, however the studies vary in analysis techniques used and, in some cases, contradict conventional theories. Validation of results through the use of field tests is rare.

An important aspect of consideration when applying performance enhancement techniques is the increase of total drag which in turn increases the cost of turbine anchoring, as well as possible increases in debris accumulation. These effects should be taken into account during an economic analysis and may not be appropriate for all applications [58]. A series of retrofitted HK alteration techniques which have been found to increase turbine performance and are summarized below:

<u>Confinement (diffuser/shroud)</u>
Confinement refers to the placement of the turbine within a confined structure such as a duct. Its theory is mostly used in tidal applications. The hydrodynamic qualities relevant to the technique are complex, a basic conceptual design of a duct can be seen in Figure 7 [59]. This concept has been extensively researched in wind-turbine design and can be applied to HK application to an extent [60].

Kumar and Sachendra [55] performed a simulation of a ducted model and reported an increase in power output of up to 38%. A similar study proved a power increase from 166 W to 249 W (50% increase) for ducted models [61]. A great deviation in results in apparent due to varying environments and modelling techniques. Another study [62] exhibited a duct increasing the power coefficient by 0.85%. A contradictory study using a BEM-RAS model [63] indicated a duct exhibiting inferior hydrodynamic forces on axial flow, decreasing the power output from 970 W to 610 W. Additionally, ducts have in cases been found to shield the rotor from debris or extreme flow conditions which may be present [55].

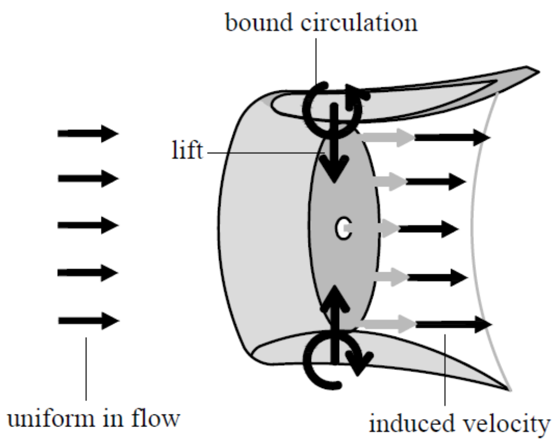


Figure 7. Conceptual design of duct [59] (Used with the permission of M Shives)

The operational TSR (as a result of inflow velocity) has been found to govern the magnitude of the confinement effect. Power curve results from a 1 m diameter ducted and un-ducted turbine tested by Smart Hydropower Gmbh are shown graphically in Figure 8. The results indicate more power is extracted through the ducted turbine as operational velocities increase [55].

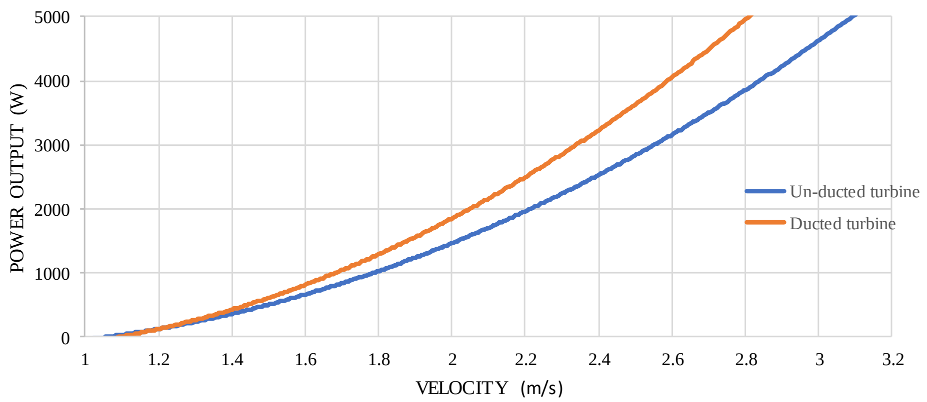


Figure 8. Comparison of ducted and un-ducted SHP turbine [30] (Used with the permission of Smart Hydropower)

A potential improvement in the efficiency of HK technologies is achieved by a carefully designed shroud mechanism (theory related to a ducted fan) which has indicated exhibited increased flow velocities through the turbine. Additionally, the shroud may be designed as a floatable structure and reduce maintenance and operational costs, simplifying anchoring and retrieval of the turbine. An exaggerated stream tube passing through an unshrouded and shrouded turbine is depicted in Figure 9, it indicates the alteration of the flow field caused by the shroud, effectively increasing the volume of fluid passing through the turbine. Gaden [64] found this effect can be demonstrated by the use of thrust ratios. By enclosing the turbine in a shroud, the total thrust is shared between the turbine and shroud resulting in a greater power output [65].

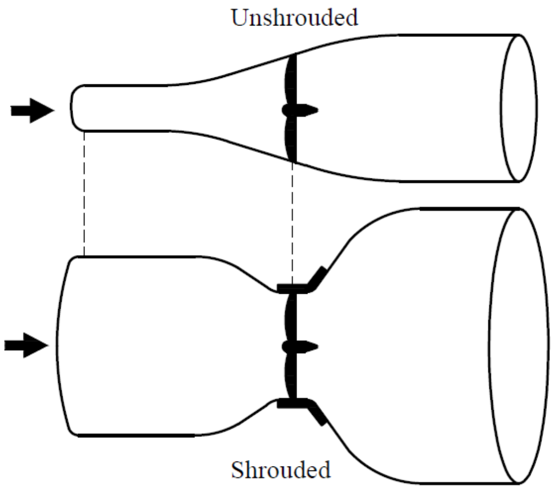


Figure 9. Shroud effect on streamlines [64] (Used with the permission of DLF Gaden)

Analysis proved contradicting results between theoretical and experimental analysis. Phillips et al. [66] performed a simplified one-dimensional analysis indicating a fourfold increase in power output, but experimental data did not show such optimistic results. Bet et al. [67] and Grassman et al. [68] proved aerodynamic features improved the power output by a factor of 2 and 5 respectively using numerical studies, though experimental results indicated an increase of only 1.25.

The use of a diffuser has become increasingly popular in recent years, due to studies indicating an escalated power output [69] [70]. A diffuser is similar to a shroud on the subject of containment yet differs with the placement being at the downstream end of the turbine, enclosing and diverging outwards at a specified angle. The effect of a diffuser on the axial velocity as found by Gaden [64] can be seen in Figure 10. The maximum axial velocity in this scenario was 2.8 m/s with no diffuser comparing to 4.1 m/s with a diffuser [64].

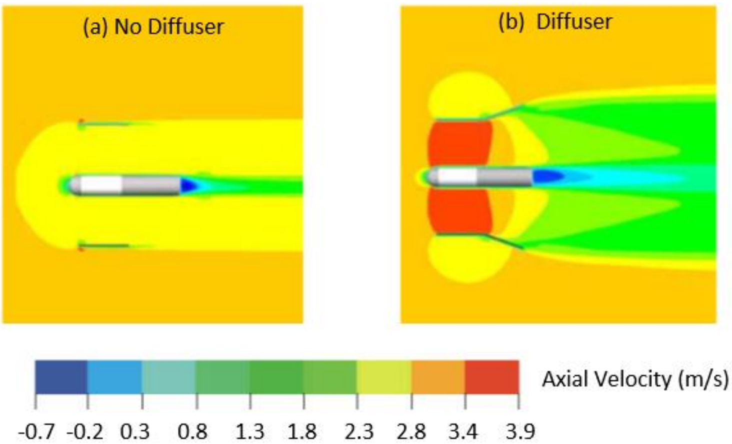


Figure 10. Velocity around a turbine with and without a diffuser [64] (Used with the permission of DLF Gaden)

Another modelled simulation study [53] proved a diffuser configuration (under certain circumstances) produces 3.1 times more power than a turbine without a diffuser. The optimum configuration found in this study proved to be a 20° diffuser with an area ratio of 1.56, which resulted in an increase in power output by a ratio of 3.1. The overall efficiency was 86.5 % (the power produced was 51.3 kW of which the freestream power available was 59.3 kW). This was well above the Betz limit; however, the difference may be explained by the calculation of the the Betz Limit being based on area swept by the turbine rotor alone (thus not including the diffuser area). Another study indicated a diffuser with area ratio 1.54 providing a 48% power increase (flange length of 0.1 rotor diameters) [57]. Recent studies into optimization of the diffuser, such as [69] proved a 71% increased C_p with a the 3rd generation diffuser.

Channel modifications

Modified channels are used to induce a sub-atmospheric pressure within a constrained area to increase flow velocity [12]. Placing a turbine in a similar channel would increase the velocity around the rotor thus increasing the power generation. Typical augmented/modified shapes for both vertical and horizontal axis turbine applications are shown in Figure 11.

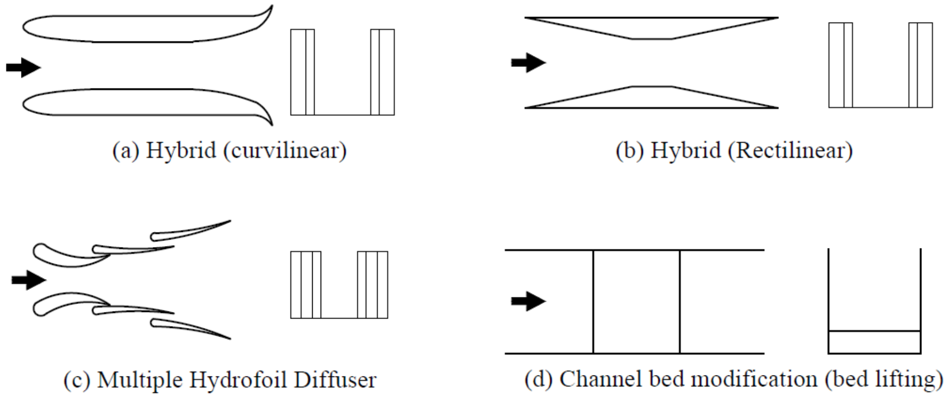


Figure 11. Channel shapes (plan and front view) [12] (Used with the permission of MJ Khan)

This augmented application follows the venturi principle used to increase velocity over a short section by reducing the channel dimensions and thereby choking the flow. For the flume to control the discharge (rather than the channel) critical flow must occur in the flume, for this to occur the specific energy (E_s) in the throat must be a minimum [71]. Ponta et al. [72] reported a velocity increase factor of 1.67 and thus a power increase factor of 4.63 from a curvilinear augmentation (A recollection of these studies can be found in ref [15]).

Multiple turbine application

The influence of the application of multiple turbines in a single cross section has been shown to affect energy output [73] [74]. Previous numerical analysis in tidal HK systems modelled as channelized flow between two basins, one finite and the other semi- infinite, proved as the number of turbines increased, the channel flow rate decreased (as the drag on the system is increased with each added turbine) however, results indicated that as the number of devices increased there was a peak in energy production and thereafter a decline [17].

To further understand the behaviour and allow investigation of multiple turbine application, the effect of a single turbine placed in a streamflow of a specific cross section must be understood (as indicated previously in Figure 6). Researchers have investigated the relationship between the power extracted from the flow and the total power which is dissipated by the presence of these HK devices. Garrett and Cummins [75] and Polagye [76] noted the HK device inflow generated a low velocity zone in the wake, when this low velocity zone mixed with the high velocity zone flowing around the device, significant energy dissipation occurred. Polagye [76] concluded as the turbine operated at an efficiency close to the maximum theoretical limit, the dissipated and extracted power can be approximated as shown in Equation 5 [75] [76].

$$\frac{P_{extracted}}{P_{dissipated}} = \frac{2}{3(1+\varepsilon)} \qquad (5)$$

Where ε defines the blockage coefficient (fraction of river area occupied by HK devices), the extracted Power ($P_{extracted}$) and Power dissipated ($P_{dissipated}$) includes extracted power and additional dissipation due to mixing.

Numerous theories of multiple turbine configuration for maximum output exist such as the triangular or "TriFrame" axial turbine configuration [77] and array flow effects analysis of various turbine blade types [49] [73] [74] [78],

A summary of the enhancement techniques found to be effective to HK application can be seen in Table 5.

Table 5. Summary of HK enhancement measures [79] [80] [59]

Enhancement measure	Advantages	Disadvantages	Preferred use
Confinement (diffuser/shroud)	i. Cost-effective. ii. Shroud may be used as a safety mechanism. iii. Technique may result in faster flow recovery downstream of the turbine (turbulence is contained). iv. Rotor size may be reduced with the use of confinement.	i. Significantly increase the modular turbine unit size. ii. May increase the blockage thus increasing upstream damming effect. iii. May not function adequately over all flow velocities.	Use in higher velocity applications (>2 m/s)
Channel modification	i. Allows a greater scope of site selection possibilities (lower velocities). ii. Flow direction may be controlled. iii. Allows drastic flow velocity change.	i. Drastic changes may cause non-uniform swirling flow, affecting turbine functioning. ii. May result in high cost civil works. iii. Additional approvals may be required (infrastructure alteration). iv. Can only be applied over a short section before flow stabilizes to a higher flow depth.	Use in lower velocity applications (<2 m/s)
Multiple turbine application	i. Greater output obtainable per section. ii. Wake effects may be used to place turbines in preferable sections.	i. Clogging effect may be significantly worse (greater blocked area) ii. Inter-turbine effects must be considered which may be difficult to predict.	Areas with a large cross-sectional area.

3.3 Operational phase enhancement

During the design life of a HK device efficient functioning in a crucial aspect to ensuring design outputs are obtained. The energy production is predicted and considered during the preliminary design analysis, this is directly related to the production and therefore profitability/success of the installation. The energy production (adapted from the AEP) over a time period T can be determined as follows (adjusted from [81]):

$$Energy = \int_0^T P(t).dt = \int_0^T \frac{\rho}{2}.A.V(t)^3.\eta_{hyd}(t).\eta_{el}.\eta_{mech} \tag{6}$$

Where $P(t)$ is the power output of the turbine, η_{mech} and η_{el} respectively refers to the mechanical efficiency (also referred to as C_p) and electrical efficiency (losses incurred within the control equipment) of the turbine, these are assumed to be constant. The stream velocity $V(t)$ and hydraulic efficiency $\eta_{hyd}(t)$ is determined for the available streamflow records; flow angle of approach; possible debris blockages etc. Turbine laboratory characterization often does not include the "water-to-wire" efficiency or η_{el} which is determined by the control equipment which convert the extracted mechanical energy to exploitable electrical power, these can critically affect the HK turbine performance [82]. Prototype testing of the total system (gearbox, generator, electrical load) is required to quantify the system efficiencies and predict performance [83].

In most prediction analyses of the design life, high positive clearance co-efficients and negligible blockages are assumed [54] [84]. However, regular debris build-up or clogging could significantly reduce this design output and thus project feasibility. Although the blockage correction also falls within the design phase [85] a large component thereof varies with site conditions and requires monitoring and further system alteration as debris remains a large obstacle and limiting factor for HK deployment [86].

Limited field testing on the operational life of a HK device has been published (also due to few of these systems operating on a permanent basis) [87]. Although a greater portion of marine systems exist, the lifespan and operational requirements differ significantly from riverine/channel systems due to the environment variations. From the few small-scale HK riverine/channel installations, relevant operational issues and conclusions/solutions may be found.

As an example, a horizontal axis HK turbine installation in Africa demonstrated by Peter Garman in 1979, installed as a floating unit with a submerged rotor in the Nile River (operating as a pumping scheme pumping water to Egypt, Sudan and Somalia) described some operational constraints. The system claimed to have many successful years of operation, however was reported to be frequently clogged by river borne plants. These plants collect around the pontoon and eventually stopped the rotor. The problem was reduced by moving the turbine slightly out of the main current [16] [88].

In another installation a 2 m diameter, four bladed, low solidity horizontal axis HK turbine was tested in Australia for an 18-month period. The turbine operators reported the turbine was adversely affected by floating leaves, seaweed and mangrove trees. Also, the turbine gearbox was damaged from a floating mangrove tree while operating at high speed, suggesting low speed rotors may be preferable to high speed rotors [85] [89].

Additional examples such as testing experiences in the UK recorded severe clogging and the operation being frequently stopped by seaweed [90]. This proves the importance of anticipating operational phase conditions during the design, additional to requiring further optimization during operation to ensure design outputs are obtained (as site conditions may vary throughout the operational life). Kumar [47] reached the following conclusions on operational considerations during a HK turbine operation analysis:

i. Variable pitch turbines may be used to minimize low starting torque, cyclic loading failure and vibration problems during operation.
ii. Good material selection, such as a composite material which has a high strength to weight ratio, excellent fatigue and corrosion resistance as well as good design flexibility results in a better operational life.

Testing and monitoring during operation allows understanding of the hydrodynamic effects of the turbine. As a result, further optimization can be done in array applications (to improve LCOE of the project) or where infrastructural influence is highly sensitive. As an example of such an influence, a test installation of a H-Darrieus turbine installed in the Roza canal obstructing approximately 17% of the cross-sectional area increased water levels 700 m upstream (±233 turbine diameters) to approximately 70% of the increase 50 m upstream (±17 diameters) [13].

HK turbines are designed to function effectively for long life-spans, even in harsh environments, however regular maintenance may be necessary. Mangold [91] indicated the HydroVolts turbine (Table 3) when operating in canal schemes required a particular set of maintenance procedures (Turbine shaft seal cartridge replaced, turbine lubricated and oil change) every 3 years, however maintenance requirements vary over the range of turbine designs. Additionally, testing and monitoring are essential components in the final installation phase, directly correlating to successful performance and durability of the system.

Efficient operation and development of a sustainable HK system require understanding water flows, densities, whether the canal is earth or concrete lined, access to site and the presence of test structures or drops nearby (impacting velocity). These are all important factors possibly influencing turbine efficiency [91]. Concerns such as potentially disrupting the water supply operations by affecting the head-discharge conditions at intakes; increasing water levels as a result of the blockage created (and potentially causing flooding) or when placed at an existing hydropower plant potentially reducing the power generation of the plant by affecting the tailwater or inflow conditions are also considered as inefficient scenarios. Additionally, a HK deployment causing unwanted sediment deposition, scouring etc. may affect the hydrodynamics of the canal [13]. These effects should be catered for during the design phase and further mitigated during operations to ensure2 an effective, sustainable and optimal system.

4 Standards and certification development

The development of standards and type certification for HK technologies is one of the critical needs to advance the development of HK projects. The International Electrotechnical Commission (IEC) [92] Technical Committee (TC) 114 are currently developing standards for Marine energy (MEC) (wave, tidal, river and ocean current) which focus on design specifications detailing design requirements for engineering integrity [52] [93]. The scope of IEC/TS 62600-2 includes development of technical specifications and requirements for river current energy conversion systems (referred to as REC systems). The IEC TC 114 together with the US Technical Group (TAG) (43 active members) from industry, academia and national labs, are collaborating with 22 countries to complete this effort. The project teams and ad Hoc Groups each focus on specific issues of design requirement, guidelines for design assessment, electrical power quality requirements to power performance testing and REC resource assessments [94][95].

For CEC (REC) systems specifically, the IEC TC 114 TS 62600-301 addresses river resource assessment and is due for publication May 2019. To develop the REC systems requires a study of their reliability under mechanical and environmental demands over its service life. The specification however does not provide guidance on reliability assessment of REC systems A recent study addressed this gap and developed a system to access REC reliability, this is done in 3 steps, respectively; Development of a model for the limit state and performance function; Identification of a specified "Random variable", and lastly calculation of the probability of non-performance and the results completed through 2 applications as described in Table 6.

Table 6: Performance evaluation applications [94]

	Description	Objective	Function
APP 1	Direct assessment of reliability of a system design for different limit states or modes of failure.	Estimate the reliability of the MEC or REC verifying it meets specific IEC target requirements for the a desired safety level.	Determining performance function G G{Actual resistance; permanent load; live load effects, capacity of the system}
APP 2	Determining design parameters ensuring the resulting structure achieves minimum target reliabilities (safety levels) for varying limit states or modes of failure using a deterministic design equation.	Design characteristics obtained to ensure achieved reliabilities match specified requirements.	Compliance test: P[G<0] = non-performance

As HK energy development grows there is an ever-increasing need for international standards to help promote an international market and accelerate cross-border acceptance of this technology. Standards also remain an important factor in assisting technology development and project developers in obtaining the necessary investment insurance and ensuring a standard of safety. This together with other key factors could assist with a success in the HK industry [95] [97].

5 Potential site conditions for HK technology

Selection of an installation site may be a difficult task when site parameters are sufficient however optimal velocities are not available. HK turbines usually require a velocity of around 2-3 m/s (based on available turbines).

Sites at existing narrowed sections (such as flume sections or syphon outlets) are usually more likely to have higher velocities readily available, examples of favourable installation sites are shown in Figure 12. Generally, well-disposed characteristics of cost-effective potential sites include high current speeds (>1.5 m/s) as these sites allow site development at acceptable LCOE's [13]. Additionally a high free-board available allows flexibility of water variation (robust sections). When selecting sites such as these, several issues such as high damming (increasing flood risks due to blockage caused) or interruption of the infrastructure operation (before installation) may occur, as hydrodynamic effects may be exaggerated by the added blockage in sensitive sections. Therefore, selection of a site with a higher available velocity along a uniform section where a smaller fraction of the cross section is used for the HK installation remains the best installation option.

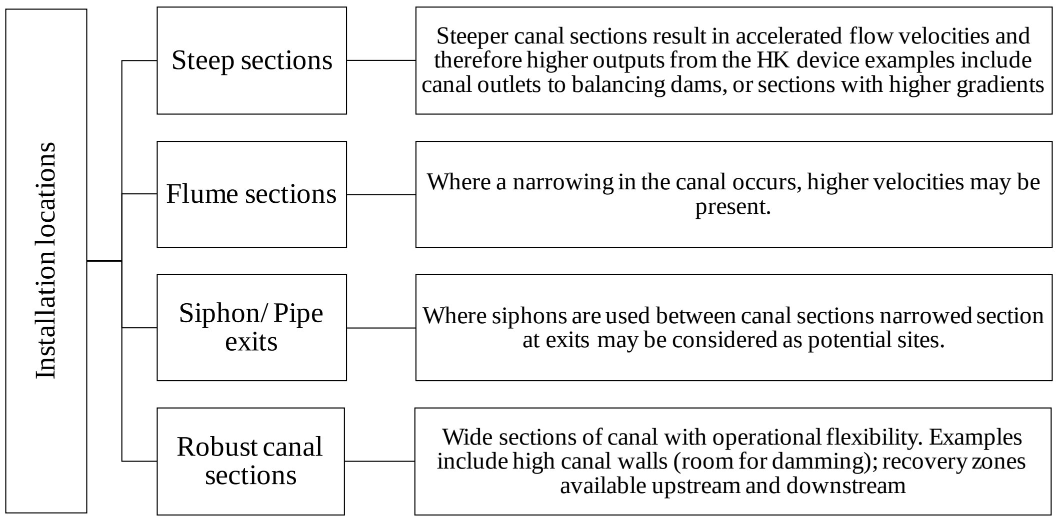


Figure 12. HK placement locations

In conjunction with site selection, a pre-feasibility study of each potential site should be undertaken, which includes, but is not limited to:

i. Identification of electricity demand, usage and transmission length;
ii. Access evaluation;
iii. Conceptual design;
iv. Preliminary costing of components.

6 HK Energy in South Africa: Case study Groblershoop HK installation

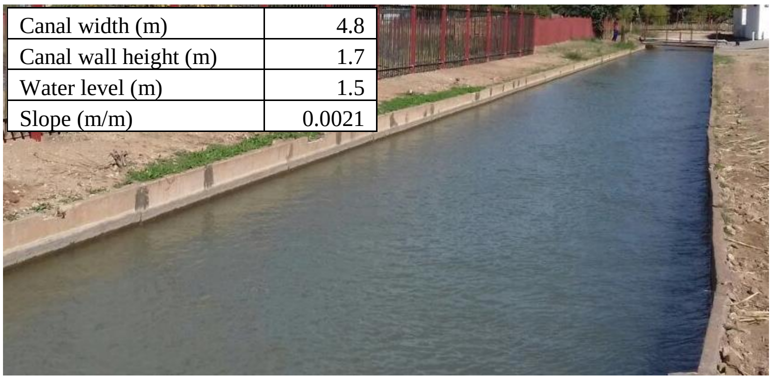
South Africa is a water stressed country receiving an average annual rainfall of around 490 mm (less than half of the world average of around 985 mm). In addition, most regions are prone to hot, dry conditions resulting in a high evaporation rate. SA receives most of its rainfall in short time periods, resulting in flood events, due to the water-scarce conditions these bursts of high runoff must be stored. There are a large number of dams which store runoff resulting in a large network of transfer schemes consisting of pumps, pipes and canals moving water from one catchment to another.

A large network of canal systems exists in SA with the Department of Water and Sanitation (DWS) asset management study database revealing a total of 47 schemes consisting of more than 6500 km's of canals. This reveals the extent of potential for HK installations in canal systems available in SA. In these systems 21 286 structures such as tunnels, syphons, weirs. control gates, chutes and drops exist, which hold a large unexploited HK potential.

Kusakana et al. [10] investigated the possibility of HK hydropower development for rural and isolated loads in South Africa. The case studies proved where adequate water resources are available in South Africa HK power generation could be the best, most cost-effective supply option in relation to wind, PV and diesel generators.

6.1 Site description

The Groblershoop HK site in the !Kheis Municipality in the Northern Cape province of SA serves as a small-scale hydropower system with a set of 2 parallel axial HK turbine sets (of 2 adjacent turbines) in series. The system is installed within the Boegoeberg Irrigation Canal system (172 km's of concrete lined canal) which was constructed in 1929 and extended in the 1970's. The canal (Figure 13) supplies 306 irrigation farmers north of the Orange river [98]. An added advantage to installation within the canal scheme is the lack of fish habitat or environmental species destruction due to the grid inlet to the canal scheme ensuring only allocated water is conveyed through the scheme to supply downstream flood irrigation.



Canal width (m)	4.8
Canal wall height (m)	1.7
Water level (m)	1.5
Slope (m/m)	0.0021

Figure 13. Typical canal section

6.2 Hydraulic analysis

The Boegoeberg dam discharges around 12 m^3/s (as indicated by an on-site gauging station) into the Boegoeberg canal at the inlet and the installation site lies approximately 60 km downstream of the inlet. The typical flow rate pattern in the canal installation section is illustrated in Figure 14, this was measured by a coupled doppler velocity meter and surface ultra-sonic level sensor installed and calibrated on site 3 months prior to installation. The corresponding average flowrate for operational days for the period depicted in Figure 14 was 6.6 m^3/s and the maximum flowrate was 8.06 m^3/s.

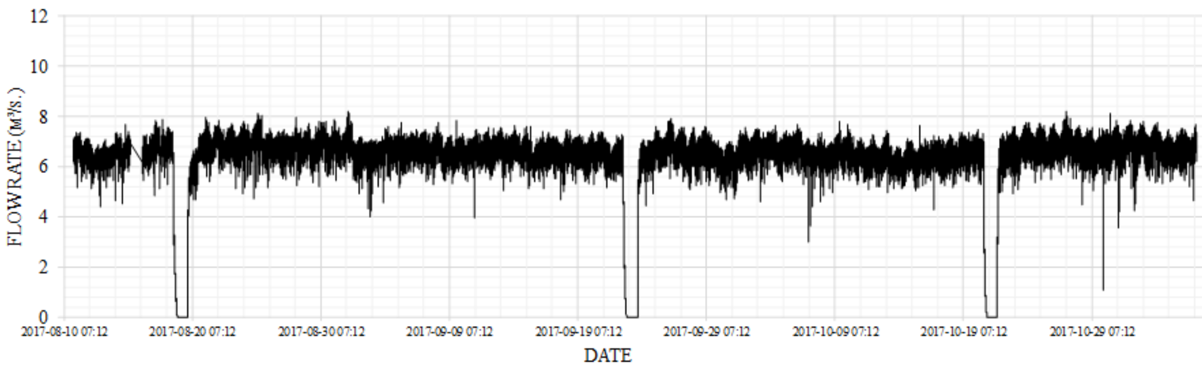


Figure 14. Flow data (representative flow data sample)

Based on historical flow data the canal is shut off for a series of short periods throughout the year for insect control and canal maintenance purposes. The flow records provided details of the number of active days, indicating the canal is operational an average of 89% of the year. Velocity mapping results indicated an average velocity of around 1.1 m/s over the cross section, with a slightly decreased velocity around the walls.

6.3 Turbine selection

The focus of the study was to develop a system generating electricity to aid the Local Municipality and evaluate the development process. The section selected for installation falls within the “robust canal section” criteria (Figure 12). At the installation point the canal has a width of 4.8 m with a uniform flow depth of 1.5 m. The installation point and upstream section have a freeboard of around 200 mm (allowing for some damming flexibility).

Initially comparison of axial and cross flow technologies indicated axial flow turbines generally have a lower minimum operating current velocity and better power coefficient [16]. At the time of installation (January 2017) the range of turbines available in SA for the size and type of installation was limited. Initially a ducted 5 kW floating axial flow turbine was considered, however due to the canal characteristics (rectangular, concrete lined) at the installation point and considerable floating debris, a bed-placed “Smart Freestream” axial flow turbine developed by Smart Hydropower GmbH, specifically designed for canal applications, was selected and imported for installation (Figure 15).

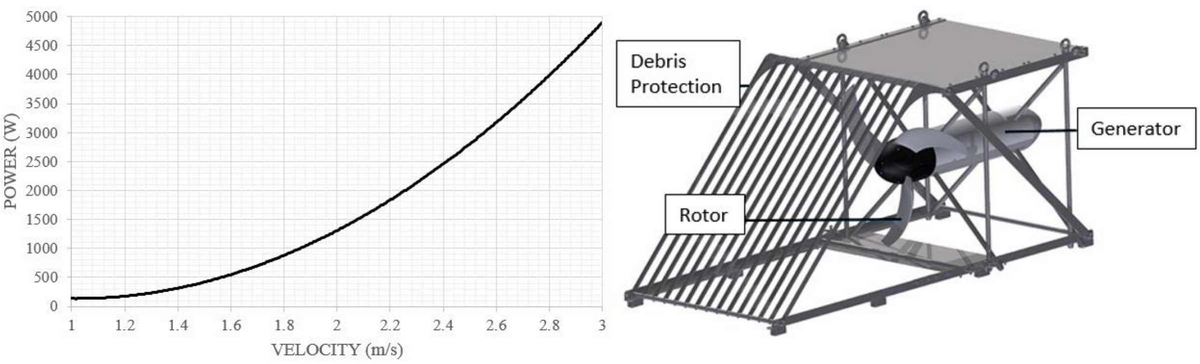


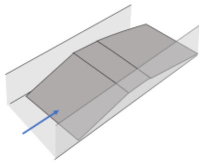
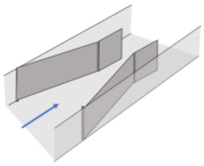
Figure 15. Smart Freestream HK turbine and performance curve [30] (Used with the permission of Smart Hydropower)

The turbine width and rigidity allowed for a system of 2 co-rotating 1 m diameter turbines to be joined and placed in an array (2 systems of 2 turbines) with additional enhancement techniques implemented where necessary. The 1 m rotor diameter turbine is confined in a frame which has a footprint of approximately 1.7 m length and 1.1 m width. The specific turbine selected was equipped with debris protection which is required as the canal is prone to falling debris (floating trees/branches etc.) Additionally, the bed-placed turbine spanning to a height of 1.12 m with hub height of 0.6 m (thus allowing 380 mm of free flow above the turbine and 100 mm distance available from blade tip to the canal bed) allows floating debris to pass over the turbine. The underwater generator and total submergence of the unit was also an advantage in theft/vandalism prevention (which is a major problem in the area of installation). The distances between turbine sets was numerically modelled and tested on site. Results indicated a 40 m distance would allowed sufficient flow recovery and the upstream damming would fall within the freeboard available during blocked conditions, with no excessive added transmission costs.

6.4 Optimization measure

Due to the low canal stream velocity (of around 1.1 m/s) at the point of installation, flow enhancement techniques were considered. The optimization measure found to be most applicable to the section (wide canal; very low flow; robust section) was the channel augmentation technique. For practical purposes and ease of operation the option of narrowing the canal sides was selected for final installation (Table 7).

Table 7. Augmentation options

Augmentation forms	Picture	Design theory
Lifting canal bed		The flow exhibits a subcritical regime therefore this theory applies where the bed level is raised causing the venturi phenomenon.
Narrowing canal sides		By narrowing the canal sides the flow area is reduced over a short distance thus increasing the flow velocity.

The following factors concerning the design and functioning of the system with the added augmentation was considered:

i. Adding a canal narrowing effect could result in blockage from large debris which would otherwise pass the large width sections.
ii. It must be ensured the reduced water level still allows for turbine submergence (reduced level in throat section).
iii. The foundations and fastening cables were initially designed to function under extra load for testing purposes and therefore was assumed sufficient for this testing phase.
iv. Due to the flat slope of the canal at critical sections upstream where little freeboard exists the backwater effect could result in overtopping, the maximum narrowed width was selected accordingly.
v. The balance between water level drop (throat section) and upstream damming levels relative to the increased velocity had to be investigated to ensure an optimal narrowed section.

The final selection of the narrowing width and length of the side plates were based on numerical modelling using HEC-RAS (although the design allowed for in field varying of the narrowed width). This optimal design (when considering damming/blockage possibilities) was found to be a narrowed width of around 2.5 m with the standard convergence angle of a venturi (21°) [99]. During testing the canal was narrowed by approximately 2 m (Figure 16) which increased the stream velocity to an average of 2.1 m/s within the throat section (output of around 2.2 kW per turbine). In the final design, the canal is narrowed by 2.4 m thus increasing the velocity to 2.8 m/s (output of around 3.9 kW per turbine). Due to the canal properties (concrete lining) no scour/corrosive effects were experienced. The 160 km canal system was numerically modelled and proved the added narrowing did not result in reduced downstream water supply.

Figure 16. Narrowed canal width with installed turbine

Analysis of the operation of the system proved that a manageable damming effect upstream (by both numerical analysis and field tests) was obtained. The maximum damming occurred just upstream of the installation and falls within the freeboard available (even during full turbine blockage). The narrowing of the canal by means of guide plates, placed at 21 degrees to the horizontal (typical venturi angle) proved to increase the power output significantly.

The installation confirmed to have no significant negative influence on the environment due to the nature of the installation and the production of "clean" renewable energy rather than use of the largely fossil-fuel driven current electricity supply far outweighs any minor environmental impacts which may have been missed.

6.5 Operation

The system of turbines were installed for a 6-month period (without the narrowing) and subject to close monitoring of debris build up, possible fluctuations in power output and occurrence of unforeseen problems. Data recording devices were linked to installed ultrasonic level sensors (placed at the points of installation) and the control system (linked to the inverters) allowing remote analysis of system functioning. Complications encountered included:

- Seasonal changes in debris build-up, especially during late summer where debris build up was significantly higher. The most significant grid debris build up was experienced on the day of canal shut-off (slow flow conditions) which was then marked on cleaning schedules thus not affecting turbine operation after shut-off periods.
- Monthly turbine "lifting" and cleaning was undertaken at planned and unplanned intervals (during observed raises in water levels.
- Unexpected blockages were experienced from floating objects and in 1 case floating deceased livestock. However, the anchoring cables were the cause of large object blockage, as the turbine grid provided protection from the blades. The final design was adjusted accordingly.

These scenarios were recorded and a maintenance manual is being developed accordingly, the final maintenance schedule will be determined after a 1-year operating period (with the narrowed section) where collected changes in power output and water-level data are balanced with the cost of maintenance to develop a sustainable low-cost operational schedule.

6.6 Final design

The final design of the system included a rigid bridge structure assembled above the installation point and will be implemented after the testing period. This design allows for the efficient removal of the turbines (by the use of a hoist) during impromptu blockages or planned maintenance. The steel plates (used to narrow the canal section) are held in place by a collapsible steel frame. The final design drawings can be seen in Figure 17 and will be constructed after the 1-year operation period. The final design results in an output of 3.9 kW per turbine and thus a total system production of around 15.6 kW 89 % of the year.

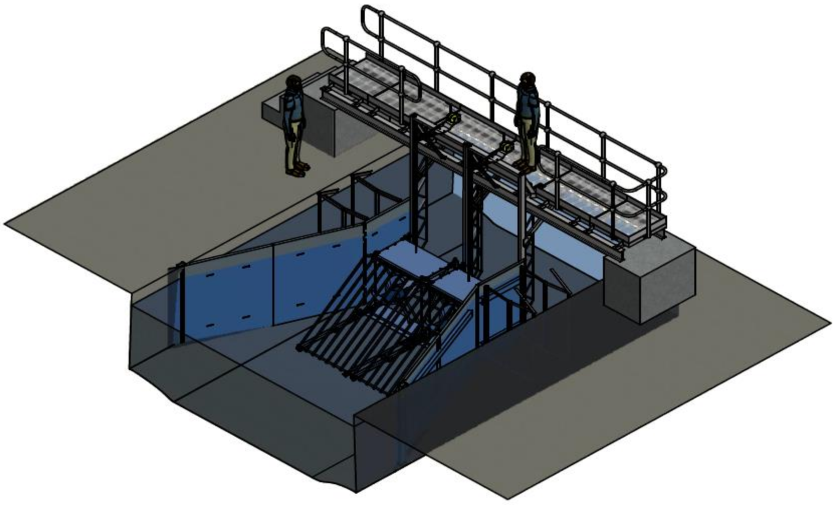


Figure 17. Final system design (1 of 2 identical systems)

6.7 Economic analysis

At the time of project implementation, the municipal electricity rate was an average of R1.26/kWh (converting to USD0.086/kWh). This low rate relates to a relatively long payback period; however, electricity costs have escalated significantly in the last 8 years and if this trend is continued the payback period could reduce significantly. The details of the investment costs which were found to be around R273 000 per turbine (including construction, labour, electrical equipment, mechanical equipment, channel augmentation and control costs) as well as estimated maintenance costs and annual income can be seen in Table 8 (with the South African Rand being equivalent to 0.068 USD). This relates to a payback period of around 6.5 years and included a 6% annual interest on investment, fixed approved energy escalation of 15%/annum for years 2019-2021 and thereafter a predicted 8 %/annum.

Table 8. Economic analysis for Groblershoop HK plant (South African Rands)

Total investment cost (4 turbine array)	R 1 093 000
Annual income (present value)	R 157 300
Annual expenses (present value)	R 12 000
Approximate payback period	6.5 years

In determining the economic feasibility of the installations, a multitude of factors should be considered. The specific installation was the first of its kind in SA and therefore incurred many unexpected costs which could have been avoided with greater freedom in site selection which resulted in incurred augmentation costs, security measure costs and due to lack of availability of these turbines in South Africa, limitations in turbine selection. It is also a well-known assumption that smaller-scale installations have a higher cost per unit of power delivered, therefore larger installations have shorter payback periods (as in [9] [100]). Also, as this project was completed through special authorizations from the SA government many legislative and regulatory approval costs which would be a major cost component in commercial projects were not incurred/included.

In SA the rising municipal cost of electricity is resulting in renewable energies sources becoming more attractive and therefore investments into these applications are increasing exponentially. When energy escalation is assumed to increase at the same rate experience during the 2014-2018 period, the HK project payback period reduces to 5.7 years, which is comparable with conventional small scale hydropower plants [9] [101].

For comparative purposes a LCOE was calculated based on predicted development, design, insurance, regulatory and environmental legislative costs in SA for a similar commercially developed HK plant with a predicted operational life of 15 years. This amounted to USD0.068/kWh which is similar to the RM2 river current turbine LCOE (USD0.08/kWh) [102]. However, it must be noted costs incurred through unpredictable changes in legislation or incorrect operational life predication (through lack of available data) could alter this value significantly.

The implementation of small-hydropower systems has been recommended by many international organisations such as the World Bank and United Nations Industrial Development, with proof of the start-up costs of small hydropower systems being almost half that of wind and solar where potential is available [61]. In a report on the assessment of HK turbines in open channel applications prepared by the United States Department of Energy it states "*Hydrokinetic energy from flowing water in open channels has the potential to support local electricity needs with lower regulatory or capital investment rather than impounding water with more conventional means.*" [13].

7 Discussion and lessons learnt

While resource assessments are essential first steps in developing this resource, more is needed to support and catalyse hydrokinetic (HK) development globally. Hydroelectric projects within conveyance infrastructure can require two- to three-year development periods, and require in-depth knowledge of regulatory, environmental, technical, and financial attributes of the small hydropower market and project development cycles that many agencies (e.g., water agencies, public water utilities, and irrigation districts) do not have.

There are limited HK turbines readily available on the market, this could be linked to the lack of knowledge in the field and therefore lack of a consistent demand in the market. Additionally, most turbines available perform at a specific operational range that is not always readily available. Canal systems hold a great potential for this technology, specifically in South Africa where the 6500 km's of canal systems hold unexploited potential. Some of the important factors to consider when installing a small-scale HK scheme is first and foremost careful site selection, thereafter evaluating reliability of flow, identifying nearby utilization of the electricity generated and the influence of the installation/enhancement on the primary function of the infrastructure. Careful selection of an optimal installation site remains a critical challenge within HK technology implementation, however this is not always possible as transmission costs are high [103] and optimal sites do not always lie in close proximity to where the power is needed. Due to this reason optimization and enhancement techniques should be considered during the design, installation and operation phases (where possible).

Barriers to HK development include: 1) Lack of awareness of resource potential; 2) Poor data coverage and varying data quality on conduit infrastructure and hydraulics (flow, hydraulic grade line); 3) Lack of knowledge of HK technologies and development process among stakeholders, including federal and state agencies, water industry associations, and water infrastructure operators (e.g., water agencies, public water utilities, and irrigation districts); as well as 4) Limited resources (staff, time and budget) to learn about HK energy and to implement a robust development process.

8 Conclusion

Several efforts are critically needed to support and catalyse HK project development globally: First and foremost, resource assessments are needed to identify project sites and to estimate the potential installed capacity by region and by nation. HK projects require in-depth knowledge of regulatory, environmental, technical, and financial attributes of the small hydropower market and project development cycles. International standards for HK assessment methodologies, including minimum site hydraulic requirements should be developed to ensure consistent and accurate assessments. Additionally, improvements in data coverage and data quality on water conveyance infrastructure and hydraulics (flow, hydraulic grade line) are needed.

Knowledge of HK technologies, e.g., HK turbines, and the development process among stakeholders, including federal and state agencies, water industry associations, and water-infrastructure operators (e.g., water agencies, public water utilities, and irrigation districts) is needed. State and local programs and funding are needed to educate and assist conduit operators implement the project development process.

With traditional hydropower development at a near standstill compared to other renewables; e.g. solar and wind, due to the high cost of impoundment and environmental permitting, HK hydropower, which leverages existing infrastructure and has relatively benign environmental impacts, offers one of the most significant opportunities to expand hydropower's contribution to the global renewable energy portfolios. Where potential is available this alternative power source could aid in overcoming the lack of power supply to disconnected areas and reduce financial burdens (in terms of electricity costs). Installation of these units not only supports sustainable development but promotes innovative research which is an important step in forming a stronger self-sustaining economy.

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