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A feasibility study of small hydro power for selected locations in Egypt

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ABSTRACT

One of the biggest challenges facing the world today is to provide access to a safe and affordable electricity supply. Depending on the river flow, small-hydropower is often a cost-effective source of renewable energy. Egypt is home to part of Africa's longest river and it is a relatively reliable source. Many small hydropower plants can be installed in run-of-river schemes or implemented in existing river infrastructure. We argue that it is essential for the Egyptian government to make use of hydropower resources, not only to meet the increasing demand but also to reduce fossil fuel use, and associated environmental pollution. This paper investigates the small hydro energy potential at selected locations in Nile Delta-Egypt and presents a feasibility study of small hydropower for these locations. The head and water flow rates for the past five years are used to find out the hydro energy potential. The annual energy of three different small hydro turbines is calculated for eight selected regions in Nile Delta-Egypt. The analysis includes a comparison between energy outputs from the three hydro turbines types. Furthermore, a MATLAB program is built to compute the efficiency of the studied turbines in each site at different heads and water flow rates. It is found that the use of Crossflow and Kaplan turbines with different sizes can enhance electric energy production at the selected sites.

1. Introduction

Nowadays, the high emissions of greenhouse gases have prompted severe changes in the atmosphere. So, it is important to move toward the use of sustainable energy resources. These resources include, for example, solar power, wind power, and hydropower. The hydropower systems use kinetic energy in running water to generate electrical or mechanical energy. The water runs through the hydro-turbine and goes back to the river to use it for other purposes. Hydropower as a renewable energy resource has many benefits including low operating and maintenance costs, no pollution nor greenhouse gas emissions, high efficiency (about 60–80%) and long-life equipment [1,2]. On the other hand, there are some drawbacks of hydropower systems such as the variation of water flow rates throughout the year, the impact of climatic changes on water availability, higher initial investment and long construction period, and lack of ability to construct them near the loads' centers in most cases.

According to the plant installed power, hydropower plant systems are classified as large-scale hydropower plants: over 100 MW capacity, medium scale hydro plants: 10–100 MW, small hydro plants less than10 MW, Mini hydro plants: 1000 - 100 kW, Micro-hydro plants: 5–100 kW and Pico hydro plants: less than 5 kW [3,4].

Small hydropower is considered as the best appropriate method of generating renewable energy. It is designed to be a run-of-river type as it requires low head and flow to drive the hydro-turbine. Many papers have investigated the utilization and assessment of low head hydropower energy [5–10]. Ref. [5] presented a numerical method to achieve the optimal size of a Small-Scale Hydro Power (SSHP) plant composed of two units, with different sizes and types, operating in parallel. Ref. [6] developed an excel software program to compute the annual energy and to propose economic indices for a small-hydro power plant by applying a sensitivity analysis method. Refs. [7–10] evaluated the SSHP development in some countries such as (Nigeria, Turkey, and India) with respect to the government policy and economic aspects.

Other papers investigated the performance and operation of small hydro plants [11–16]. Ref. [11] presented a probabilistic approach for the generation reliability evaluation of the municipal waste water-based micro-hydro power plant. Optimal location of a hydropower plant using the mixed-integer nonlinear programming method was presented in Ref. [12]. Thirteen hydro-turbine system architectures were examined to select the most appropriate turbine architecture for a low-head small-scale hydro specification in Ref. [13]. Ref. [14] analyzed the significant factors affecting the performance and operation of the hydropower turbines. The analysis covered their various categories,

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performance, operation, and cost. Ref. [15] investigated the impact of irrigation projects on the feasibility study for installing SSHP plant in India. Ref. [16] analyzed the technical and economic feasibility of an SSHP plant for domestic use in Italy. Different solutions and combinations of pipes, turbine, and storage tanks were analyzed in order to identify the most convenient solution.

Many researchers developed different methods to determine the correlations for the cost of different components of SSHP plants [17–20]. Ref. [17] developed the correlations for the cost of the SSHP components based on the actual quantities of various items having general rates. The authors determined the SSHP plant cost as a function of cost-sensitive parameters for different types of generators and turbines. Ref. [18] investigated a series of equations to determine the electro-mechanical equipment costs from the basic parameters such as net head and power. The equations were depended upon the type of hydro turbines, i.e. Kaplan, semi Kaplan, Pelton, and Francis turbines. Other correlations of cost were developed in Ref. [19] based on the water head, installed capacity, and ratings such as rated kVA and Power Factor (PF) as cost-influencing parameters. Ref. [20] developed a correlation to determine the cost of the equipment and proved that the cost of the electro-mechanical equipment was decreased with the increase in the water head.

Many different methods were used to analyze the cost of SSHP plants [21–25]. Ref. [21] presented a methodology to evaluate the technical and economic potential of SSHP plant with a rated capacity of less than 10 MW. Ref. [22] proposed a method to find the most economical choice for installing SSHP plants. The method was based on the use of economic profitability indices, such as the Net Present Value (NPV). Ref. [23] presented a techno-economic analysis of few decentralized SSHP projects in remote locations in India. The capital cost of the SSHP projects was determined for a capacity range between 10 and 100 kW. In Ref. [24] a small hydropower plant in Spain was studied from an energetic and economic perspective and RETScreen package (a freeware software) was used to examine the viability of the facility. A techno-economic comparative study of low head hydropower between the penstock and non-penstock systems was discussed in Ref. [25].

Egypt is a well-electrified country, with 99% of households connected to the electricity system. Egyptian electricity demand has grown significantly in recent years due to the country's socio-economic development. Electricity in Egypt is generated mainly from thermal electric power plants. Fossil fuel is the cornerstone of the electric production system. Burning these fuels results in the production of carbon dioxide (CO_2) -the primary heat-trapping, “greenhouse gas” responsible for global warming. Applying renewable energy alternatives can potentially reduce CO_2 emissions. One of these alternatives is small hydropower technology. Egypt has a long river which is a very good hydraulic energy source. Many small-hydro power plants can be installed in run-of-river schemes or implemented in existing river infrastructure. Egypt has to make use of its hydropower resources, not only to meet increasing demand but also for reducing the fossil fuels environmental pollution.

This paper presents an analyzing study to assess the small-hydro energy potentiality for selected locations in Delta-Egypt. The study is based on a real date five years ago. The analysis examines different types of small-hydro turbines and different types of generators for eight sites in Delta Egypt. According to the head and water flow rate of the sites, the most efficient configuration for each location is recommended.

The rest of the paper is organized as follows: section 2 discusses the criteria required for selecting the turbine type, section 3 presents a comparison between different generator types that can be used with small-hydro turbines, section 4 presents the mathematical equations used to compute the hydro turbine output power and energy, section 5 presents an economic analysis for the SSHP plants, section 6 describes the selected sites, section 7 discusses the procedure used for evaluating small-hydro energy in Egypt and section 8 presents the simulation and results. Finally, section 9 concludes the paper.

2. Criteria for selecting the appropriate small-hydro turbine

Selecting the appropriate type of the hydro turbine for a particular situation often depends mainly on the amount of the available head and water flow rate in the location. Specific speed of a turbine is one of the important indices for designing the hydro turbines. This section discusses the important issues required for the selection of a hydro turbine, the essential equations required to compute the specific speed and the dimensions of different water turbine types.

2.1. Hydropower turbines types

The selection of the most suitable turbine type depends upon both the flow rate and the water head at the selected site [26]. Hydropower turbines are mainly categorized as impulse and reaction types. In impulse turbines, the water pressure is turned into kinetic energy before entering the runner, but in reaction turbines, the water pressure applies a force on the face of the runner blades. Impulse turbines have a better performance in high and medium heads, while, the reaction turbines are better in the low head and high flow rate sites [27]. There are various types of impulse turbines including Pelton, Turgo and Cross-flow turbines. Whereas, the reaction turbines types include Francis, Propeller and Kaplan turbines. Table 1 shows the operating head classification of each hydro-turbine type. Fig. 1 explains the different types of hydro-turbines [28], whereas Fig. 2 shows the operating range of different hydro-turbines for a given head and flow [14].

According to Fig. 2, the range of SSHP is less than 10 MW size and less than 10 m height. So, the turbines which can be used in this rang are Cross-flow, Francis and Kaplan. In the following subsections, the three types will be defined and their specific speed and dimensions will be illustrated in details.

2.1.1. Cross-flow turbines

The cross-flow turbine can be used for a wider scale of water heads (between 0.5 and 200 m). Water enters the turbine directed by one or more guide-vanes located upstream of the runner and crosses it two times before leaving the turbine [29]. However, Kaplan and Francis's turbines have higher peak efficiency than the cross-flow turbine.

The main advantages of the cross-flow turbine include its low price, good regulation, and easy maintenance due to its simple construction. There is another advantage that it has a flat efficiency curve which leads to a better performance than the two other turbine types. Due to its better performance, even at partial loads, the cross-flow turbine is well-suited to stand-alone electricity generation. It is mainly used in small-hydro power units for small run-of-the-river schemes, as the flow rate in small rivers which varies seasonally [30].

2.1.2. Francis turbines

This turbine is called ‘mixed flow turbine’, as the water enters through the outer periphery of the runner in the radial direction and

Table 1
Operating head classification of different hydro-turbines.

Turbine Type	Head Classification		
	High (> 50 m)	Medium (10–50 m)	Low (< 10 m)
Impulse	- Pelton - Turgo - Multi-jet - Pelton	- Cross-flow - Turgo - Multi-jet Pelton	- Cross-flow
Reaction		- Francis (spiral case)	- Francis (open flume) - Propeller - Kaplan

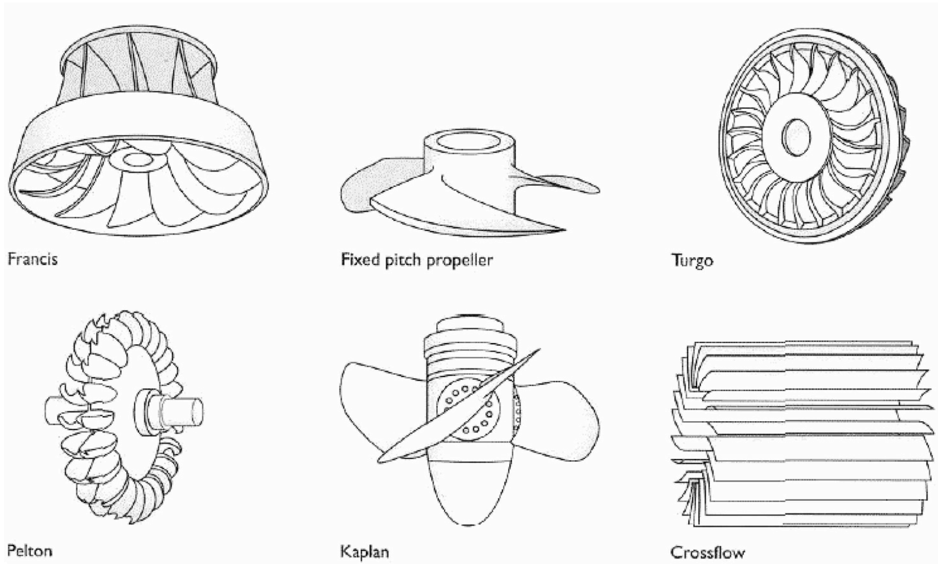

Fig. 1. Different types of water turbines.

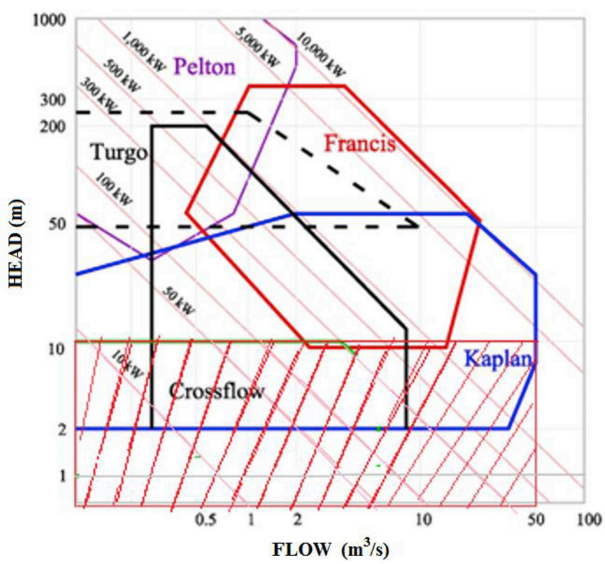

Fig. 2. Hydro-turbines characteristics in terms of water head and flow rate.

leaves it in the axial direction [31]. Francis turbine has mainly two types: open flume and closed types. In open flume type, the turbine is immersed under water of the headrace in a concrete chamber and discharge into the tailrace through the draft tube. The disadvantage of this type is that the runner and the guide-vane mechanism are under the water and they are not open either for inspection or repair without draining the chamber [32]. In the closed type, the water is led to the turbine through the penstock whose end is connected to the spiral casing of the turbine. The open flume type is used for the sites of 10 m water head whereas; closed type is preferred for sites with water head above 30 m.

2.1.3. Kaplan turbines

This turbine is an axial-flow type, the inlet guide-vanes can control the amount of flow passing through the turbine be opening or closing it. When it is fully closed, the water will stop completely and bring the turbine to rest [29,31]. Kaplan turbines can be used across a wide range of water flow rates and heads, but it is preferred in low head sites with high flow rates, as it is more effective in lower heads than other turbine types, other turbines are more effective on higher heads. Typically, it can be used on sites with rang of net heads from 1.5 to 20 m and peak flow rates from 3 m^3/s to 30 m^3/s. For these ranges, the power output is ranging from 75 kW up to 1 MW. The main disadvantage of Kaplan turbines is that they are expensive.

There are three types of Kaplan turbines; vertical axis, horizontal axis (also called S-turbines) and bulb turbines. Vertical-axis turbines are preferred in sites with a small footprint, whereas horizontal axis or 'S-turbines' are suitable for a larger system footprint. Vertical turbines are designed for the water-energy utilization at relatively low heads. These turbines are usually provided with a gear drive connecting them to the generator. Bulb Kaplan turbines are located within the main flow. The horizontal axis and bulb turbines are technically slightly more efficient than vertical axis because the inlet flow does not have to change direction which leads to a decrease in the hydraulic losses. The application heads range from 1.5 m to 25 m with an output up to 50 MW [33]. In reality, the differences between the three types are not significant, so the decision of turbine choice is depending on suppliers and prices.

2.2. Specific speed of turbines

Specific speed is the main numerical classification of a hydro turbine. This number characterizes the speed of the turbine at its maximum efficiency with respect to its flow rate and power. Specific speed can be determined independently of turbine size. Given the fluid flow conditions and the desired shaft output speed, the specific speed can be calculated and consequently the appropriate turbine design is selected. Hence, the specific speed is used to reliably scale an existing design to a new size with the corresponding performance.

Mathematically, the specific speed can be calculated as a function of maximum power and net head (expressed as N_s) or as a function of the flow rate discharge and net head (expressed as n_q) [29,34]. For the first case, the specific speed N_s is the turbine rotation speed (r.p.m) working under a fall of 1 m and delivering a power of 1 kW as given by (1).

$$N_s = \frac{N * \sqrt{Pt}}{H_n^{5/4}} \tag{1}$$

Where N: turbine speed in (r.p.m).

H_n: net water head in (meter).
P_t: turbine output power in (kW).

For the second case, the specific speed n_q is the turbine rotation speed (r.p.m) working under a fall of 1 m and a flow of 1 m^3/s as given by (2).

$$n_q = \frac{N^* \sqrt{Q}}{H_n^{3/4}} \tag{2}$$

Where Q: water discharge (m^3/s)

The relationship between N_s and n_q is expressed as:

$$N_s \approx 3 * n_q \tag{3}$$

2.3. Hydropower turbines dimensions

Once the turbine type, specific speed, and net head are known, the fundamental dimensions of the turbine can be assessed. Each type has its own shape and construction as explained before in Fig. 1. So, there will be different dimensionality equations according to the turbine shape and operation [29,35].

2.3.1. Cross-flow turbines

The main dimensions of this type are the runner diameter, runner length, and the jet thickness or nozzle width. They can be formulated as functions of the net head, water flow, and rated turbine speed.

$$D_r = \frac{40^* \sqrt{Hn}}{\mathrm{N}} \tag{4}$$

$$L_r = \frac{0.81^* \mathrm{Q}}{Dr^* \sqrt{Hn}} \tag{5}$$

$$t_j = \frac{0.233^* \mathrm{Q}}{Lr^* \sqrt{Hn}} \tag{6}$$

Where:

D_r : runner diameter in meters
L_r : runner length in meters
t_j: jet thickness or nozzle width in meters

2.3.2. Francis turbines

In this type, the main dimensions are the outlet and inlet diameters. They are formulated as functions of the net head, rated turbine speed, and specific speed.

$$D_3 = 84.5\left(0.31 + 2.488\frac{Ns}{995}\right) * \frac{\sqrt{Hn}}{N} \tag{7}$$

$$D_1 = \left(0.4 + \frac{94.5}{Ns}\right) * D3 \tag{8}$$

$$D_2 = \frac{D3}{0.96 + 3.8 * 10^{-4} * Ns} \tag{9}$$

Where:

D_3 : outlet diameter in meters
D_1 : inlet diameter in meters.
D_2 : inlet diameter in meters for $Ns > 163$,
If $Ns < 163$ then $D_1 = D_2$

This type covers a wide range of specific speeds, going from 30 to 400 corresponding to the high and low heads.

2.3.3. Kaplan turbines

The outer and inner diameters of the runners represent the main dimensions of this type. They are formulated as functions of the net head, rated turbine speed, and specific speed.

$$De = 84.5(0.79 + 1.60 * 10^{-3}\, Ns) * \frac{\sqrt{Hn}}{N} \tag{10}$$

$$Di = \left(0.25 + \frac{94.5}{Ns}\right) * De \tag{11}$$

Where:

De : outer diameter of the runner in meters
Di : The hub (inlet) diameter of the runner in meters

Generally, the Kaplan turbines exhibit much higher specific speeds than Francis types.

2.4. Efficiency of hydro-turbines

The available water head and flow conditions are the criteria for selecting the appropriate turbine's type. The related efficiency curves of the turbine depend on the rated head, runner diameter, turbine specific speed, and the turbine manufacturer/design coefficient. The efficiency equations for different turbine types can be deduced from a large number of manufacture efficiency curves for different water heads and flow conditions [36]. The calculation of hydro turbines efficiency differs according to the turbine's configuration. These equations depend on many factors such as the specific speed, runner size, rate of discharge … etc. Following are the efficiency equations for the three turbine types.

2.4.1. Cross-flow turbines

The turbine efficiency, η_q, can be computed using the following equation:

$$\eta_q = 0.79 - 0.15\left(\frac{Q_p - Q}{Q_p}\right) - 1.37\left(\frac{Q_p - Q}{Q_p}\right)^{14} \tag{12}$$

Where Q_p is the peak efficiency flow which can be computed as $Q_p = Q_d$, and.Q_d is the design flow (flow at the rated head and full gate opening in m^3/s).

2.4.2. Francis turbines

A significant factor for comparing different turbine types is their relative efficiencies at both design point (peak efficiency, $\hat{\eta}_p$) and reduced flows, η_q. The peak efficiency can be computed using (13):

$$\hat{\eta}_p = (0.919 - \hat{\eta}_{nq} + \hat{\eta}_d) - 0.0305 + 0.005R_m \tag{13}$$

$$\hat{\eta}_{nq} = ((n_q - 56)/256)^2 \tag{14}$$

$$\hat{\eta}_d = (0.081 + \hat{\eta}_{nq})(1 - 0.789d^{-0.2}) \tag{15}$$

Where $\hat{\eta}_{nq}$: specific speed adjusted to peak efficiency;

$\hat{\eta}_d$: runner size adjusted to peak efficiency;
D: runner size of Francis turbine in meter.
R_m: turbine manufacture/design coefficient (2.8–6.1; default = 4.5), refer to online manual [36].

The efficiency at reduced flow can be computed as:

$$\eta_q = \left\{1 - \left[1.25\left(\frac{Qp - Q}{Qp}\right)^{(3.94-0.0195nq)}\right]\right\}\hat{\eta}_p \tag{16}$$

Where.

Q_p: peak efficiency flow which can be computed as $Q_p = 0.65\, Q_d {n_q}^{0.05}$
Q_d: the design flow (flow at the rated head and full gate opening in m^3/s)

2.4.3. Kaplan turbines

The peak turbine efficiency can be computed as:

$$\hat{\eta}_p = (0.905 - \hat{\eta}_{nq} + \hat{\eta}_d) - 0.0305 + 0.005R_m \quad (17)$$

$$\hat{\eta}_{nq} = ((n_q - 170)/700)^2 \quad (18)$$

$$\hat{\eta}_d = (0.095 + \hat{\eta}_{nq})(1 - 0.789d^{-0.2}) \quad (19)$$

Where:

$\hat{\eta}_{nq}$: Specific speed adjusted to peak efficiency;
$\hat{\eta}_d$: runner size adjusted to peak efficiency;
d: the runner size of Kaplan turbine

The efficiency at reduced flow can be computed using the following equation:

$$\eta_q = \left\{\left[1 - 3.5\left(\frac{Q_p - Q}{Q_p}\right)^6\right]\right\}\eta_p \quad (20)$$

Where Q_p: peak efficiency flow which can be computed as. $Q_p = 0.75\ Q_d$

3. Selection of generator

Selection of a suitable generator is the next step after selecting the turbine type and size. Both synchronous and asynchronous generators can be used for small scale-hydro applications. Generator selection depends on a number of factors including the generators cost, available power and the type of electrical output (i.e. AC/DC, frequency, and voltage). Generally, hydropower generators are rated on a continuous-duty basis under specified service conditions to deliver net kVA output at rated speed, frequency, voltage, and power factor. Following is a brief description of the three available generator types.

3.1. Types of generators

3.1.1. Synchronous generator

Synchronous generators (SG) are usually equipped with a DC electric or permanent magnet excitation system (rotating or static) associated with a voltage regulator to control the output voltage before the generator is connected to the grid. They can supply the reactive energy required by the power system. The main advantages of SGs are that they can operate on both grid-connected and isolated modes and they can provide any amount of reactive power. But most grid-connected small hydro schemes are hardly operated in isolated mode [37]. SGs are preferred for large hydropower stations, where the water flow via the dam is nearly constant, but they are not preferred in small hydropower, as they are more expensive and have larger sizes than Induction Generators (IGs) and Permanent Magnet Synchronous Generators (PMSGs) [29].

3.1.2. Induction Generators

In IGs, there is no possibility of voltage regulation as they are running at a speed directly related to the system frequency. They draw their excitation current from the grid and absorb reactive energy by their own magnetism. So, they cannot operate in an isolated mode as they are incapable of providing their own excitation current [29,37]. IG construction is simpler, lighter and cheaper than SG and they do not require synchronization or voltage control. But the IG operates at a lagging power factor because the machine is magnetized from the stator. This means that less power is available with a given current compared to the PMSGs.

3.1.3. Permanent Magnet Synchronous Generators

In a PMSG, the magnetic field of the rotor is produced by the permanent magnets. There is no need for the excitation circuit. The main advantages of PMSGs include their high efficiency and energy, no additional power supply is required for the excitation, and they have high reliability due to the absence of the mechanical components such as slip rings. They are lighter and therefore they possess the higher power to weight ratio compared to other generator types. Due to these advantages, the PMSGs are becoming an interesting solution for small hydropower turbine applications [38,39].

3.2. Voltage and frequency control

In SSHP system, when the system operates in on-grid mode, both the active and reactive power are controlled by the grid, but when it is operated in off-grid mode, the generator terminals frequency and voltage must be kept constant during the speed fluctuations. Thus, various control methods are required for maintaining both the frequency and voltage within their limits [40,41]. The voltage value can be maintained at its acceptable limits by changing the excitation of the generator. Whereas, the frequency can be controlled by matching the power generation to the load through the governor control [42].

3.2.1. Control methods of SG

The SGs can operate in isolated mode and they are appropriate for small hydro-power plants. The voltage is controlled by controlling the excitation of the SG [47]. The excitation system consists of protective elements, controllers, and regulators to control the field current. By using an SCR based excitation system, the output voltage can be regulated statically. Moreover, the closed-loop control system of excitation can regulate the voltage magnitude to be within acceptable limits even in the disturbance periods [40,41]. The acceptable limits are typically within ± 10% [46].

The governor is used to regulate the voltage and the speed of the generator. For islanding operation, the governor regulates the active power and frequency (P–f) while the exciter is used to regulate the reactive power and voltage (Q–V) [43–45]. Islanding status may cause a variation in the electric load thus results in a frequency deviation according to the generator swing equation [41]. The problem of frequency deviation comes from it can run under/over frequency relays and consequently stop the generator. The speed governor should be able to maintain the frequency within acceptable limits and fulfill the system resynchronization requirements [46]. The generating power can be controlled by changing the feeding water flow according to the load variations while maintains the system frequency at the desired value [47].

The relation between the active power and the speed of the SG can be expressed by the swing equation as:

$$2H\Delta\omega_s = \Delta P_m - \Delta P_e \quad (21)$$

where H is the generator inertia, ΔP_m is the mechanical power changes, ΔP_e is the changes in electrical power changes and $\Delta\omega_s$ is the generator speed changes. From (21), it is obvious that the changes in active power are proportional to the changes in generator speed.

Mechanical power control is achieved by opening or closing the water flow valves. The transfer function of the hydro-turbine model can be formulated as [47]:

$$\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{-T_w s + 1}{0.5\ T_w + 1} \quad (22)$$

where ΔG is the change in gate position and T_w is the water starting time, which represents the period required to accelerate the water from standstill to the initial velocity.

3.2.2. Control methods of IG

There are three types of IGs: Self-Excited Induction Generator (SEIG), Double Fed Induction Generator (DFIG) and Permeant Magnet Induction Generator (PMIG). The IGs have a problem in maintaining both the frequency and voltage within their acceptable limits. They are often installed with capacitors or Automatic Voltage Regulator (AVR) to control the voltage [48]. The SEIGs are found to be most suitable for small hydropower systems. They have many advantages including; reduced size, brushless construction, low maintenance cost, no need for excitation of DC power supply, no synchronizing problem and self-short-circuit protection capability [49].

In the literature, various controllers were applied to control the frequency and voltage in isolated systems [50–66]. A Direct Voltage Control (DVC) technique to control the frequency and voltage of a stand-alone wind-driven SEIG with variable loads was presented in Ref. [50]. The controller was composed of a lead-lag corrector, a Proportional-Integral (PI) controller, and a feed-forward compensator [50]. Authors in Ref. [51] discussed the control of autonomous SEIG over a varying speed of turbines. A static synchronous compensator along with a Variable Frequency Drive (VFD), was proposed for frequency and voltage control for a small-hydro turbine driven SEIG system [52]. A simple technique for controlling the SEIGs operation in isolated small hydropower system was presented in Ref. [53]. The technique combined both traditional and modern approaches applied to SEIG for islanding operation of microgrids. By using that technique there is no need to compensate the inductive loads separately. A Thyristor Switched Capacitor (TSC) and dump load-based controller for controlling the frequency and voltage of standalone SEIG-based hydro system was presented in Ref. [54]. To regulate the voltage of a single-phase SEIG, a static VAR compensator involved a fixed capacitor in parallel with a Thyristor Switched Reactor (TSR) and a TSC was proposed in Ref. [55]. A shunt connected inverter with a battery bank on the DC side was utilized to regulate the voltage magnitude and frequency of a SEIG in Ref. [56]. Authors in Ref. [57] presented a proposed controller for the frequency and voltage of the SEIG supplying static/dynamic. The controller consisted of a three-phase insulated gate bipolar transistor based Current Controlled Voltage Source Inverter (CC−VSI), DC chopper, DC bus capacitor, and AC inductors. A frequency and voltage controller system suitable for the stand-alone SEIG driven with an unregulated turbine was presented in Ref. [58]. The controller consisted of a three-phase four-wire shunt active filter and a controlled dc load. A proposed control system composed of a PWM based VSI was applied to modify the characteristic of an isolated SEIG in a low head, small hydropower plant. The technique was used to improve the compensation of the reactive power, voltage regulation and the frequency stabilization [59]. Ref. [60] presented a voltage source PWM bidirectional converter for voltage and frequency control of a three-phase SEIG driven by a hydraulic turbine.

In small hydropower applications, the frequency and voltage of a single-phase SEIG were maintained by using power switches and PI controller derived by a Pulse-Width Modulation (PWM) controller [61]. A simple technique for frequency and voltage controller for SEIG with variable DC link voltage was proposed in Ref. [62]. A constant voltage constant frequency (CVCF) PWM converter without regulating the DC capacitor voltage was used for that purpose. Another technique considered the Voltage Source Inverter (VSI) with dump load was suggested in Ref. [63]. The VSI utilized a three-phase PWM inverter composed of six transistors. Refs. [64,65] suggested a small hydropower plant equipped with IGBT based two-stage converters to maintain the voltage and frequency to constant values. A proposed computer-controlled excitation system was used to maintain the output voltage of a SEIG by sensing the output voltage. Electronic Load Controller (ELC) used to control the frequency and voltage of the SEIG was presented in Ref. [66]. The ELC was a blend of an uncontrolled rectifier, DC chopper, sifting capacitor, and an arrangement dump load.

3.2.3. Control methods of PMSG

In the islanded mode, the PMSG is controlled by a DC-DC boost converter and a three-phase VSI. The control technique aims to regulate the DC link voltage by controlling the duty cycle of the DC-DC boost converter. A PWM control technique is used to control the three-phase VSI in order to turn the DC-link voltage to the specified voltage and frequency [67].

Additional power electronic interface is required to convert the variable generating frequency and voltage into a constant load frequency and voltage. Ref. [68] used two back-to-back PWM power converters whereas an IGBT-PWM active rectifier was used as a voltage regulator controlled by a current control method in Refs. [69–71]. A Voltage Source Converter (VSC) was applied to control the frequency and voltage of a PMSG. The VSC was composed of Insulated Gate Bipolar Transistors (IGBTs) based three-leg half-bridge module [72].

Two devices are used for AC-DC conversion. The first one is the passive diode rectifier, it can easily convert the AC to DC but cannot control the output voltage. The second device is the active rectifier, which has a switching circuit topology of AC-DC power conversion. The active rectifier is used to convert the variable voltage and frequency to a constant DC voltage. In case of a variable-speed small-hydro power system based PMSG, the power is produced at variable voltage and frequency.

4. Turbines output power and energy

Hydro-electric generation depends on two factors: the quantity and the head of falling water. Regardless of the water path through an open channel or penstock, the power generated in a turbine can be computed by Refs. [29,73]:

$$P_t = \rho * g * H_n * Q * \eta_t \tag{23}$$

Where:

P_t power in Watt generated in the turbine shaft.
ρ water density (1000 kg/m^3).
H_n net head (m).
Q water flow rate (m^3/s).
g gravity acceleration constant (9.8 m/s^2).
η_t turbine efficiency (normally 80–90%).

A turbine converts water pressure energy into mechanical energy at the turbine shaft, which drives a coupled generator to produce electrical energy.

5. Economic analysis

Economic analysis is the process of evaluating the opportunity of a project by comparing benefits with costs. An investment in an SSHP project involves different types of costs and revenues distributed along the time life of the project. The costs include fixed cost (or capital cost) and variable cost. The fixed costs include civil works, power transmission line, electro-mechanical components cost, etc., while the variable costs include depreciation of equipment, operation and maintenance, and replacement costs.

5.1. Economic calculation

The costs of any SSHP project are divided into two categories: capital and variable costs. The income of the project is based only on the sale of electrical energy. The calculations of the fixed and variable costs are illustrated in the following subsections.

5.1.1. Capital costs

The capital costs of SSHP projects can be divided into two main components;

1 Civil works construction of the SSHP plant and any infrastructure development.
2 Electro-mechanical equipment costs.

The Civil works consist of the following subcomponents; diversion weir and intake, the tailrace channel, forebay and spillway, head race channel, penstock, and powerhouse building. In this paper, the selected locations have a water head less than 4 m, so the system should be without penstock. This gives several advantages such as simple civil construction and low installation costs [74].

The cost equations of the civil works are related to the water head, H, and the rated power capacity, P, of the project and can be expressed as:

(i) Cost per kW of diversion weir and intake (US$):

$$C_1 = 186.216\, P^{-0.2368}.\, H^{-.0597} \tag{24}$$

(ii) Cost per kW of powerhouse building (US$):

$$C_2 = 1389.16\, P^{-0.2351}.\, H^{-0.0585} \tag{25}$$

The total civil cost per kW, *Cc* is expressed by,

$$C_c = C_1 + C_2 \tag{26}$$

Electro-mechanical equipment for the SSHP project include the required generators, turbines, transformers, cabling and control systems. These costs tend to vary significantly less than the civil engineering costs, as they are not greatly influenced by the site characteristics. The equations used to calculate the cost of each electro-mechanical component are given as follows as [75];

(i) Cost per kW of turbines (US$):

- For Kaplan turbine:

$$C_K = 39398\, P^{-0.58338}.\, H^{-0.113901} \tag{27}$$

- For Frances turbine:

$$C_F = 30462\, P^{-0.560135}.\, H^{-0.127243} \tag{28}$$

- For the Crossflow turbine:

The cost of the crossflow turbine is equal to half the cost of the Pilton turbine [36]. So, the cost equation of the Crossflow turbine can be calculated as:

$$C_{CF} = 10486.65\, P^{-0.3644725}.\, H^{-0.281735} \tag{29}$$

(ii) Cost per kW of the generator (US$):

$$C_3 = 1179.86\, P^{-0.1855} H^{-0.2083} \tag{30}$$

(iii) Cost per kW of electrical and mechanical auxiliary (US$):

$$C_4 = 612.87\, P^{-0.1892}.\, H^{-0.2118} \tag{31}$$

(iv) Cost per kW of transformer and switchyard equipment (US$):

$$C_5 = 281\, P^{-0.1803}.\, H^{-0.2075} \tag{32}$$

The cost per kW of electromechanical equipment, C_{EM}, is:

$$C_{EM} = (C_K, C_F \text{ or } C_{CF}) + C_3 + C_4 + C_5 \tag{33}$$

The other indirect costs are determined as a percentage of the construction costs which are taken as 13% of the sum of the cost of civil works and electromechanical equipment [76].

The total cost, TC, per kW of SSHP project is obtained as follows:

$$TC = 1.13(Cc + C_{EM}) \tag{34}$$

5.1.2. Variable costs

The annual operations and maintenance costs (O&M) are often determined as a percentage of the investment cost per kW. They include labor, tax, and consumable materials. For large hydropower plants, they are typically on average around 2%–2.5% whereas for SSHP plants this range is between 1% and 6% [77].

5.2. Methods of economic evaluation

The economic investigation and evaluation are considered as one of the main factors of industrial projects. In this study, the evaluation aims to investigate whether the SSHP project is economic or not. The main commonly used methods for economic evaluation include; Net Present Value (NPV) method, Benefit-Cost ratio method, Payback method, Return-On-Investment (ROI) method and Internal Rate of Return (IRR) method [78]. In this study, the NPV method is used to analyze the profitability of investment in an SSHP project. This method is characterized by considering the time value of money and allows investors to compare projects so they can take better decisions. The NPV can be defined as the difference between both revenues and expenses, which discounted with a fixed periodic interest rate. It is computed over the time life period of the project. In SSHP projects, the life period of the project is usually taken as thirty years.

The decrease in the NPV is used as an indicator to classify different projects. The projects with negative NPV will be rejected since this means the discounted benefits during the lifetime period of the project can't cover the initial costs of the project. In comparing a group of projects, the project with the greatest positive NPV is the best one. The NPV value is sensitive to the discount rate. The inability to select an appropriate rate may change the profitability of the project. This discount rate is depending on the inflation rate. Its value usually has a range between 5% and 12% [78,79]. The NPV can be computed using the following equation.

$$NPV = \sum_{i=1}^{n} \frac{R_i - (I_i + O_i + M_i)}{(1+r)^i} + V_r \tag{35}$$

where I_i is the investment in time *i*, R_i is the revenue in time i, O_i is the operating cost in time i, M_i is the maintenance cost in time *i*, V_r is the residual value of capital invested over the lifetime, *n* is the life time of the project and *r* is the periodic discount rate. The period rate is taken as %25 of the annual rate.

6. Sites description

In this study, eight different Egyptian sites are chosen to install small-scale hydro plants. These sites are located along the Delta of the Nile River. The chosen sites have a low head, low flow rate and spacious areas away from urban, which make them excellent positions for the establishment of small hydropower stations. The locations are chosen to cover eight sites (El-Reah El-Towfiqy (TW) – Zefta (ZE) – Rashed (RA) – Damita (DA) – El-Mansouria (MA) – El-Reah El-Beheary (RB) – El-Reah El-Menofy (RM) – El-Reah El-Nasery (RN)). The elevation map in Fig. 3, indicates the selected sites.

The head and water flow rates for the past five years (2011–2016) collected by the Egyptian ministry of water resources and irrigation are used to find out the hydro energy potential. Table A1 and A2 in Appendix A, show the average monthly net head and annual flow rate of the selected sites for the last year (2016).

7. Procedure for evaluating small-scale hydro energy for the selected sites

The following procedure is used to evaluate the selected sites for installing an SSHP plant:

1. Collect the required data for the selected site (water flow rate and head),
2. Determine the construction dimensions and speed of different turbines type and consequently design the proper small hydro turbine for that site,
3. Select the generator type and rating appropriate for that site,
4. Determine the output power and energy for the site,

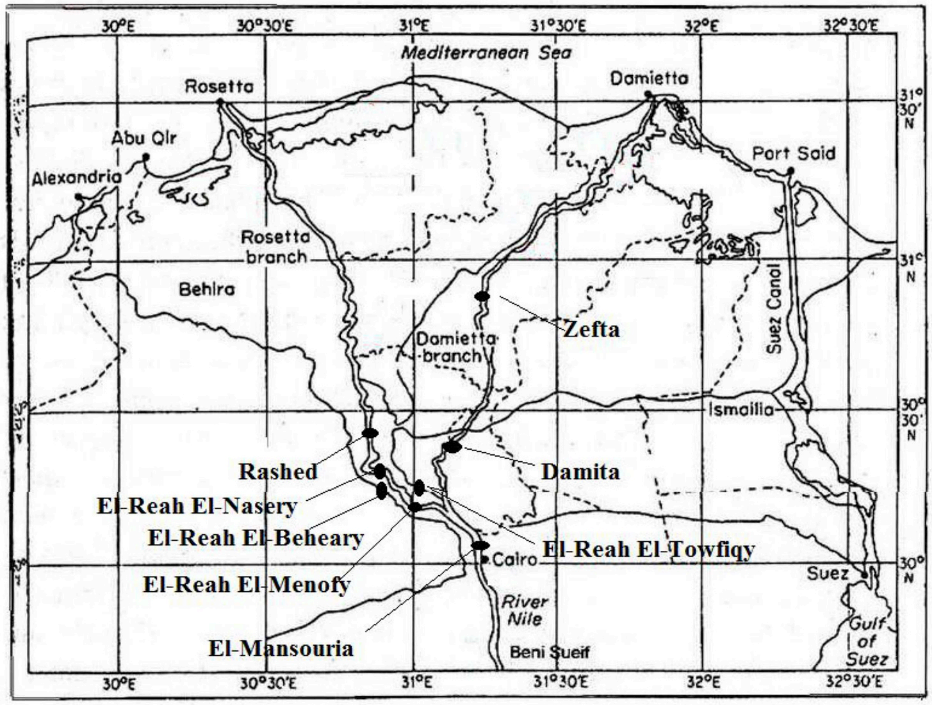

Fig. 3. Locations of the main nile river bridges.

5. Repeat the above steps for each site, and
6. Analyze and discuss the results.

The procedure is illustrated in the flowchart shown in Fig. 4.

8. Simulation and results

The selected sites represent several areas with different average water head and rate. Simulation is performed for the three hydropower turbines at each location. Firstly, the flow rate of water head data is measured, then the geometry dimensions parameters of the selected small-hydro turbine are calculated. The small-hydro turbine efficiency, output power, and energy for all sites are then computed by using a created MATLAB program. These steps will be explained in details in the following subsections.

8.1. Water flow-rate and water head data

The flow rate of water is determined by measuring the river's water flow velocity and cross-section areas in the selected site. Both the Nile river flow and water head are changed throughout the year seasons, so it is important to measure water flow-rate at various intervals of the year. In this study, Monthly Flow Duration (MFD) curves have been obtained for the development and installation of the small-scale power plants by recording water flows and heads from maximum to minimum values. The MFD curves are used to assess the expected availability of head and flow variations to select the suitable type of the turbine and generator. Fig. 5 shows the net head for the eight selected sites throughout the year. It can be observed that RASHID (RA) site has the highest net head around the year. El-Reah El-Beheary (RB) and El-Reah El-Nasery (RN) sites have the lowest net head around the year. Fig. 6 shows the flow rate for the selected sites. The El-Reah El-Beheary (RB) site has the highest water flow rate through the year and Zefta (ZE) site has the lowest water flow rate.

8.2. Design of small hydro turbine

Depending on the available water flow-rate and net head at the selected sites, the suitable hydro turbine is suggested. Then the geometry dimensions parameters are determined according to (4)–(11). The net heads of all selected sites are less than 5 m depending on the hydro-turbines characteristics shown in Fig. 2. For this head, the Francis turbines are not suitable as they are used for net head larger or equal 9 m. The two available turbines are both Kaplan and Cross-flow turbines. Table 2 present the geometry dimensions parameters of the two turbines for each site.

8.3. Selection of generator type and rating

Generally, SGs are more expensive and have a larger size than other generators' types for small ratings (below 1 MW). For these reasons, synchronous generators are not preferred in small hydro plants. The two suitable generators types for small-scale ratings are the IGs and the PMSGs. However, for power ratings from 300 to 1000 kW, PMSGs are lighter in weight, smaller in size and higher in efficiency compared to IGs. Although IGs have lower investment cost, PMSGs are more cost-effective value over the total life cycle of the project. PMG has the highest annual power output, with a 2.2% increase over SEIG for an IEC (International Electrotechnical Commission). So, PMSGs are chosen to be integrated with the small-scale hydro turbines used in this study.

8.4. Small-hydro turbine efficiency, output power, and energy

The efficiencies of the two suitable turbines (Kaplan and Cross-flow hydro-turbine) are calculated from the efficiency equations of each turbine according to (12) to (22). Fig. 7 shows the efficiency of the two turbines at each location.

The output power of both Kaplan and Cross-flow turbines for each site is shown in Fig. 8. The Kaplan turbine is more efficient than Cross-Flow turbine at all the selected sites, but for net head less than 2 m and flow rate less than 20 m^3/s, Cross-Flow is more efficient (at RN site).

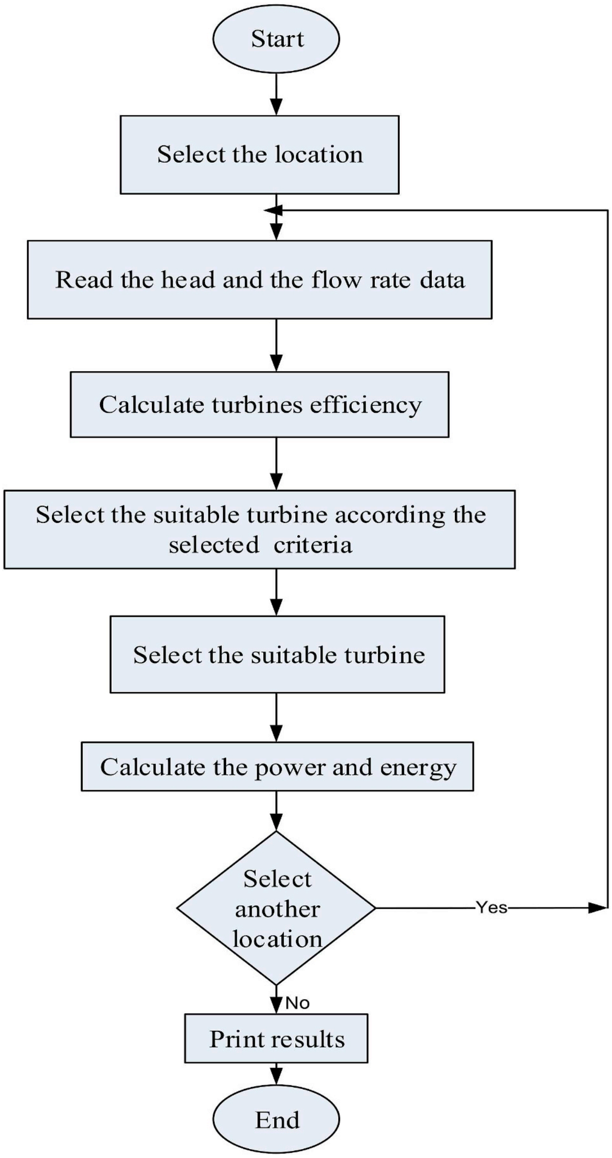

Fig. 4. The procedure for evaluating small-hydro energy.

The annual energy generated from each turbine at the selected sites is shown in Table 3. Although the water flow rate and net head are not the highest at DA site, the annual energy generated at this site is the largest energy of all the selected sites as the output energy depends on both the net head and flow rate. This means that an economic optimization analysis is required to detect the best site.

8.5. SSHP plants cost

An economic analysis for the cost of various components of civil works and electromechanical equipment of SSHP projects with head less than 5 m and rated capacity less than 1000 kW has been carried out. Table 4 illustrates the detailed cost items results from the economic analysis of the SSHP plants for three hydro-turbine types at the selected locations in Delta Egypt.

Table 4 shows that the cost of the SSHP project is increased with the decrease in the project capacity where the maximum cost obtained at Zefta (ZE) site which has the minimum rated capacity. Moreover, the cost of the electromechanical equipment is about 80% of the total capital cost as the system without penstock. The cost of the turbine is the most affected component where, its cost is about 60% of the total electromechanical cost equipment, while the cost of the generator is about 20%. The cost of the system using Kaplan turbine is somewhere more than that using either Francis turbine or Crossflow turbine.

9. Conclusion

This paper presented a preliminary feasibility study and a detailed assessment of small hydro energy potential in Egypt. The paper investigated the small hydropower at eight sites in Delta-Egypt. The study was based on a real date for five years ago and examined different types of small-hydro turbines and different types of generators for the selected sites. A Matlab program was built to compute the turbines efficiencies for each site at the different head and water flow rates. According to the annual energy generated the most efficient configuration for each location is recommended. Out of this study, it can be concluded that: the most suitable small-hydro turbines used for heads less than 5 m are Kaplan and Crossflow turbines. In most sites, the Kaplan turbine is more efficient. The expected total energy that can be produced from the eight sites is 15.6 GWh. The crossflow turbine has a lower cost than the Kaplan for the locations of rated power less than 1000 kW. The most suitable Egyptian sites for small-hydro power generation was assessed and the following conclusions were observed:

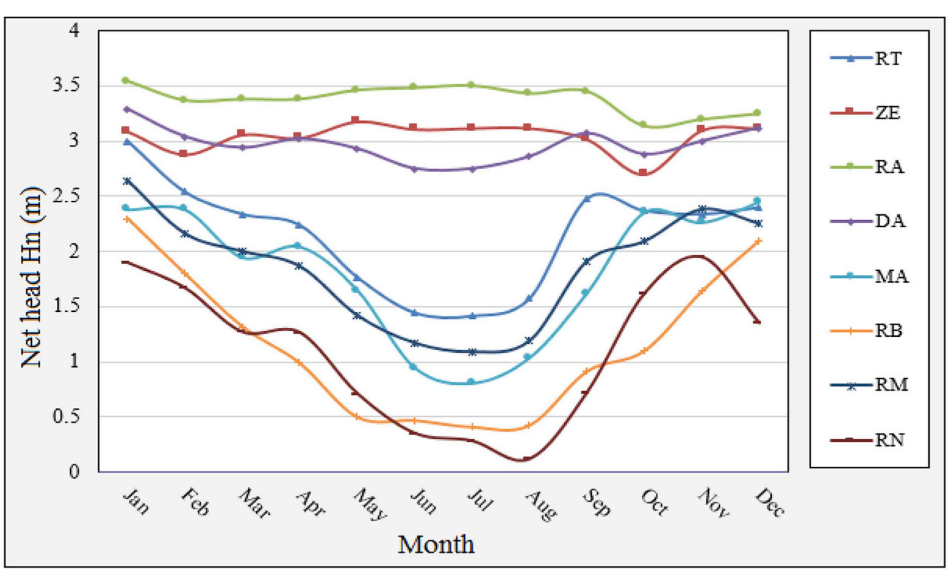

Fig. 5. The net head for the selected sites.

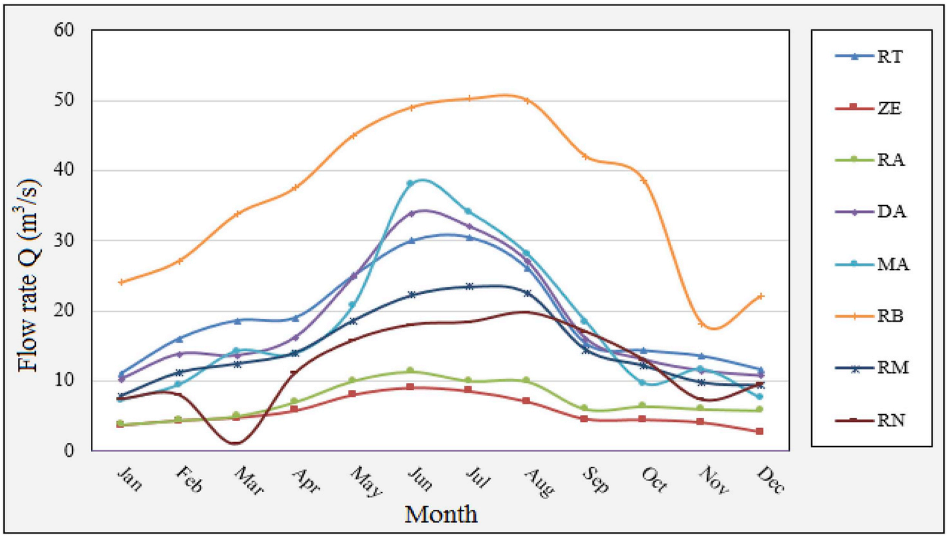

Fig. 6. The flow rate for the selected sites.

Table 2
The geometry dimensions parameters for Kaplan and Crossflow turbines.

Location	Kaplan turbines			Crossflow turbines	
	H_n	D_e	D_i	H_n	D_r
RT	3	1.6904	0.59076	3	0.34641
ZE	3.18	1.4391	0.55403	3.18	0.35665
RA	3.54	1.5565	0.59061	3.54	0.37629
DA	3.29	1.8316	0.63098	3.29	0.36277
MA	2.452	1.5812	0.54472	2.452	0.31318
RB	2.3	1.5314	0.52757	2.3	0.30332
RM	2.64	1.4869	0.53512	2.64	0.32496
RN	1.95	1.41007	0.48577	1.95	0.27929

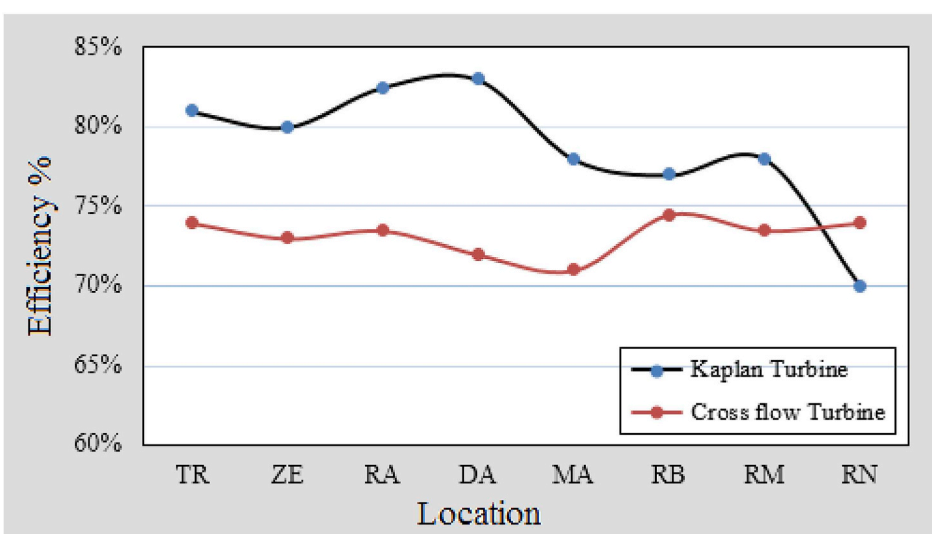

Fig. 7. The efficiency of the Kaplan and Cross-flow hydro-turbines at each location.

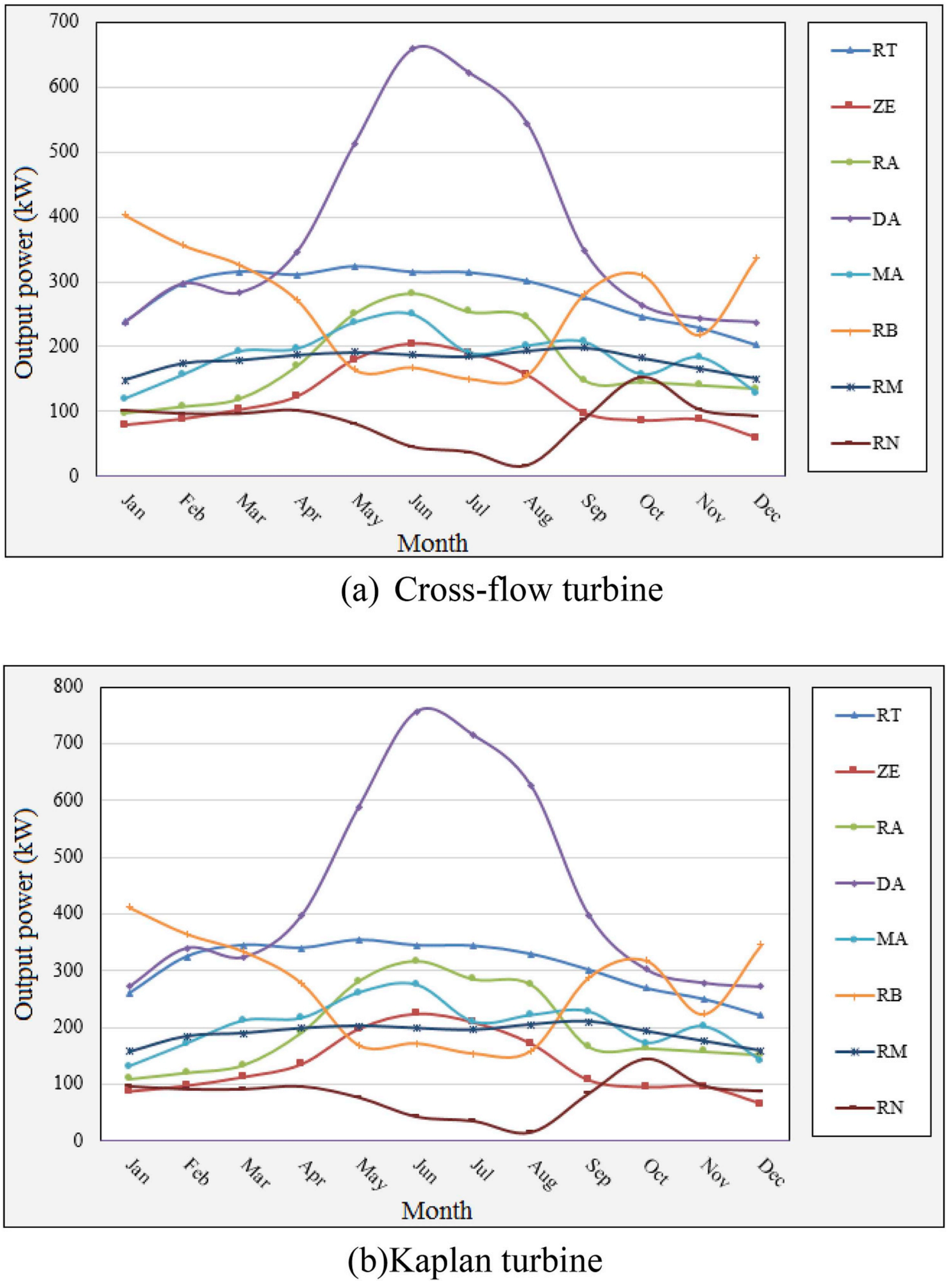

Fig. 8. Output Power of both Kaplan and Cross-flow turbines at the selected sites.

Table 3
Annual energy output.

No.	Locations	Annual turbine electrical energy generation(kWh)	
		Kaplan	Cross-flow
1	DA	3804785	3300537
2	RT	2646949	2418200
3	RB	2336340	2260485
4	MA	1755313	1597785
5	RA	1691449	1506927
6	RM	1634950	1540626
7	ZE	1146397	1046087
8	RN	633389	669582

1 El-Reah El-Beheary (RB) and El-Reah El-Nasery (RN) sites have the lower net head around the year.
2 El-Reah El-Beheary (RB) site has the most amount of water flow rate around the year.
3 Damita (DA) site has the highest values of electric power and annual energy.
4 Reah El-Nasery (RN) site has the lowest values of electric power and annual energy.
5 Damita (DA) and El-Reah El-Beheary (RB) sites have the lowest values of the capital and operation and maintenance costs per kW, whereas Reah El-Nasery (RN) and Zefta (ZE) sites have the highest values.

The study proved that the small hydroelectric projects can be created in many sites in Egypt so that it can be considered as a good alternative for solving a part of the Egyptian energy crisis.

Table 4
Cost details of SSHP plants.

	Item \ Site	TW	ZE	RA	DA	MA	RB	RM	RN
	Head(m)	897	280	392	1093	1000	1132	606	377
	Rated power (kW)	34.86	45.77	42	33.1	34.38	33.52	38.54	43.92
Civil Components	**Diversion weir and intake $/kW**	263.41	345.17	317	250.1	259.81	253.30	291.02	331.20
	Power house $/kW	298.27	390.94	359	283.3	294.19	286.82	329.56	375.12
	Subtotal Cost of civil components ($/kW)	591.08	1126.28	920.17	522.96	570.62	536.69	748.36	1014.64
Electrical & Mechanical Equipment	**Francis Turbine**	658.46	1290.10	1047.30	580.62	632.36	592.54	839.87	1146.71
	Kaplan Turbine	645.66	970.89	833.26	585.37	656.87	639.27	772.18	999.81
	Crossflow Turbine	265.89	326.01	299.52	251.44	271.76	269.15	293.67	341.59
	Generator	134.17	165.18	151.51	126.74	137.17	135.82	148.47	173.18
	Electrical and mechanical auxiliary	65.66	80.03	73.66	62.16	67.14	66.53	72.37	83.95
	Transformer and Switchyard	1124.18	1861.32	1571.99	1020.96	1108.43	1064.04	1354.38	1745.43
Kaplan Turbine	**Subtotal M & E costs* ($/kW)**	1422.45	2252.26	1930.99	1304.16	1402.62	1350.86	1683.94	2120.55
	Total Capital cost ($/kW)	42.6735	67.5678	57.9297	39.1248	42.0786	40.5258	50.5182	63.6165
	O&M costs (3% total capital cost) $/kW	1056.8	1697.5	1444.86	963.3	1046.69	1008.19	1262.87	1613.36
Francis Turbine	**Subtotal M & E costs* ($/kW)**	1355.07	2088.44	1803.86	1246.5	1340.88	1295.01	1592.43	1988.48
	Total Capital cost ($/kW)	40.6521	62.6532	54.1158	37.395	40.2264	38.8503	47.7729	59.6544
	O&M costs (3% total capital cost) $/kW	1111.38	1542.11	1357.95	1025.71	1132.94	1110.77	1286.69	1598.53
Crossflow Turbine	**Subtotal M & E costs* ($/kW)**	1409.65	1933.05	1716.95	1308.91	1427.13	1397.59	1616.25	1973.65
	Total Capital cost ($/kW)	42.2895	57.9915	51.5085	39.2673	42.8139	41.9277	48.4875	59.2095
	O&M costs (3% total capital cost) $/kW	897	280	392	1093	1000	1132	606	377

*** M & E costs: Mechanical & Electrical Costs**

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Appendix A

Table A1
Average Monthly Net Heads (meter) of the Selected Sites in the year 2016

Site Month	RN	RM	RB	MA	DA	RA	ZE	TW
Jan	1.9	2.64	2.3	2.38	3.29	3.54	3.09	3
Feb	1.67	2.16	1.8	2.381	3.04	3.37	2.88	2.54
Mar	1.27	2	1.32	1.946	2.94	3.38	3.06	2.34
Apr	1.265	1.864	0.99	2.045	3.02	3.38	3.03	2.24
May	0.711	1.42	0.5	1.651	2.93	3.46	3.18	1.77
Jun	0.35	1.17	0.47	0.945	2.75	3.48	3.11	1.45
Jul	0.28	1.09	0.41	0.804	2.75	3.5	3.12	1.42
Aug	0.116	1.19	0.426	1.036	2.86	3.43	3.12	1.58
Sep	0.72	1.91	0.915	1.623	3.07	3.45	3.02	2.48
Oct	1.62	2.09	1.1	2.356	2.88	3.14	2.7	2.37
Nov	1.95	2.38	1.64	2.264	3	3.2	3.1	2.34
Dec	1.35	2.25	2.1	2.452	3.12	3.25	3.12	2.4

Table A2
Average Monthly Flow Rate (m^3/s) of the Selected Sites

Site Month	RN	RM	RB	MA	DA	RA	ZE	TW
Jan	7.43	7.8	24	7.2	10.2	3.8	3.6	11
Feb	8	11.15	27.1	9.4	13.8	4.4	4.3	16
Mar	1.05	12.4	33.76	14.2	13.6	5	4.7	18.6
Apr	11.14	14	37.5	13.8	16.2	7	5.7	19
May	15.8	18.6	45	20.7	24.8	10	8	25
Jun	18	22.2	49	38	33.9	11.3	9	30
Jul	18.4	23.42	50.2	34	32	10	8.5	30.5
Aug	19.73	22.5	50	28	27	9.9	7	26

(*continued on next page*)

Table A2 (*continued*)

Site Month	RN	RM	RB	MA	DA	RA	ZE	TW
Sep	17	14.4	42	18.4	16	6	4.5	15.3
Oct	13	12.1	38.6	9.6	13	6.4	4.4	14.3
Nov	7.3	9.7	18.2	11.6	11.4	6	4	13.5
Dec	9.5	9.3	22	7.5	10.7	5.8	2.65	11.6

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