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Feasibility Analysis of Airborne Wind Energy System (AWES) Pumping Kite (PK)

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ABSTRACT

A variety of renewable energy production devices can compete with one another, relative to their technical and economic advantages. Wind power is in the first rank in this competition when compared to other energy production systems. The kite pump system or kite generator is one of the airborne wind power systems that is powered by a flying kite. In this paper, a 47kW kite power system with wind velocity of 8 m/s at elevation of 100 meters and a projection area of 20 m^2 with maximum lift to drag ratio of 12.6 and tether angle of 30 degrees is modeled. The forces taking into account in the traction and retraction phase are kite's effective parameters such as power factor, asymmetric factor, pumping efficiency and cycle power have been investigated using MATLAB® and Excel™. The power curve of this system is illustrated in the process of power production. In a separate table, input and output of analysis are shown. For economic analysis, SAM (System Advisor Model) software has been utilized. The power coefficient was simulated up to 53%-55% of the reeling factor. In the economic analysis of the 47-kilowatt system, the annual energy that has been generated is 101,221 kWh and the Levelized cost of energy (LCOE) calculated is 7.66 ¢ / kWh. Overall, the results of the present research show a promising prospect in this category.

Keywords:
AWES and pumping kite; Power cycle; reeling factor; Power factor; Levelized cost of energy; asymmetric factor

1. Introduction

Airborne wind energy systems are a suitable alternative to horizontal axis wind turbines. This system harvests wind energy by flying airfoils. The airfoil encounters the wind perpendicularly, which leads to harvesting more electrical power due to higher interaction with the kite surface. This system has access to higher elevation where high-speed wind flow is present which a specific advantage when compared to wind turbines is.

Pumping kite system consists of a tether that is connected to a winch situated on the ground. As the kite flies upward by the lift force, it rotates the winch and consequently the mechanical energy is

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converted to electrical power by a generator. The Kite Power generates power in three phases known as Traction, Transition, and Re-Traction [1].

In the Traction phase, the kite's aerodynamic forces are enabled by the lift force which is on an upward trend as the kite elevates to higher altitudes. In the meanwhile, as the kite is rising to higher elevations, the tether is being pulled out to that specific altitude as well [2].

As the traction phase completes, the system roles into the Transition phase where the angle of attack will decrease and consequently the reduction of the traction force will follow. In this intermediately phase, the winch starts to rotate in the opposite direction which will pull the kite to a lower elevation [3]. At this lower elevation, the "Reel-In" or "Retraction" phase starts which produces less energy in comparison to the reel-out phase due to lower wind velocity.

Retraction takes place at high velocity, low traction force, and the contrary attraction phase [5]. The pumping kite models components consist of (see Figure 1 and Figure 2):

i. the wing components, KCU (Kite Control Unit), wind wane, etc.
ii. The cable and tether adjustment system (e.g. unit control and sensors)
iii. Static components (e.g. mounted tether, launching and landing system)
iv. Mechanical power converter (e.g. drum and generator)
v. Electrical converter (e.g. battery, inverter, transformer and other electronic components)

Kite power system consists of station infrastructure and monitoring equipment which is situated on the ground.

Fig. 1. The flying kite of kite power system [4]

Fig. 2. The power train of kite power system [5]

2. Methodology
2.1 Pumping Kite Power Generation

Power generated by the Pumping Kite Power is derived from a similar equation as it is for the turbine wind power calculation equation. The difference is that in this formula, *Kite Velocity Coefficient (C_{kite})* is introduced. Accessible wind power is calculated by below equation [6]:

$$P = \frac{1}{2}\rho A C_{kite} V^3 \tag{1}$$

Where the wind speed is *V* and the kite's surface area is *A* in Eq. (1). Kite coefficient is a dimensionless factor which demonstrates kite velocity to affect the power production process. Kite's speed is many times higher than wind velocity, however it is limited by the tether speed, total drag force (sum of kite and tether's drag forces) and power coefficient (59% Betz limit). Kites coefficient depends on kite to wind speed ratio. The kite coefficient is quite similar to the turbine's tip speed ratio.

$$C_{kite} = \frac{V_{kite}}{V_w}\left(C_L - C_D\frac{V_{Kite}}{V_w}\right)\sqrt{1+\left(\frac{V_{kite}}{V_w}\right)^3} = \frac{V_{kite}}{V_w}C_D\left(\frac{C_L}{C_D} - \frac{V_{kite}}{V_w}\right)\sqrt{1+\left(\frac{V_{kite}}{V_w}\right)^3} \tag{2}$$

In the equation above, V_{kite} is kites speed and V_w is wind velocity. Electrical power is derived by average tether angle and powertrain's efficiently [6].

$$P_e = \frac{1}{2}\rho A C_{kite} V^3 \mathrm{h}_{gearbox}\mathrm{h}_{generator}\cos\theta \tag{3}$$

2.2 Power Cycle

The Loyd represented kite flight modes of traction, retraction and power cycle to calculate kite's power in a complete cycle. The Power cycle is superposition of traction and retraction phases. The asymmetry factor is one of the most important factors to calculate complete cycle power. The asymmetry factor (*AF*) is an important factor which multiples by rated tether reel-out speed and derives maximum tether reel-in speed.

$$V_{R,max} = AF * V_{T,rated} \tag{4}$$

The multiplication of Rated power and power (pumping) efficiency derive maximum power cycle. In other words:

$$P_{Cycle,max} = P * P_E \tag{5}$$

The Loyd described that the amount of energy harvested by wind, can be calculated by knowing the wing's surface area and the lift and drag coefficients. The Loyd represented the relationship between lift and drag coefficients with Thrust, T and Crosswind Velocity, $V_{k,c}$, which are demonstrated in Figure 3.

Wind speed V_w and reel-out speed V_{out} interact in the pumping cycle. The Apparent wind V_a is approximately equal to $V_{k,c}$ in the high lift to drag ratio scenario [7]. This is shown in Figure 3.

$$V_a \sim V_{k,c} = (V_w - V_{out})\frac{C_L}{C_D} \tag{6}$$

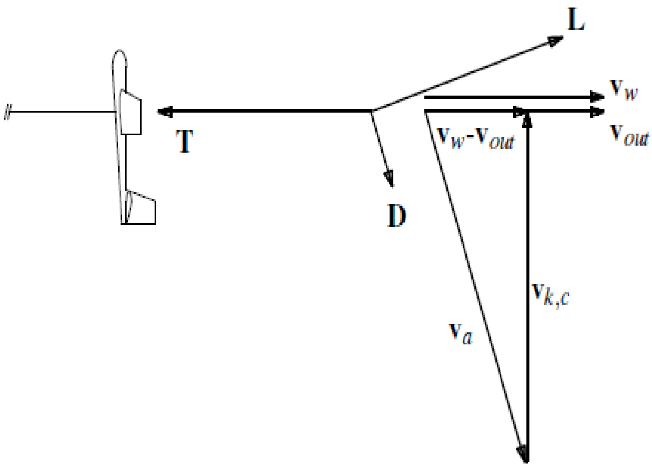


Fig. 3. The flying kite's velocities and forces at the variation of wind streams [1]

The first important conclusion is finding that there is a direct relationship between the crosswind kite speeds with lift-to-drag ratio, in the case where kite speed is much higher than the wind speed. The reel-out speed reduces both kite and apparent wind speeds. It is obvious that V_{out} cannot be higher than V_w. At the same time, Tether force is a function of density, wing's surface area and apparent wind velocity, which can be calculated, with close approximation, for high-values of C_L/C_D [2].

$$T \approx L = \frac{1}{2}\rho V_3^2 A C_l \tag{7}$$

2.3 Limiting Tether Force and Power: The Three-Phase Strategy

A strategy for pumping kite power systems is to divide the wind spectrum into three phases. For low wind speeds $0 \le V_w \le V_{n,T}$, there are no constraints for the tether force and power generation. For medium winds, $V_{n,T} \le V_w \le V_{n,P}$ the tether force is limited by a higher reel-out speed, while maximum power generation is not achieved yet.

For high winds, $Vn,p \le V_w$ the power and the tether force limits are reached. These three phases are controlled by KCU. $V_{n,t}$ is the tether force limit wind velocity where reel-out speed increases and consequently leads to power reduction. So, tether force should be constant at this phase. V_n is the rated speed to produce rated power. $V_{n,p}$ is the power limit speed at which no matter how much the tether reel-out speed would increase (with reel-in speed constant) the power produced stays at a constant rate [2].

2.4 Maximal Pumping Cycle Power

The system is considered a full pumping cycle with a traction (or reel-out) phase and a retraction (or reel-in) phase. The goal is to determine the reel-out speed v_{out} and the reel-in Speed v_{in} where the average mechanical power over one pumping cycle P_c is maximal. Defining the dimensionless factor $V_{out\ by}$ Vout=ϒout.Vw, the tether force in the traction phase can be derived from Eq. (11) as:

$$T_{out}=\frac{1}{2}\rho V_w{}^2 A\ (1-\Upsilon_{out})^2 F_{out} \tag{8}$$

With the dimensionless force factor F_{out}

$$F_{out} = \frac{{C_L}^3}{{C_D}^2} \tag{9}$$

Similarly, the tether force in the retraction phase is given by

$$T_{in} = \frac{1}{2}\rho {V_w}^2 A\ (1+\Upsilon_{in})^2\ F_{in} \tag{10}$$

With the dimensionless quantity v_{in} defined by $V_{in}=\Upsilon_{in}.V_w$. The kite needs to be compensated in the reel-in phase, thus [2]

$$F_{in} = C_D \tag{11}$$

The average power over one cycle is

$$f_c = ((1-\Upsilon_{out})^2 - \frac{F_{in}}{F_{out}}(1+\Upsilon_{in})^2)\left(\frac{\Upsilon_{out}\Upsilon_{in}}{\Upsilon_{out}+\Upsilon_{in}}\right) = \frac{P_c}{P_W \text{ A Fout}} \tag{12}$$

In this paper, the conventional Sport's air foil (i.e. NACA002416) is considered. The maximum and minimum lift-to-drag ratios are assumed to be 12.6 and 3 respectively [3-8]. The input parameters are shown in Table 1 [9-14]:

Table 1
The 47kW kite power system's input parameters

CL max	0.26
CD max	0.0206
L/D max	12.6
CL min	0.06
CD min	0.02
L/D min	3
Kite surface area	20 m^2
Elevation angle	60
Tether angle	30
Azimuth angle	0

3. Results

The 47kW kite power system's analysis output is shown in Table 2. The results show cyclic power produces less power than rated power. The power reduction is deducted by Kite's traction force, Kite's Aerodynamic force, Kite's maximum load, Tether's maximum traction force, power train energy losses and reel-in mode. Reel-in mode consumes energy to decrease elevation when less power is produced due to an inappropriate angle of attack. Critically, if the elevation is not decreased, the kite has a risk of collapsing.

Table 2
The 47kW kite power system's output parameters

Rated power	47 kW
Cyclic power	25.7 kW
Electrical power	42.3 kW
Kite's traction force	40.1 N
Kite's Aerodynamic force	40KN
Kite's maximum load	5.5 KN / m^2
Kite's weight	13.5kg
Tether length	200 m
Tether diameter	40 mm
Tether's maximum traction force	110 KN
Reel-out reeling factor	30%
Reel-in reeling factor	57%
Kite's velocity	70.56 m/s
Tether's reel-out velocity	2.4 m/s
Tether's reel-in velocity	4.56 m/s

3.1 Technical Analysis

The lift-to-drag ratio is assumed to be 12.6 with the drag coefficient of 0.0206. The reel-out and reel-in, factors are considered 30% and 57% respectively. The tether force and tether load are concerned at a one complete cycle.

The kite's traction (aerodynamically) force F_{out} is derived to be 41.92 N. The kite aerodynamic force (at the drag coefficient of 0.90) is obtained to be 40 kN. This force is approximately similar to average tether traction force. The rated electrical power obtained is 42.3 kW (at drivetrain efficiency of 90%). Figure 4 shows the power curve of the 47kW system at a rated velocity of 8 m/s. Figure 5 show three curves of cyclic, mechanical, and electrical Powers.

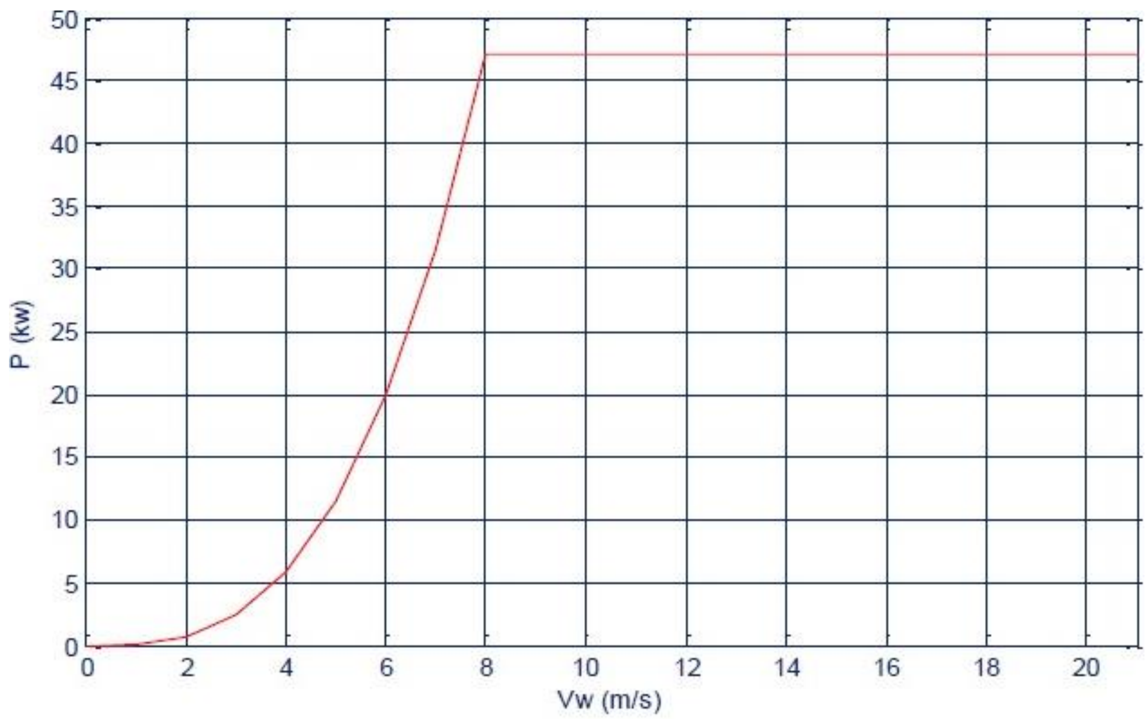


Fig. 4. Power curve, at tether angle = 30-degree, asymmetry factor = 5

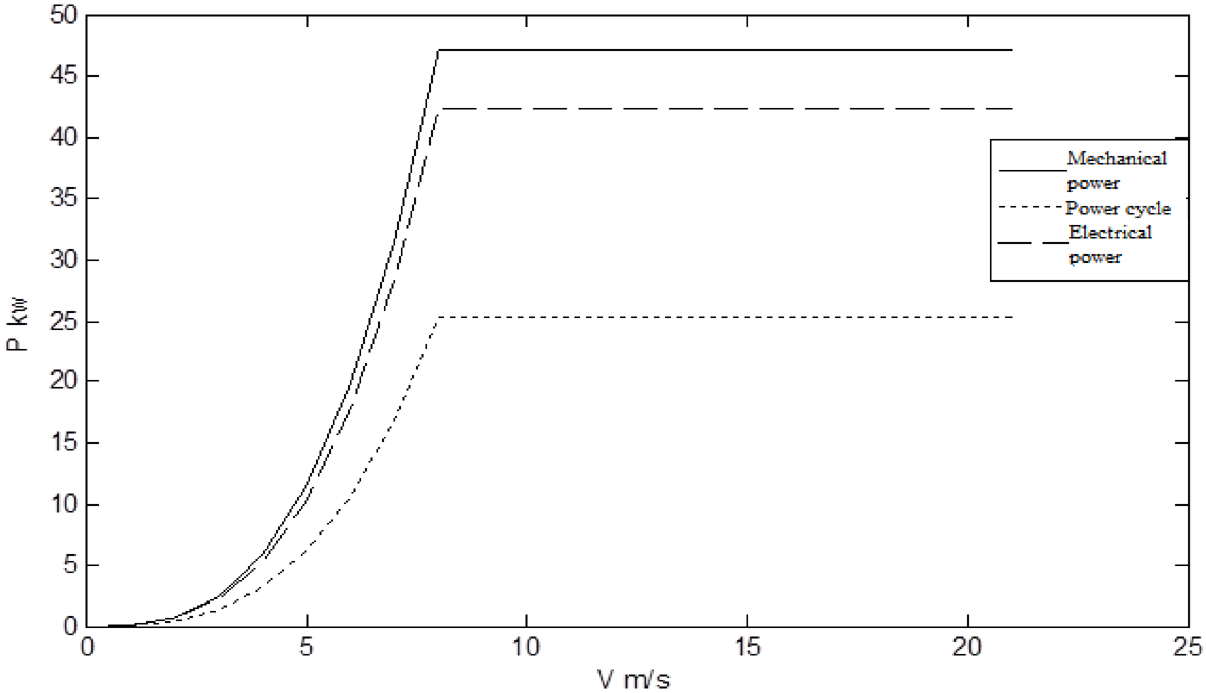


Fig. 5. Pumping kite mechanical power, electrical power and power cycle at rated power 47 kW

3.2 First Economic Model

The power kite plant mounting cost of $12,063.00 is calculated by the economic model of references [1-14]. In this study, Arizona State's city of Phoenix's average wind speed was used as input data in the simulation (by SAM software). The Arizona state's average wind speed is 6.56 m/s at a height of 100 m.

Electricity costs 1.5 cents per kWh and the inflation rate is considered at 13% per year. The tax rate, inflation rate, and US federal discounted rate are considered 25%, 2.5% and 2% respectively. The first economic model ignored the loan but the depreciation of 10% rate was considered in that model. The life cycle is assumed to be 20 years (see Table 3).

Table 3
Economic Analysis result of pumping kite system

AEP	101,221 kWh
CF	% 45.00
LCOE (nominal)	7.66 ¢/kWh
LCOE (actual)	6.07 ¢/kWh
NPV	$44,855.00
Payback period	9.4 years
Discount payback period	12.1 years
IRR	8 %
Net capital cost	$12,7063.00

Economic analysis of a wind turbine that is simulated with the same specification is shown in Table 4 for comparison purposes. The results indicate that the wind turbine produces more power annually but the CF and NPV of kite power is more and LCOE, payback period and net capital cost of kite power is less than a wind turbine. The wind turbine has a high weak effect. This means that the distance between two turbines in a wind farm is compulsory and hence yields to accommodate lower number of turbines in a given wind farm area. The kites have low weak effect which translates into more kites in an equally compared wind farm area.

Table 4
Economic Analysis result of wind turbine system

AEP	118,207 kWh
CF	28.10%
LCOE (nominal)	10.62 ¢/kWh
LCOE (actual)	8.02 ¢/kWh
NPV	$17452
Payback period	13.6 years
Discount payback period	20.3 years
IRR	4 %
Net capital cost	$188000

The power kite's power production and cash flow are shown in Figure 6 and Figure 7.

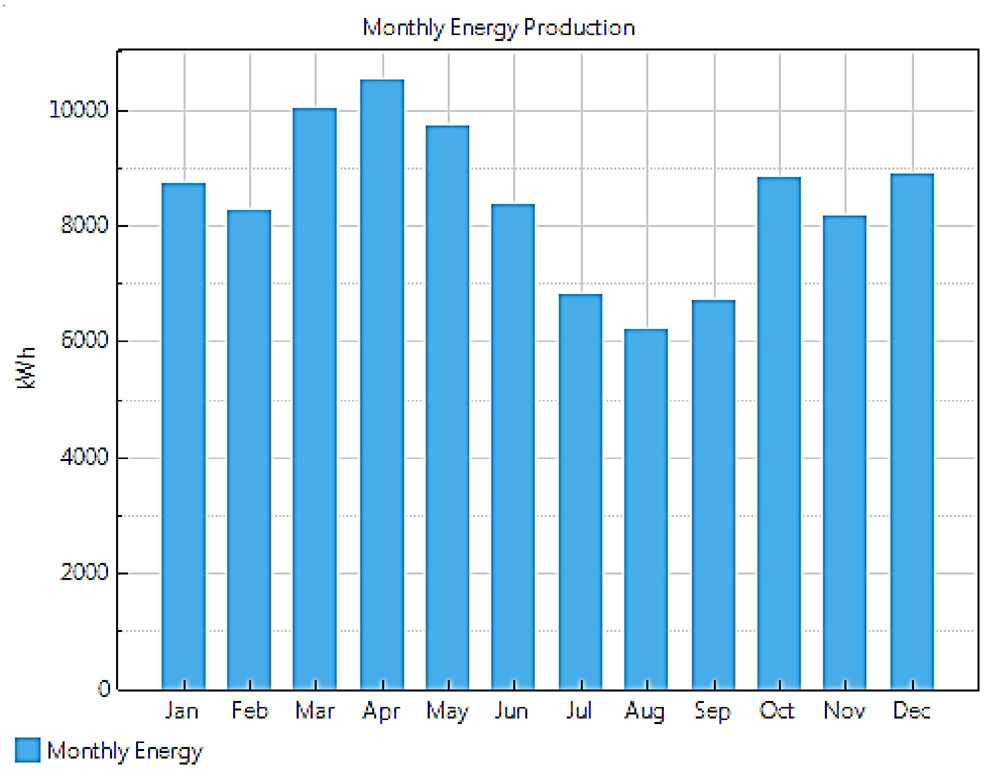


Fig. 6. Power production in different month

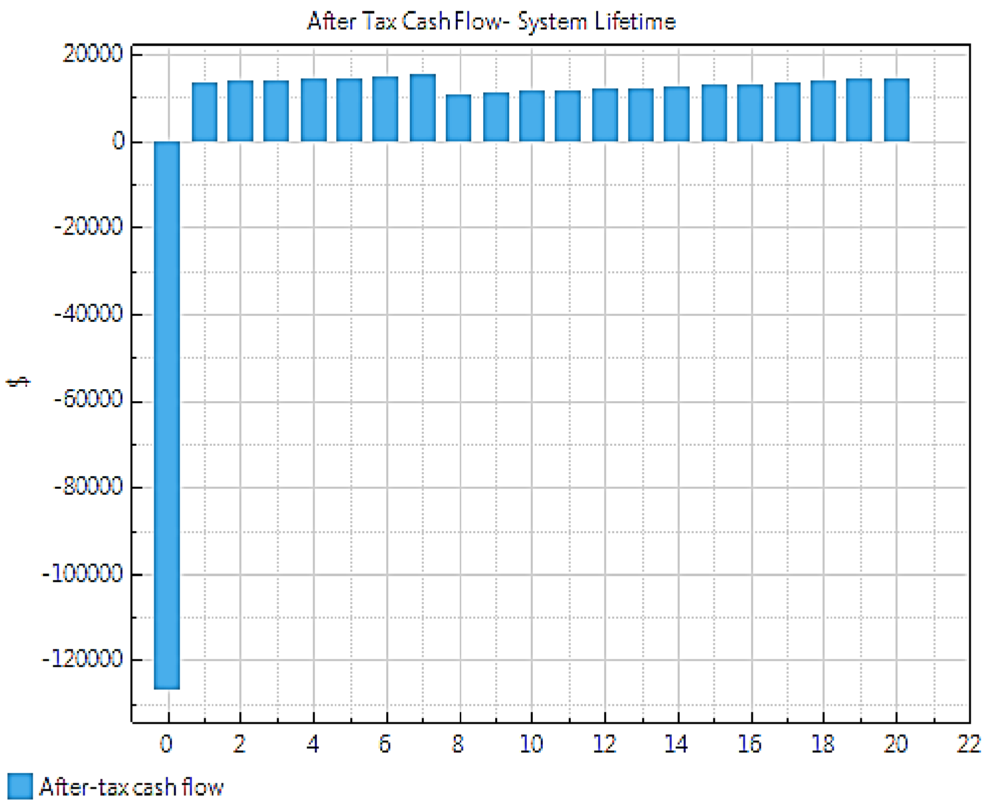
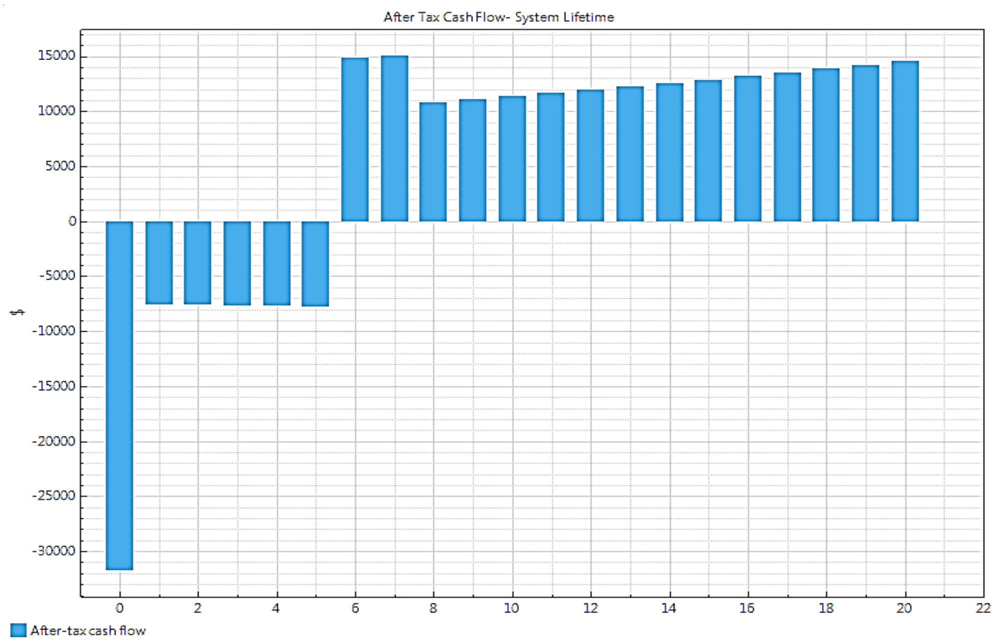


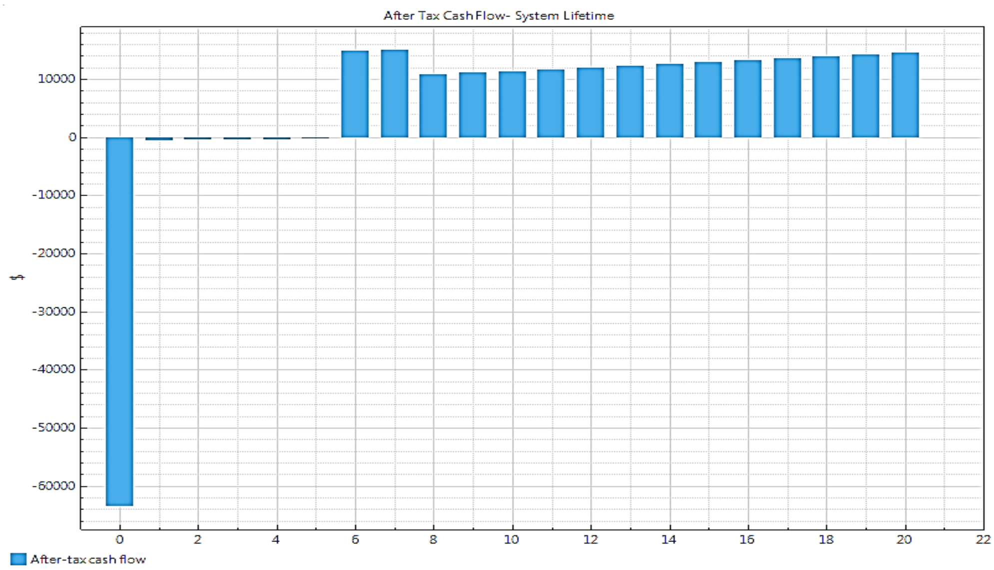
Fig. 7. 20 years life cycle cash flow of pumping kite

3.3 Second Economic Model

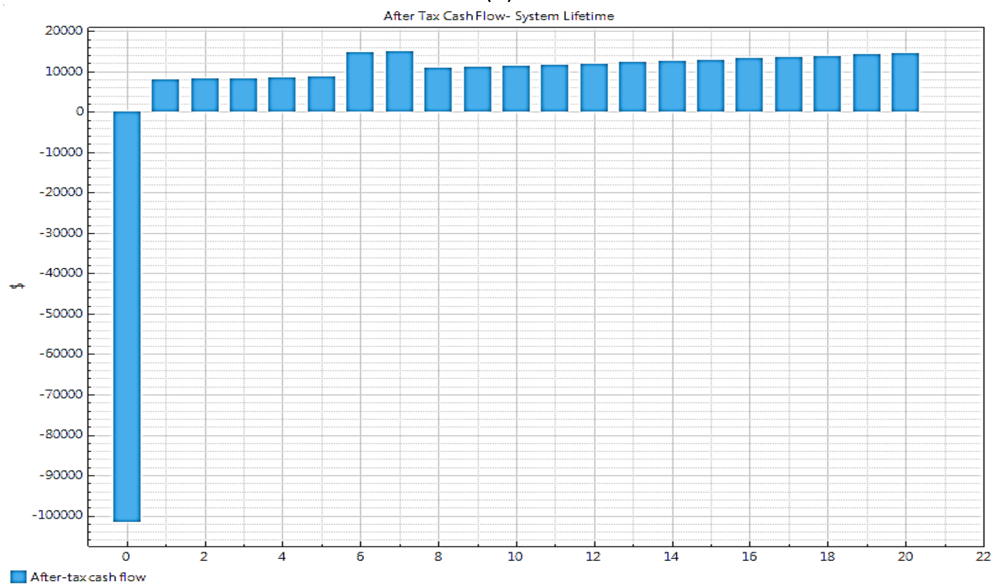
In this model, a 47kW pumping kite system with a loan is considered. The project's loan allocation rates, by priority, are 75%, 50% and 25% (see Figure 8). The loan's repay period is 5 years and repay interest rate is 6%.



(a)



(b)



(c)

Fig. 8. Cash Flow rate after loan allocation: (a) 75%, (b) 50%, (c) 25%

The 75% loan allocation does not change payback period, LCOE and nor the cash flow rate after fifth year and yet NPV and IRR rise to $44989.00 and 9% respectively. The cash flow rate is negative till the fifth year because in the first five years, the loan is repaid. Other contributing factors to this negative trend are tax payments, inflation rate, depreciation rate and the payback period. If 50 % of the capital cost is allocated to the loan, the values do not change except NPV of $44,944.00, which is less than the last model but it is more than the model without loan allocation. IRR is 9% as well. At last, 25 % loan allocation is demonstrated. NPV decreases to $44,891.00 but this amount is still more than the first economic model. IRR is constant in this model and the first payback years the cash flow rate is no longer negative.

As a proposal for continuation of this research, it is foreseen that a computational fluid dynamics investigation of steady flight of the kite is possibly useful for system identification [15]. Also, the regional study of the economic aspects of the kite system will more effectively address the needs for a green energy [16].

4. Conclusions

In the technical analysis of the power kite system, the traction and retraction forces were direct contributors and the balance between effective forces were calculated. This balance, in the system, is seen at the nominal wind speed of 8 m/s on the power curve. In fact, the design of the pumping kite, is sensitive to changes in lift-to-drag ratio and hence the threshold where this ratio starts to decrease must be avoided. The cyclic power produces less energy than the rated power because of the reel-in mode, Kite's traction force, Kite's Aerodynamic force, Kite's maximum load, Tether's maximum traction force and powertrain's energy losses. As a result, the economical parameters reached AEP of 101221 kW, CF of 45%, and LCOE of 7.66 ¢/kWh, NPV of $44,855.00 and payback period of 9.5 years. These findings indicate the appropriate value of a sustainable energy system.

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