The Use of Wind Energy to Reduce Energy Consumption of Shrimp Farm Aerators: A Case Study of Thailand

Supakit Worasinchai[1]*, Pimpa Limthongkul[2], Kiatkong Suwannakij[2] and Wanita Powsakul[2]

[1]Renewable Energy Laboratory, Materials for Energy Research Unit, National Metal and Materials Technology Center, 114 Thailand Science Park, Khlong Luang, Pathum Thani

[2]Electrochemical Materials and System Laboratory, Materials for Energy Research Unit, National Metal and Materials Technology Center, 114 Thailand Science Park, Khlong Luang, Pathum Thani

* Corresponding author. E-mail address: supakitw@mtec.or.th

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Abstract

The level of the dissolved oxygen in the grow-out water is one of the most important parameters that govern the quality of shrimp production. The generation of dissolved oxygen in intensive farms relies heavily on mechanical aerators which consume a large amount of energy. Reduction of this energy consumption could be beneficial for farm owners as it reduces the operational cost of the farm.

This article presents a study of using wind power to reduce the operational cost of the paddle-wheel aerators. A hybrid system, which combines the wind power source to the motor-based electric system was designed and evaluated under Thai wind conditions. The study showed that the investment has a long payback period of around 18 years and this is mainly because of the high energy cost of the wind turbine. Results also showed that reduction of this cost and the improvement of the wind turbine performance can be implemented in parallel to improve the cost-effectiveness of the system. Therefore, the use of wind power to supply power to the aerator system will not be cost-effective until the energy cost of the wind turbine has been improved.

Keywords: Wind turbine, American windmill, shrimp farm, energy consumption, payback period

Introduction

Shrimp industry is one of the largest export businesses of Thailand, ranking the first in the world in 2011 with a total export value of 427,580 million baht (Paneetatyasai, 2011). This amount of export is in part due to the quality of the shrimp production.

A significant amount of energy is required to successfully operate the shrimp farm. Previous research had showed that the majority of the energy consumption is mainly used for water pumping and aeration process, accounting for more than half of the total energy usage (Figure 1) (Kim et al, 2015). The mechanical aeration system consumes about quarter of the total energy and any reduction of this cost will undoubtedly improve the energy efficiency and cost effectiveness of the farm. This paper investigates the possibility of employing the wind power to reduce this operating cost.

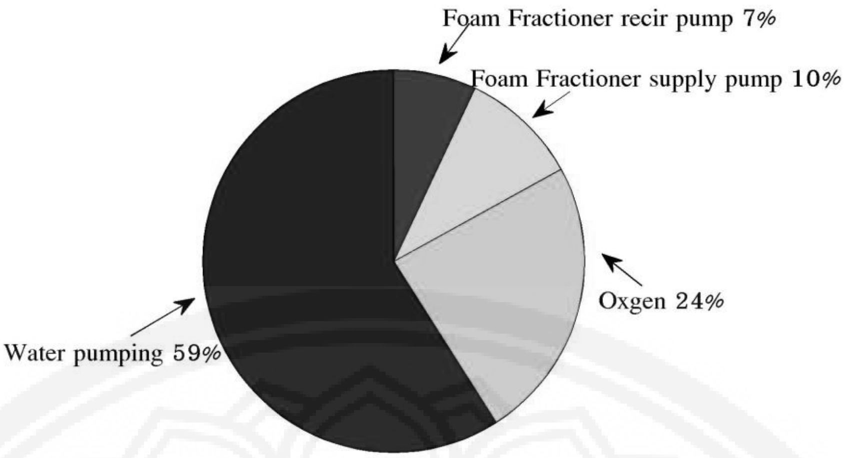

Figure 1 Energy usage in the shrimp farm (Kim et al., 2015)

Paddle-wheel aeration system

The most common aeration system used in farm is the paddle-wheel type. The basic components consist of a set of paddle wheels, a geared motor, and a floating system (Figure 2). During operation, the rotating wheel splashes water into the air and effectively increases the surface contact between air and water, leading to an increased amount of oxygen transfer. This oxygen transfer depends upon many factors such as paddle geometry, location of the paddle relative to water (how deep that the blade is immersed into the water), and paddle rotational speed. Previous investigations on Taiwanese paddle wheel aerators showed that immersing the paddle wheel too deep will reduce the splash effect while the water resistance increases significantly (Peterson & Walker, 2002). Boyd reported that the most efficient oxygen transfer rate was achieved when the paddles extended 9-11 cm into the water and at the rotating wheel speed of 80 rpm (Boyd, 1998). Power required to drive the system is estimated to be 1kW for each 40 cm of paddle wheel length (Boyd, 1998).

Figure 2 A fraction of the paddlewheel aerator

The paddle wheel aerator considered in this study is a locally made aerator. It consists of 16 wheels and is driven by a 3HP motor. Table 1 summarizes specifications of the paddle wheel used in this study.

Table 1 Paddle wheel parameters

Parameters	Values
Diameter (m)	0.64
Paddle width (m)	0.18
Paddle height (m)	0.15
Paddle length extended to the water (m)	0.05
Motor (HP)	3

Power to drive the paddle-wheel aerator

Although there is a guideline in sizing the motor for the paddle wheel, the correlation is not be applicable to all paddle types due to the variation of the paddle geometry. Estimation was conducted during this course of study.

The torque required is a product of resistive force and radius of the paddle. The force exerted by the water resistance can be expressed in term of drag coefficient as

$$F = \frac{1}{2}\rho A V^2 C_d \tag{1}$$

where F is the water resistance, ρ is water density, A is the area of the paddle that is extended to the water, V is the velocity that the paddle hits the water, and C_d is the drag coefficient of the paddle. The drag coefficient needed to calculate the water resistance is not available in literatures due to its distinct configuration. It is then experimentally estimated by the authors by applying a known weight (or force) to the paddle arm and then measuring a rotational speed of the paddle. The experiment was repeated five times. From the measured rotational speed, the velocity that the paddle hits the water can be calculated from

$$V = \omega R \tag{2}$$

For a steady rotational speed, the force is equal to the weight applied. It can be expressed as

$$F = mg\, sin\theta = \frac{1}{2}\rho A V^2 C_d \tag{3}$$

The drag coefficient was found to be 0.6226. Based upon this drag value, the torque required to drive the paddle set at the operational speed of 85 rpm is 105.15 N-m. The power needed for the aerator is then must be at least 935 Watt or 1.25HP.

Hybrid system

The wind energy was chosen as an energy source for this application as shrimp farms are normally located in remote areas with relatively strong wind. Moreover, power from the wind can be harvested when it is most needed as the power for aeration is most needed at night where the oxygen content in water is low due to no additional oxygen generation from plant species. A multi-bladed (or American windmill) was selected because of its high starting torque at low wind speeds (Figure 3). The turbine rated power is 400W at a design wind speed of 5.5 m/s (Figure 4). The detail specification of the turbine is summarized in Table 2.

Figure 3 The turbine used in this study

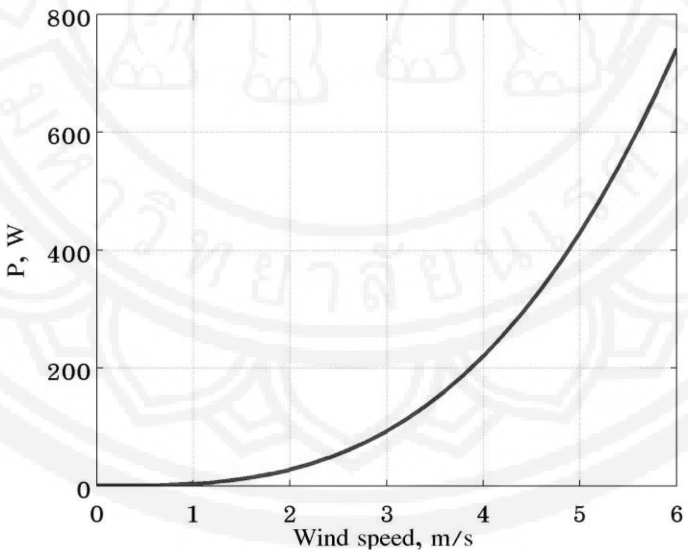

Figure 4 Power curve of the turbine

Table 2 Turbine parameters

Parameters	Value
Blade	Flat plate
Number of blades	30
Diameter (m)	4.267
Hub height (m)	15
Design wind speed (m/s)	5.5
Rated power (W)	400
Cost (baht) (USA Economic Development Co., LTD, 2015)	150,000

Differential gear systems were designed to combine the turbine to the motor-based aerator together. The total power of the hybrid system is 2.5HP; the primary and secondary motors are rated at 1.5 and 0.5HP, respectively and the rated power of the turbine is 400 W (or 0.54HP).

During operation, the two motors run continuously to provide power to the paddle. The wind turbine will add an additional power to the system when the wind is sufficiently high. The system was designed such that the rotational speed of the paddle-wheel is kept relatively constant at 85 rpm. This final operating speed is dependent upon the differences between the rotational speed of the sprocket and the rotational speed of the primary motor (the rotational speed of the primary differential gear is constant during the operation). This high operation is connected to the low operation of the turbine using a sprocket. At the low-speed operation side, the wind turbine is also connected to the secondary motor through a differential gear.

A schematic diagram of the system is presented in Figure 5. Table 3 shows variations of rotational speed, torque, and power through the process at different wind speeds.

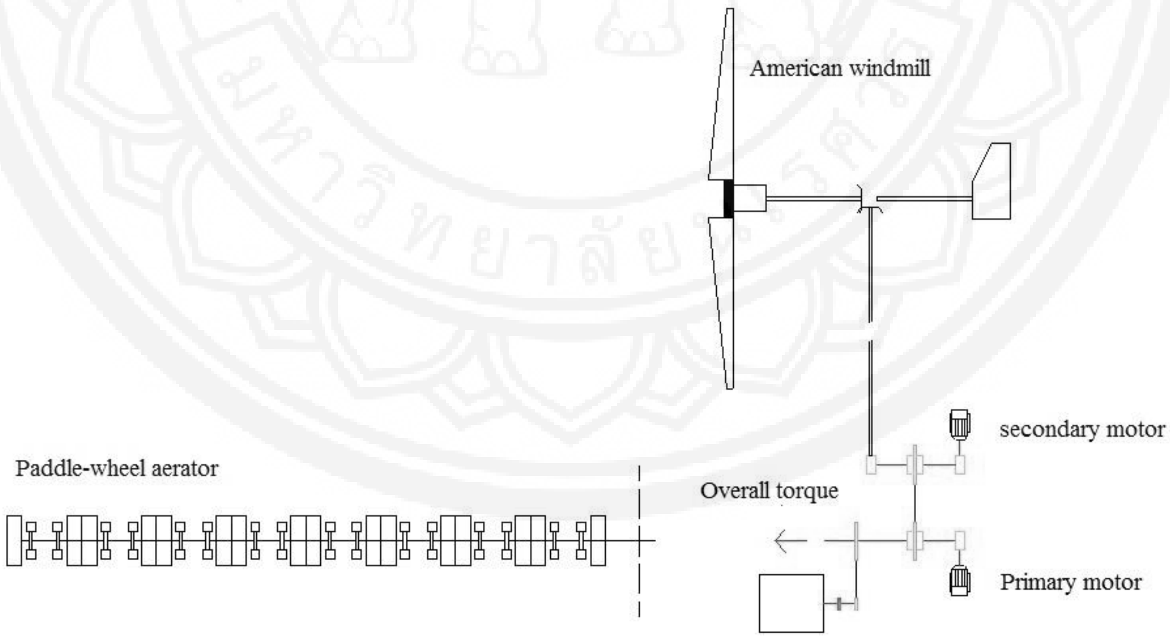

Figure 5 Schematic of the hybrid system

Table 3 Variation of rotational speed, torque, and power

Wind speed	Wind turbine			Secondary motor			Output of the 1st gear			Sprocket			Primary motor			Out of the 2nd gear		
	Omega	Torque	Power	Omega	Torque	Power	Omega	Torque	Power	Omega	Torque	Power	Omega	Torque	Power	Omega	Torque	Power
0	0.000	0.0000	0.0000	3.73	100	373	1.6785	200.0000	335.7000	8.3925	36.0000	302.1300	8.9	125.7303	1119	8.6463	147.9274	1279.0170
0.2	0.063	0.3271	0.0209	3.73	100	373	1.7073	196.6417	335.7188	8.5363	35.3955	302.1469	8.9	125.7303	1119	8.7182	146.7091	1279.0322
0.4	0.127	1.3082	0.1672	3.73	100	373	1.7360	193.4596	335.8505	8.6801	34.8227	302.2655	8.9	125.7303	1119	8.7901	145.5211	1279.1389
0.6	0.191	2.9435	0.5644	3.73	100	373	1.7648	190.5092	336.2080	8.8239	34.2917	302.5872	8.9	125.7303	1119	8.8620	144.3730	1279.4285
0.8	0.255	5.2329	1.3379	3.73	100	373	1.7935	187.8423	336.9041	8.9677	33.8116	303.2137	8.9	125.7303	1119	8.9339	143.2741	1279.9923
1	0.319	8.1764	2.6130	3.73	100	373	1.8223	185.5073	338.0517	9.1115	33.3913	304.2465	8.9	125.7303	1119	9.0058	142.2334	1280.9219
1.2	0.383	11.7740	4.5153	3.73	100	373	1.8511	183.5497	339.7637	9.2554	33.0390	305.7874	8.9	125.7303	1119	9.0777	141.2595	1282.3086
1.4	0.447	16.0258	7.1701	3.73	100	373	1.8798	182.0124	342.1531	9.3992	32.7622	307.9377	8.9	125.7303	1119	9.1496	140.3609	1284.2440
1.6	0.511	20.9316	10.7028	3.73	100	373	1.9086	180.9354	345.3325	9.5430	32.5684	310.7993	8.9	125.7303	1119	9.2215	139.5457	1286.8194
1.8	0.575	26.4916	15.2390	3.73	100	373	1.9374	180.3565	349.4151	9.6868	32.4642	314.4736	8.9	125.7303	1119	9.2934	138.8219	1290.1262
2	0.639	32.7056	20.9040	3.73	100	373	1.9661	180.3113	354.5136	9.8306	32.4560	319.0622	8.9	125.7303	1119	9.3653	138.1970	1294.2560
2.2	0.703	39.5738	27.8232	3.73	100	373	1.9949	180.8332	360.7409	9.9744	32.5500	324.6668	8.9	125.7303	1119	9.4372	137.6785	1299.3001
2.4	0.767	47.0961	36.1220	3.73	100	373	2.0236	181.9539	368.2098	10.1182	32.7517	331.3889	8.9	125.7303	1119	9.5091	137.2736	1305.3500
2.6	0.830	55.2725	45.9260	3.73	100	373	2.0524	183.7032	377.0334	10.2620	33.0666	339.3301	8.9	125.7303	1119	9.5810	136.9894	1312.4971
2.8	0.894	64.1030	57.3605	3.73	100	373	2.0812	186.1092	387.3244	10.4058	33.4997	348.5920	8.9	125.7303	1119	9.6529	136.8325	1320.8328
3	0.958	73.5877	70.5509	3.73	100	373	2.1099	189.1986	399.1958	10.5496	34.0558	359.2762	8.9	125.7303	1119	9.7248	136.8095	1330.4486
3.2	1.022	83.7264	85.6226	3.73	100	373	2.1387	192.9967	412.7604	10.6935	34.7394	371.4843	8.9	125.7303	1119	9.7967	136.9269	1341.4359
3.4	1.086	94.5193	102.7011	3.73	100	373	2.1675	197.5272	428.1310	10.8373	35.5549	385.3179	8.9	125.7303	1119	9.8686	137.1908	1353.8861
3.6	1.150	105.966	121.9119	3.73	100	373	2.1962	202.8129	445.4207	10.9811	36.5063	400.8786	8.9	125.7303	1119	9.9405	137.6073	1367.8908
3.8	1.214	118.063	143.3802	3.73	100	373	2.2250	208.8751	464.7422	11.1249	37.5975	418.2680	8.9	125.7303	1119	10.0124	138.1822	1383.5412
4	1.278	130.822	167.2317	3.73	100	373	2.2537	215.7341	486.2085	11.2687	38.8321	437.5876	8.9	125.7303	1119	10.0843	138.9211	1400.9289
4.2	1.342	144.231	193.5916	3.73	100	373	2.2825	223.4095	509.9324	11.4125	40.2137	458.9392	8.9	125.7303	1119	10.1563	139.8296	1420.1452
4.4	1.406	158.295	222.5853	3.73	100	373	2.3113	231.9194	536.0268	11.5563	41.7455	482.4241	8.9	125.7303	1119	10.2282	140.9131	1441.2817
4.6	1.470	173.012	254.3385	3.73	100	373	2.3400	241.2814	564.6046	11.7001	43.4307	508.1442	8.9	125.7303	1119	10.3001	142.1768	1464.4297
4.8	1.534	188.384	288.9763	3.73	100	373	2.3688	251.5121	595.7787	11.8439	45.2722	536.2008	8.9	125.7303	1119	10.3720	143.6257	1489.6807
5	1.597	204.410	326.6243	3.73	100	373	2.3975	262.6273	629.6619	11.9877	47.2729	566.6957	8.9	125.7303	1119	10.4439	145.2647	1517.1261
5.2	1.661	221.090	367.4080	3.73	100	373	2.4263	274.6421	666.3672	12.1316	49.4356	599.7305	8.9	125.7303	1119	10.5158	147.0987	1546.8574
5.4	1.725	238.424	411.4526	3.73	100	373	2.4551	287.5708	706.0073	12.2754	51.7628	635.4066	8.9	125.7303	1119	10.5877	149.1324	1578.9660
5.6	1.789	256.412	458.8837	3.73	100	373	2.4838	301.4272	748.6953	12.4192	54.2569	673.8258	8.9	125.7303	1119	10.6596	151.3701	1613.5432
5.8	1.853	275.054	509.8266	3.73	100	373	2.5126	316.2242	794.5440	12.5630	56.9204	715.0896	8.9	125.7303	1119	10.7315	153.8165	1650.6806
6	1.917	294.350	564.4069	3.73	100	373	2.5414	331.9745	843.6662	12.7068	59.7554	759.2996	8.9	125.7303	1119	10.8034	156.4757	1690.4696

It can be seen from Table 3 that the overall torque generated by the turbine is small at low wind speeds. With increasing wind speed, the turbine spins at a faster rate (between 20 and 30 rpm) and helps the secondary motor to drive the second differential gear. The power generated is transferred to the main gear set by a sprocket which is intended to increase the rotational speed to around 80 rpm. The power generated by the sprocket is then combined with the power generated by the primary motor. Calculations of the rotational speed and torque at the paddle showed that the system can provide sufficient torque and the paddle. It is also observed that the total power at high wind speeds is significantly higher than the power required. At this circumstance, the secondary motor can be turned off to further reduce the energy consumption. This amount of energy saving greatly depends on the variation of wind quality at the site of interest.

Wind variation

In this investigation, the system was installed to a standard shrimp farm at Chantaburi province. However the size of the farm is quite large (2.5 Rai or 4000 m^2) and the hybrid system was not intended to supply all the oxygen into the pond and only one unit of the aerator was studied here (as shown in Figure 2). Previous research showed that this site has shape and scale factors of 1.97 and 3.17, respectively at the turbine hub height [DEDE, 2001]. The variation of the wind speed is traditionally expressed in terms of Weibull distribution function (Tunsutapanich, Mungkung, & Gheewala, 2006). It is a frequency-based representation of the wind data and basically tells how frequent a particular wind speed occurs, allowing a calculation of number of hours that wind speed higher than a particular value. The variation is

$$F(V) = \left(\frac{k}{V}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{4}$$

where V is wind speed, k is shape factor, and C is scale factor. The scale and shape factors are site-specific and are related to each other as follows:

$$V = c\Gamma\left(1 + \frac{1}{k}\right) \quad (5)$$

where Γ is the gamma function and k defines the uniformity of the wind. It can be seen that the value of C is proportional to the average wind speed and thus can be interpreted as a characteristic speed of the site while k defines the shape of the distribution.

Figure 6 shows the Weibull distribution of this site. It can be seen from the Figure that wind speed at this site is relatively low (around 2 m/s). The possibility that the wind will be higher than a particular value can be obtained by integrating the function over the wind speed range.

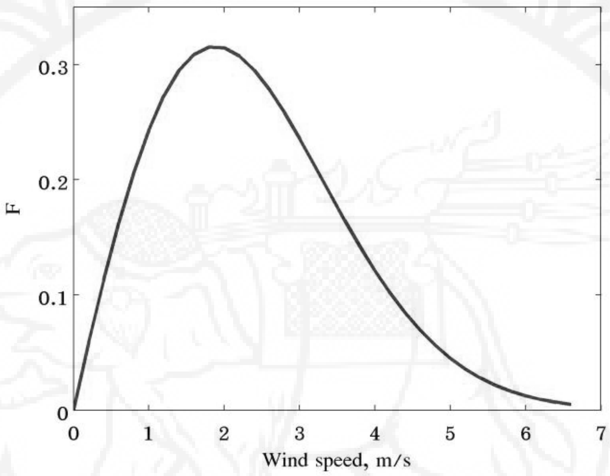

Figure 6 Weibull distribution

Energy prediction

Energy consumption: original system

Due to the variation of the oxygen level throughout the day, the paddle-wheel aerator is not used all the time. A survey at a shrimp farm showed that the aerator will be turned on three periods a day, namely between 8.00 am and 11.00 am, between 13.00 pm and 16.00 pm, and between 18.00 pm to 6.00 am. The 3HP motor operating at 380 V will consume a power of 2.238 kW. With 18 hours of operation, this will account for 2.238 x 18 x 30 = 1208 kWh/month (14,496 kWh/year) which costs 3,373 baht a month (or 40,476 baht a year) (Tunsutapanich, Mungkung, & Gheewala, 2006).

Energy consumption: hybrid system

In the hybrid system, the primary motor (1.5HP) will be turned on for a full 18 hours and the secondary motor will be turned off when the wind is higher than 3 m/s. The 1.5HP motor will consume 1,119 x 18 x 30 = 604 unit a month. The secondary motor will operate when the wind speed lower than 3 m/s. Integration of the Weibull function gives 13 hours of operation a day and will consume 373 x 13 x 30 = 145 unit, giving a total unit of 750 with a cost of 2007 baht a month (or 24,084 baht a year).

Energy generated by the wind turbine

The energy generated by the wind turbine depends on the wind turbine characteristic and the variation of the wind. The annual energy production of the turbine can be calculated from

$$AEP = 8760\,\Sigma\,P(V_i)F(V_i) \qquad (6)$$

Where P is power of the turbine and F is the Weibull distribution of the site. The power curve of the turbine has already been shown in Figure 4.

The addition of the wind system increases the capital cost of the paddle-wheel system. Table 4 summarizes capital cost of the two systems. It can be observed that the cost of the hybrid system is dominated by the cost of the wind turbine.

Table 4 Capital costs of the original and hybrid systems

Original system		**Hybrid system**	
Equipment/parts	**Estimated price (Baht)**	**Equipment/parts**	**Estimated price (Baht)**
AC Motor	7,400.00	Secondary AC Motor	2,450.00
Pulley	652.00	Primary AC Motor	5,000.00
Belt	310.00	Wind Turbine	150,000.00
Gear Box	6,800.00	Worm Gear Speed Reducer [1]	6,800.00
Motor + Gear Box	5,000.00	Worm Gear Speed Reducer [2]	3,000.00
Shaft	1,930.00	Worm Gear Speed Reducer [3]	3,000.00
Universal Joint	3,250.00	Sprocket	880.00
Paddle Wheel	7,840.00	Roller Chain	255.00
Buoy	3,625.00	Pedestal	10,000.00
Other Parts	2,000.00	Shaft	1,930.00
Total	**33,182.00**	Paddle Wheel	20,000.00
		Buoy	5,000.00
		Other Parts	2,000.00
		Total	**210,315.00**

The discounted payback period (DPP) which accounts for the time value of money is employed in this study to evaluate the effectiveness of the hybrid system. The discounted cash flow of each year can be calculated from the following equation:

$$DPP = \frac{I}{EC \times (1+i)^n} \qquad (7)$$

When I is the investment of the system, EC is the energy saving that the hybrid system can save each year, i is discounted rate which is assumed to be 7% in this study.

The cash flow of the system is summarized in Table 5 and it can be seen that the payback period of the hybrid system is 18 years and it is not cost-effective. Since the main cost of the system is the turbine cost, the effect of the turbine cost on the payback period has been evaluated (Fig. 7). The evaluation indicates that the investment will be attractive when the cost of the turbine is lower than 100 baht/W. In other words, the cost of a 1000W turbine should not be higher than 100,000 baht.

Table 5 Cash flow

Year	Investment (Baht)	Present value factor $PV = \frac{1}{(1+i)^n}$	Discounted value (Baht)	Cumulative discounted cash flow (Baht)
0	210,315 - 33,182 = 177,133	1.000	16,391	-160,742
1		0.935	15,319	-145,423
2		0.873	14,317	-131,107
3		0.816	13,380	-117,727
4		0.763	12,505	-105,222
5		0.713	11,687	-93,536
6		0.666	10,922	-82,614
7		0.623	10,207	-72,406
8		0.582	9,540	-62,866
9		0.544	8,916	-53,951
10		0.508	8,332	-45,618
11		0.475	7,787	-37,831
12		0.444	7,278	-30,553
13		0.415	6,802	-23,752
14		0.388	6,357	-17,395
15		0.362	5,941	-11,454
16		0.339	5,552	-5,902
17		0.317	5,189	-713
18		0.296	4,850	4,136

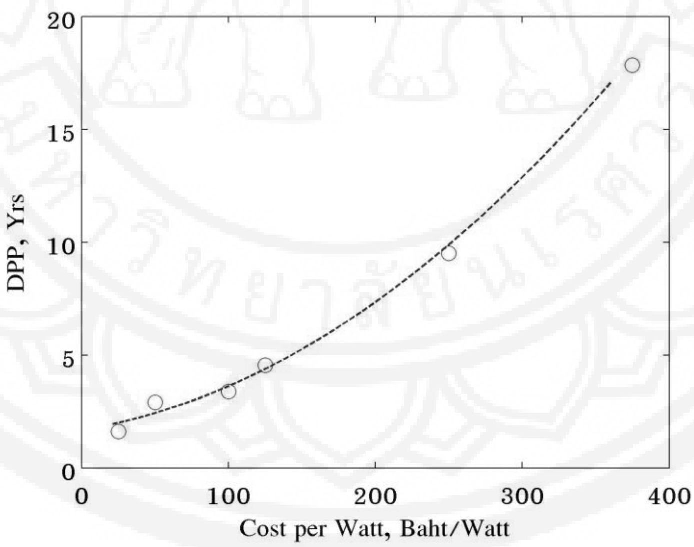

Figure 7 Payback period

The effect of electricity cost and the average wind speed on the discounted payback period was also conducted and the results are presented in Figure 8. It can be observed that the changes are in an approximately linear fashion and the increase of electricity cost and the average wind speed results in a shorter discounted payback period. The higher slope of the wind speed line indicates that the wind speed has a significant impact on the cost-effectiveness of the system, suggesting that installation of the hybrid system at a location having high average wind speed will make the investment more attractive.

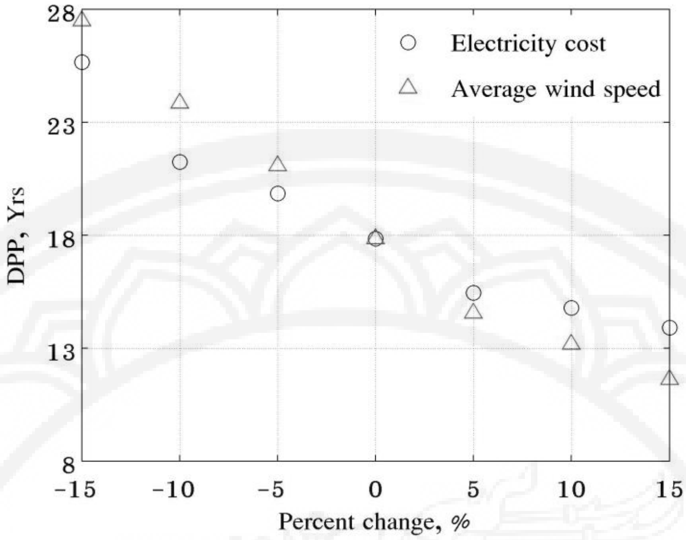

Figure 8 Effects of electricity cost and average wind speed on DPP

Conclusion

The effects of using wind power to reduce the operational cost of the paddle-wheel aerators had been investigated in this paper. A hybrid system which consists of a series of motors and wind turbine has been designed and evaluated. It was found that the system can deliver sufficient power to the paddle-wheel aerators under different wind conditions. It was also found that the hybrid system can reduce the energy consumption by 495 unit per month (1,365 Baht per month or 16,961 Baht each year which is around 40% of the operating cost). However, payback period analysis indicates that the system has a long payback period and this is mainly because of the high energy cost of the wind turbine. The study of the effect of the average wind speed and the electricity cost on the payback period were also conducted. It was shown that the increase of the average wind speed can significantly reduce the payback period of the hybrid system, suggesting that site selection of the turbine is vitally important. Similar effect was observed in case of the electricity cost but at a lesser extent.

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