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Research Article

Energy and Economic Analyses of a New Ducted Small Wind Turbine

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Abstract
Growing energy demand and considering the importance of environmental issues in recent decades, the utilization of renewable energies is expanding accordingly. Among renewable energies, wind power and technology are growing and evolving more rapidly than other renewable energies. This research studied turbine is modified Wuxi Ruifeng 2KW 48V with two new ducts (Sii and Prototype). Wind data of four areas in Iran has been used to analyze energy production and cost in different wind patterns. Levelized Cost of Energy and Annual energy production for the wind turbine with and without ducts are evaluated in different areas. Results showed that ducts in high wind speeds have little effect on increasing annual energy production and reducing energy cost (ducts can even negatively impact). However, in areas with low wind speeds, they can increase annual energy production by up to 4 times and reduce energy costs by up to 2.5 times.
Keywords: Ducted Wind turbine, Annual Energy Production, Levelized Cost of Energy, Duct Efficiency, Wind Lens

Introduction

In recent decades, regarding the Paris agreement and Kyoto Protocol, it is clear that the world is ready to change energy production and greenhouse gas emissions. Nowadays, many countries are taking their first steps toward a new era of the energy system. In addition to the achievement of new technologies, humans gradually tend to develop new energy sources. In the last decades, introducing new energy sources and enhancements of their market share has been a slow process. IEA (International Energy Agency) reports, almost half of the world's new installed power generation capacity contributed to renewable energies since 2014 (IEA (International Energy Agency), 2018) (Pishgar-Komleh and Akram, 2017). Therefore, wind energy – like other renewable energy sources geographically distributed and decentralized – is growing its share in current global energy markets (Noorollahi et al., 2016a, 2016b, 2017).

This project has been established to develop the distributed generation in Iran and increase electricity generation from renewable energies. Iran requires a severe policy for assessment and creating distributed generation plants to reduce the Levelized Cost of power generation by the wind-lens turbine and improve its technology. This research investigates annual energy production

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and the Levelized cost for new developed ducted wind turbine by our research team in four different Iran areas.

In 1956, Lilley and Rainbird (1965) investigations on the windmill, which are equipped with ducted land-type, reported 30% increment in power output. It was reported that the windmill's power is relative to the expansion of a duct cross-section. In the 70s, significant experiments of wind tunnels were conducted by Gilbert et al. (1978), Igra (1980), and Kogan and Seginer (1963) who their results are more critical than preliminary investigations. The first study of the modern wind turbines, equipped with ducted, was presented by Igra (1981). Igra (1976) pointed to the duct's positive impact on the output power efficiency and noted that the cross-sectional area's excess increment toward the output stream led to flow separation within the duct and reduced the wind turbine efficiency.

Furthermore, Igra showed the effect of the ducted turbine, which is tested in a wind tunnel. Results show an 80% increment of efficiency. In the 80s, Gilbert and Foreman, (1983) and Igra, (1981) studied turbines with a similar mechanism as the known Diffuser-augmented wind turbine based on wind energy concentration employing a diffuser around the wind turbine. The boundary layer control, slots on the diffuser, and the increasing pressure drop simultaneously prevented the flow separation and increased the wind turbine's inlet flow (Said et al., 2017; Vasel-Be-Hagh, 2017; Waewsak et al., 2017).

Phillips et al. (1999) tested a ducted wind turbine named Vortec 7. The original idea of the wind-lens turbine was given from the Vortec 7. Another improvement of this area was Abe and Ohya (2004), who test small wind turbines by adding a flanged diffuser. Their results showed an increment in production capacity and power coefficient.

Ohya et al. (2008), performed experimental studies and simulations of the diffuser shroud. They succeeded in presenting the next generation of turbines called wind-lens turbines. The most important feature of their turbine was an expanding loop designed at the end of the duct.

Because of limited financial resources and maximum energy density, researchers always tried to maximize the wind turbine's power output. It was 1956 when diffuser augmented wind turbines were introduced, which, as they claimed, 65% of the ideal bare turbine's maximum power could be achievable (Lilley et al., 1956). Nevertheless, high initial and O&M costs were impediments to its development, and it was unsuccessful in economic aspects at that time (Van Bussel, 2007). However, by some improvements in fluid dynamics analysis, scientists pave the way for diffuser augmented wind turbines to re-emerge.

Al-Sulaiman and Yilbas (2015) carried out a thermo-economic analysis of ducted wind turbines. Using exergy analysis and mathematical modeling, they investigated the impact of external/internal cross-sectional area ratio and free flow velocity on turbines' performance. Their investigations resulted in decreasing in total energy cost as a function of wind velocity. Nikolić et al. (2015), using MATLAB's Simulink and fuzzy-neural network algorithm, improved a model to determine the effect of some main parameters shrouded wind performance turbines. The simulation data is used as input for their model to calculate the effects of adding flow diffuser on the power factor, rotation velocity, and torque coefficient.

Kosasih and Hudin (2016) performed an optimization study on the ducted micro-wind turbine's geometrical characteristics. Three different types of wind turbines are studied, namely straight diffuser, nozzle-diffuser, and diffuser-brim. A micro-turbine executed their experiments with 190 mm rotor diameter. Setting up a straight diffuser and a nozzle-diffuser let to 60% and a diffuser-brim lets 63% increase in output power's performance. Although increasing the diffuser's length, no effect was observed, but using the brim to increase the turbine's efficiency, decreasing cut-in speed, and improving optimal value were also observed.

In recent years, Part of the competition between renewable energy sources depends on a technology level. The high-density energy resources or the efficiency of technologies play a deterministic role in the current energy market. By reducing the energy demand, high-efficiency energy technologies (Ahmadi-Baloutaki et al., 2015), wind turbine technology has been significantly developed and improved during the past decade. The Invelox turbine and wind-lens turbine (Allaei and Andreopoulos, 2014) are examples of high energy-efficient wind turbines. Researchers have shown increasing wind power utilizations possible via lens around the rotor (Shirgholami et al., 2016).

Recent investigations revealed that increasing the efficiency and introduction of renewable energies in energy systems should be considered a strategic policy for Iran's energy system, especially in the power generation sector (Masukume et al., 2018).

The study areas

Four areas in Iran with different wind conditions have been analyzed for duct efficiency and the ducted wind turbine's economic feasibility. The geographical properties and Weibull function parameters at the 10-meter level for study areas are provided in Table 1. These four areas are almost representing various wind conditions in Iran.

Table 1. Geographical properties and Weibull function parameters in 10-meter level

Stations	Latitude	Longitude	Height	Air density ratio (adr)	k	c
	deg.	deg.	m	-	-	m/s
Zabol	31.1	61.5	490	0.96	1.67	7.49
Sardasht	36.1	45.5	1557	0.86	1.64	4.51
Aligoodarz	33.4	49.7	2022	0.82	2.64	4.57
Rafsanjan	30.4	55.9	1524	0.86	2.68	5.15

Air density in the station to air density in sea level that calls air density ratio (adr), (k) is shape factor, and (c) is a scale factor in Weibull function. Graph of Weibull function parameters for 10-m level wind speed in study areas is shown in Figure 1. The figure curve shape shows higher tiling in Zabol station, which means a more significant share of higher wind speed in this area. We know that small wind turbines are more suitable in areas with lower wind speeds area.

Wind turbine and duct selection

Small wind turbines must be designed to have the functionality of working in an adverse condition of the building. To promote these turbines in urban areas, their safety must be assured, does not cause inconvenience to the public, and it should be examined that how much a building can withstand the vibrations of the turbine rotor. The turbine needs to be matched with the environment in terms of appearance. Among the mentioned problems, the small wind turbine equipped with a lens can provide a few solutions for these problems (Stankovic et al., 2009).

The turbine which is studied in this research is Wuxi Ruifeng 2KW 48V(Wuxi, 2020). This model of the turbine with precisely designed ducts is a case study for this research work. Figure 2 shows the original Wuxi Ruifeng 2KW 48V wind turbine (without duct). Figure 3 shows the rotor diameter and power curve to wind speed for Wuxi Ruifeng 2KW 48V wind turbine.

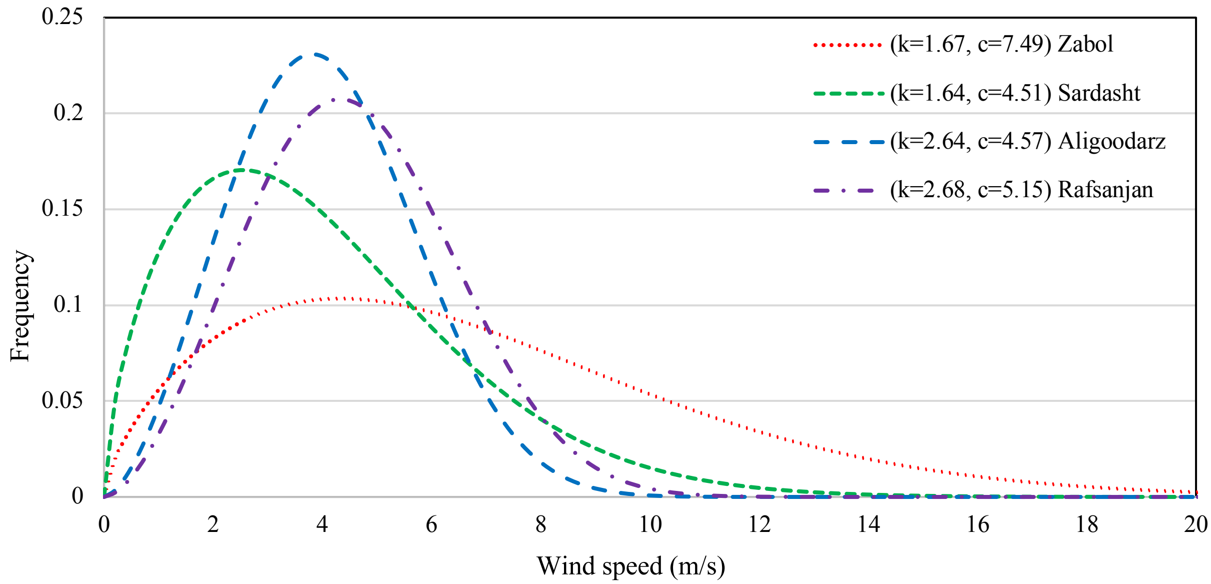


Figure 1. Weibull function parameters for 10-m level wind speed in study areas

Figure 2. Original Wuxi Ruifeng 2KW 48V wind turbine (without duct)

In this research work, we have simulated and designed two different ducts for Wuxi Ruifeng 2KW 48V wind turbine, calls S ii (Type A) and prototype (Type B). Type-A has caused the maximum power coefficient from 0.37 to reach 0.714 (Ohya and Karasudani, 2010), and type-B has caused the maximum power coefficient from 0.35 to reach 1.4 (Ohya et al., 2008). Ducts have been analyzed for power output and cost of energy. The shape and schematic of ducts are shown in Figure 4 and Figure 5, respectively. The ducts dimension for this wind turbine is shown in Table 2.

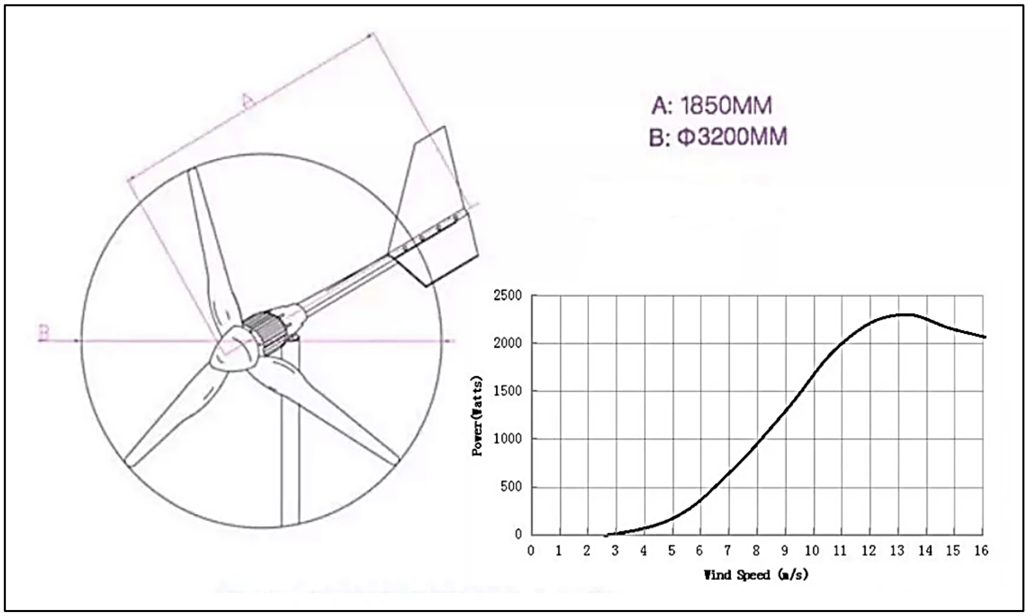


Figure 3. Rotor diameter and power curve for Wuxi Ruifeng 2KW 48V wind turbine

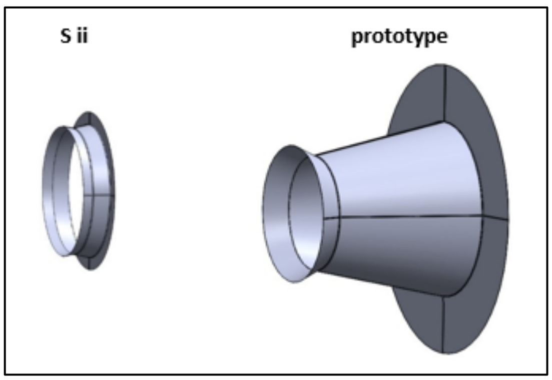


Figure 4. The shape of the simulated ducts

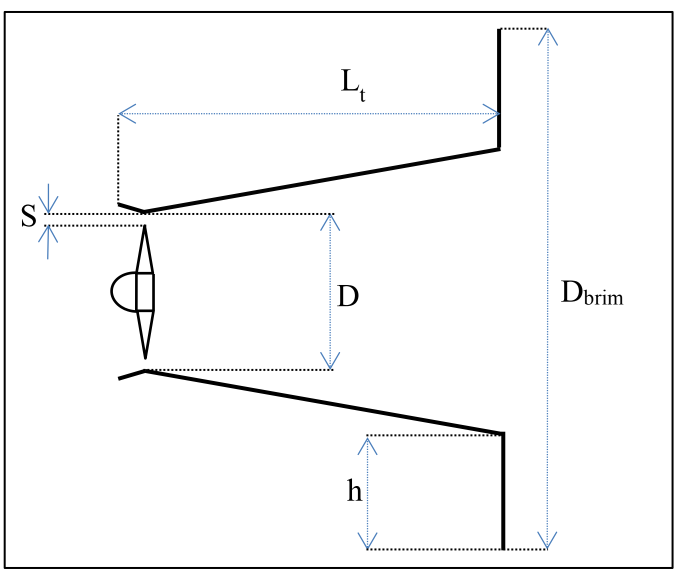


Figure 5. Schematic of ducted wind turbine

Table 2. The ducts dimension

Properties	Unit	Ductless W.T	D.W.T type A	D.W.T type B
Rotor diameter	m	3.2	3.2	3.2
S	m	-	0.025	0.025
D	m	-	3.25	3.25
L_t / D	-	-	0.225*	1.470*
L_t	m	-	0.731	4.777
h / D	-	-	0.1*	0.5*
h	m	-	0.325	1.625
μ= (exit area / throat area)	-	-	1.119*	2.345*
D_{brim}	m	-	4.09	8.23
Total area	m^2	8.04	13.13	53.17

* from (Ohya and Karasudani, 2010)

Power curve

Ducts will increase wind speed, and turbines will feel the higher wind speed and produce power corresponding to that wind speed (Ohya and Karasudani, 2010). Therefore, to draw the ducted turbine power curve, it is sufficient to scale the ductless turbine power curve's wind speed. Suppose at wind speed (V_d), ducted turbine power (P_d) equals with ductless turbine power (P) at wind speed (V). The wind speed scale is obtained from the following equations:

$$P = P_d \tag{1}$$

$$0.5\,\rho\,C_p\,A\,V^3 = 0.5\,\rho\,C_{p_d}\,A\,V_d^3 \tag{2}$$

$$C_p\,V^3 = C_{p_d}\,V_d^3 \tag{3}$$

$$\frac{C_p}{C_{p_d}} = (\frac{V_d}{V})^3 \tag{4}$$

$$V_d = \sqrt[3]{\frac{C_p}{C_{p_d}}}\,V \tag{5}$$

Duct Power Coefficient (at equal power (P = P_d)) (DPC)= $\frac{C_{p_d}}{C_p}$

$$V_d = \sqrt[3]{\frac{1}{DPC}}\,V \tag{6}$$

Where (ρ) is air density, (A) is the rotor swept area; (Cp) is ductless turbine power coefficient, and (Cp_d) is ducted turbine power coefficient. For a turbine with or without a duct at equal power, DPC always remains constant. According to equations (5), to obtain the ducted turbine power curve, the ductless turbine's wind speed is scaled to (Vd) in each power. for example, according to Figure 6, the duct has caused maximum power coefficient (C_{Pmax}) from 0.4 to reach 1 (Ohya and Karasudani, 2010), and we will have:

$$V_d = \sqrt[3]{\frac{C_p}{C_{p_d}}}\ V = \sqrt[3]{\frac{0.4}{1}}\ V = 0.74\ V \qquad or \tag{7}$$

$$DPC = \frac{C_{p_d}}{C_p} = \frac{1}{0.4} = 2.5 \quad \Rightarrow \quad V_d = \sqrt[3]{\frac{1}{DPC}}\ V = \sqrt[3]{\frac{1}{2.5}}\ V = 0.74\ V \tag{8}$$

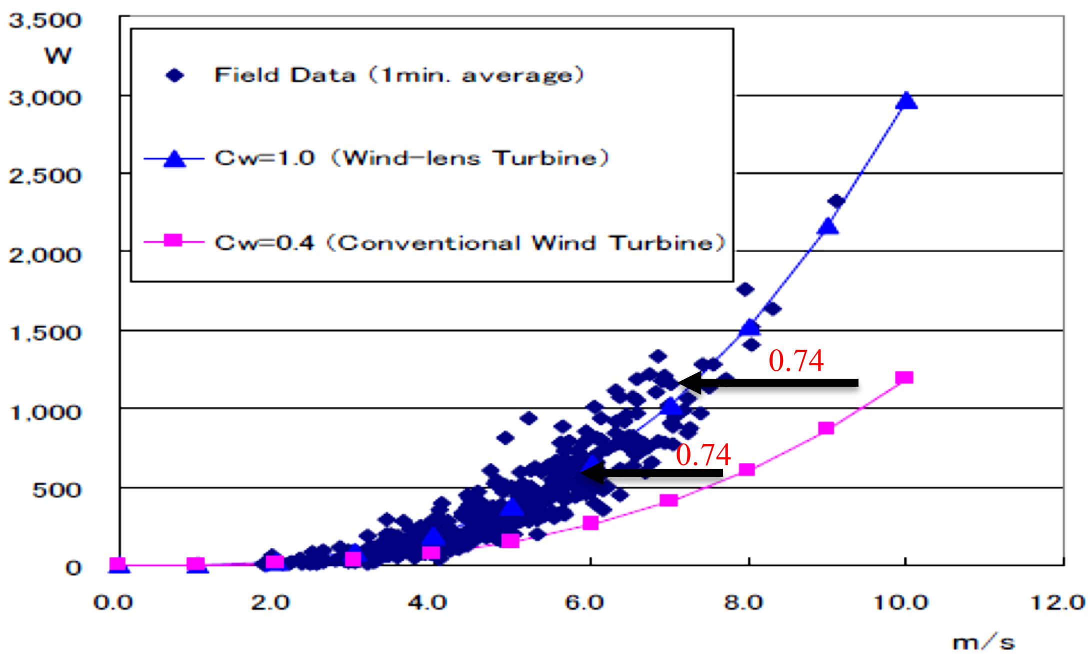


Figure 6. Ductless wind turbine power curve and ducted wind turbine experiment data (Ohya and Karasudani, 2010)

According to Figure 6, by scaling the ductless wind turbine power curve's wind speed to 0.74, the ducted wind turbine power curve will be obtained.

According to the equations (5) for type-A and type-B duct, we will have:

$$\text{type} - \text{A}: \ V_d = \sqrt[3]{\frac{C_p}{C_{p_d}}}\ V = \sqrt[3]{\frac{0.37}{0.714}}\ V = 0.8\ V \qquad or \tag{9}$$

$$DPC = \frac{C_{p_d}}{C_p} = \frac{0.714}{0.37} = 1.93 \quad \Rightarrow \quad V_d = \sqrt[3]{\frac{1}{DPC}}\ V = \sqrt[3]{\frac{1}{1.93}}\ V = 0.8\ V \tag{10}$$

$$\text{type} - \text{B}: \ V_d = \sqrt[3]{\frac{C_p}{C_{p_d}}}\ V = \sqrt[3]{\frac{0.35}{1.4}}\ V = 0.63\ V \qquad or \tag{11}$$

$$DPC = \frac{C_{p_d}}{C_p} = \frac{1.4}{0.35} = 4 \quad \Rightarrow \quad V_d = \sqrt[3]{\frac{1}{DPC}}\ V = \sqrt[3]{\frac{1}{4}}\ V = 0.63\ V \tag{12}$$

To draw the power curves for the ducted wind turbine type-A (D.W.T type-A) and the ducted wind turbine type B (D.W.T type-B), the power curve of the ductless wind turbine (Ductless W.T) scaled to 0.8 and 0.63 at equal power, respectively (see in Figure 7). According to Figure 7, cut-in and cut-out are changed. These changes are shown in Table 3.

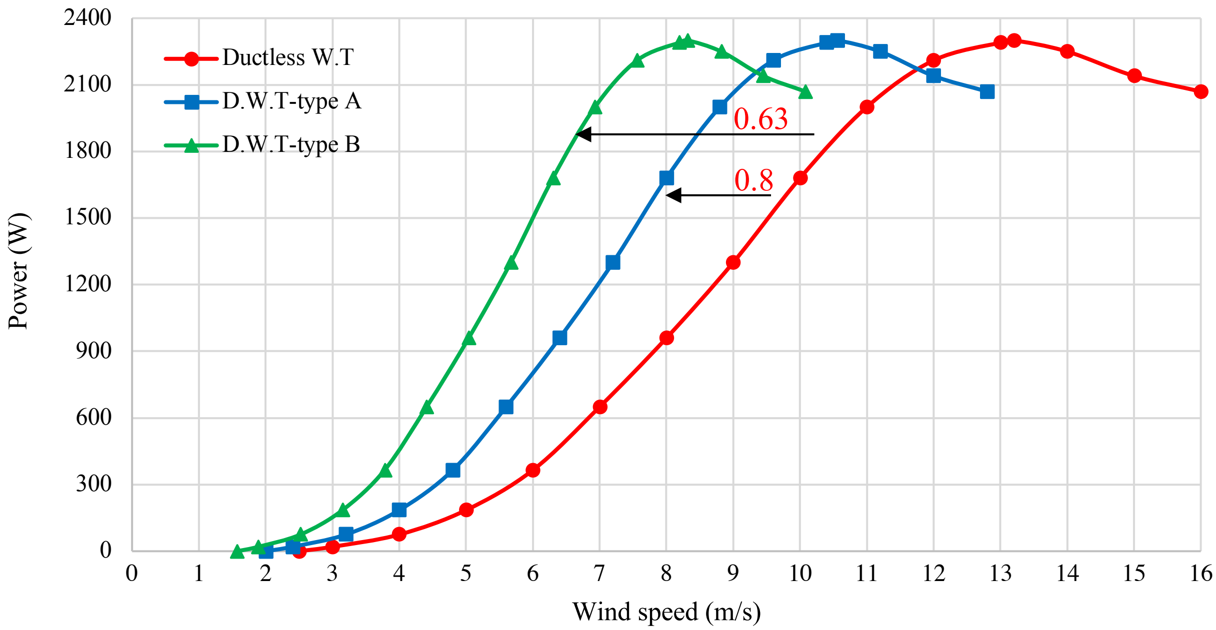


Figure 7. Power curve to wind speed for ductless and ducted wind turbines for type-A and type-B

Table 3. Properties of the ducted and ductless wind turbines

Properties	Unit	Ductless W.T	D.W.T type A	D.W.T type B
Maximum Power	W	2300	2300	2300
Cut-in speed (V_c)	m/s	2.5	2	1.575
Cut-out speed (V_f)	m/s	16	12.8	10.08
Max-power wind speed	m/s	13.2	10.56	8.316

The following results are obtained by adding the ducts:

1. More output power at the same wind speed.
2. Cut-in, cut-out, max-Power wind speed is reduced.
3. Maximum output power (2300 Watts) is equal for all.
4. Maximum output power is reached at a lower wind speed by the ducted wind turbine.

Annual Energy Production (AEP)

The AEP define as energy output for a wind turbine for one year (Hau, 2006; Powell, 1981; Torres et al., 2003). The AEP(v) can be suggested as:

$$AEP(v) = 8760\,\frac{\rho}{\rho_0}\,P(v)\,f(v) \tag{13}$$

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \tag{14}$$

Where f(v) is Weibull distribution; P(v) is power curve data (KW); (ρ) is air density (kg/m^3); (ρ_0) is air density in standard conditions (kg/m^3); (k) is shape factor and (c) is scale factor (m/s). By using of relation (13) and Table 1, annual energy production to wind speed (AEP(v)) for 4 areas, are shown in Figure 8.

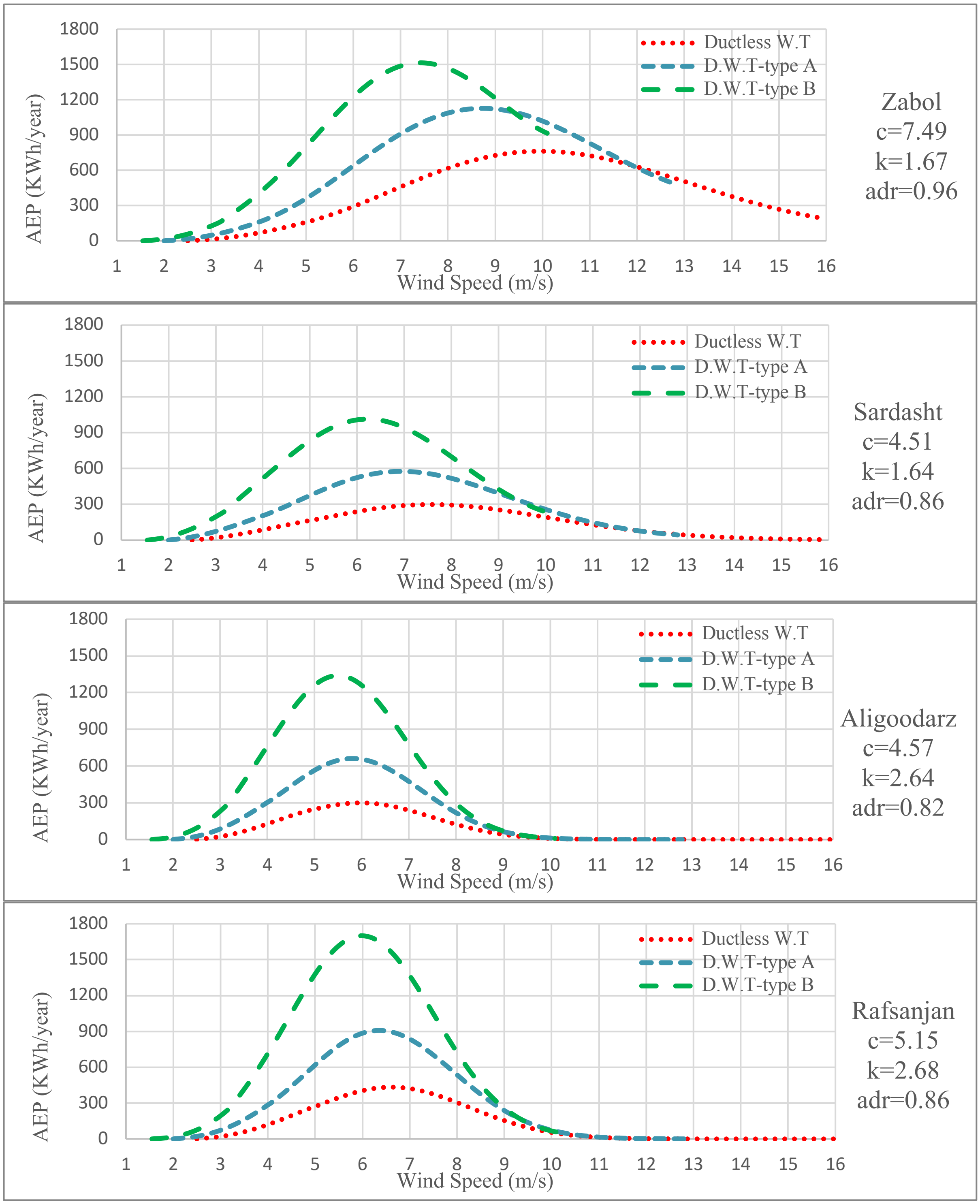


Figure 8. AEP to wind speed for different areas

By calculating the area under the curves of Figure 8 or solving the following integral of relation (15) for different areas, Figure 9 is obtained, which shows the AEP diagram of the turbines in each area based on DPC. Results revealed that the DPC for Ductless W.T, D.W.T type-A, and type-B are 1, 1.93, and 4, respectively.

$$AEP = \int_{v_c}^{v_f} AEP(v)\, dv \tag{15}$$

Where V_c is cut-in wind speed (m/s), and V_f is cut-out wind speed (m/s).

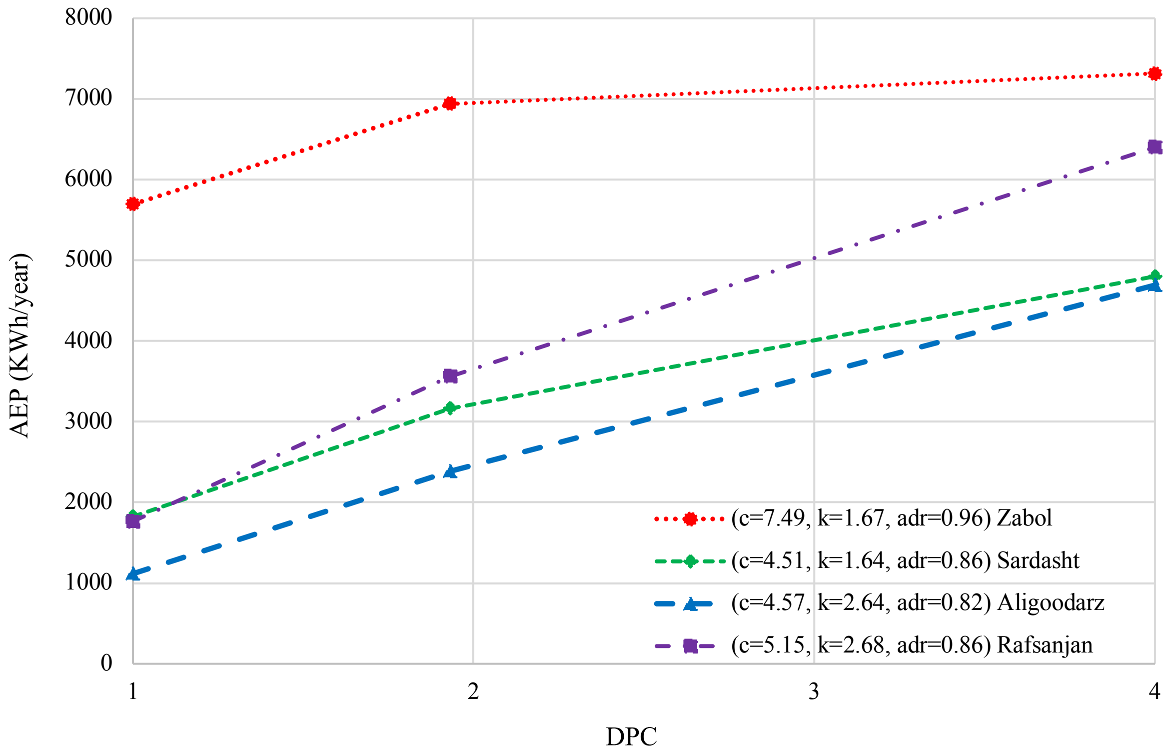


Figure 9. AEP to DPC for different areas

A ducted wind turbine's AEP is expected to be DPC times of the ductless wind turbine's AEP, which is not always the case.

Computation results show that the ducted wind turbines have different AEP based on the area wind speed, turbine design, and DPC. For this reason, duct efficiency is defined. This index for a ducted wind turbine can be different in each area with different wind conditions. Equation (16) shows the duct efficiency.

$$Duct\ efficiency = \left(\frac{AEP\ with\ duct}{AEP\ without\ duct}\right) / \ DPC \tag{16}$$

Where the AEP is annual energy production, and DPC is duct power coefficient. Duct efficiency can be more than 100% because, at any wind speed, it is possible that a ducted turbine can produce power more than DPC times a ductless turbine. The reason for increasing the power more than DPC times is as follows:

Suppose at the same wind speed ($V_d = V$), ducted turbine power is (P_d), and ductless turbine power is (P). The wind turbine power scale is obtained from the following equations:

$$V = V_d \tag{17}$$

$$\sqrt[3]{\frac{P}{0.5\, \rho\, C_p\, A}} = \sqrt[3]{\frac{P_d}{0.5\, \rho\, C_{p_d}\, A}} \tag{18}$$

$$\sqrt[3]{\frac{P}{C_p}} = \sqrt[3]{\frac{P_d}{C_{p_d}}} \tag{19}$$

$$\frac{P}{P_d} = \frac{C_p}{C_{p_d}} \tag{20}$$

$$P_d = \frac{C_{p_d}}{C_p}\, P \tag{21}$$

Where (ρ) is air density; (A) is the rotor swept area; (Cp) is ductless turbine power coefficient, and (Cpd) is ducted turbine power coefficient.

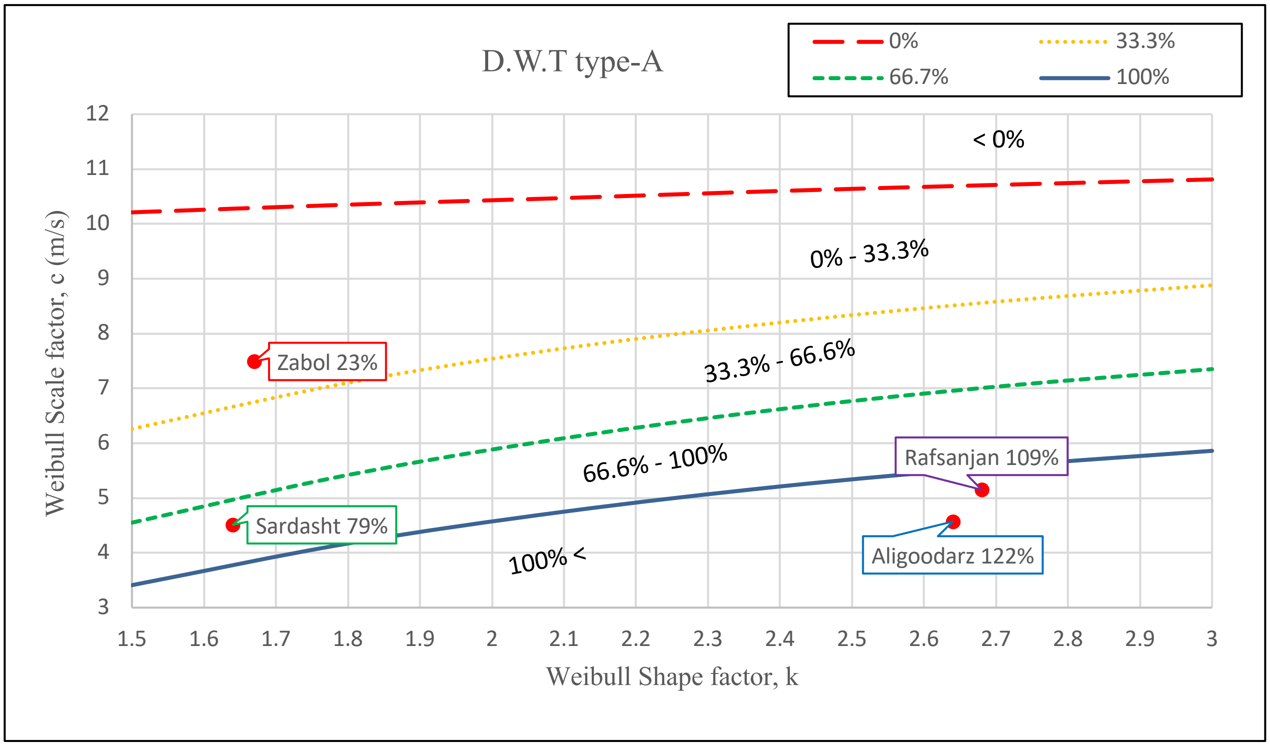
$\frac{C_{p_d}}{C_p}$ in equation (21) isn't DPC, because turbine powers in the Cpd and Cp aren't equal. For this reason, at the same wind speed, Pd can be greater than DPC*P and thus $\left(\frac{AEP\ with\ duct}{AEP\ without\ duct}\right)$ can be greater than DPC, and as a result, Duct efficiency is more than 100%. By calculating duct efficiency, Figure 10 presents duct efficiency for all areas.

Based on computation and results are shown in Figure 9 and Figure 10, the following results emerge:

1. By adding duct to the turbine, AEP is increased in all areas
2. In different wind conditions, duct efficiency varies.
3.

AEP for Ductless W.T, D.W.T type-A and type-B in different Weibull parameters include of: scale factor (c) = (4, 7, 10) and shape factor (k) = (1.5, 2, 2.5) are shown in Figure 11.

According to the information emerges from Figure 11, the following results can be summarized:
1. The shape factor (k) has directly related to AEP. In very low wind speeds, this relationship is reversed due to the reduction of cut-in speed.
2. The scale factor (c) has directly related to AEP. In extreme wind speeds, this relationship is reversed due to reducing the cut-out speed.
3. The DPC has directly related to AEP. In extreme wind speeds, this relationship is reversed due to the reducing cut-out speed. Thus the duct has a negative effect and reduces the AEP.



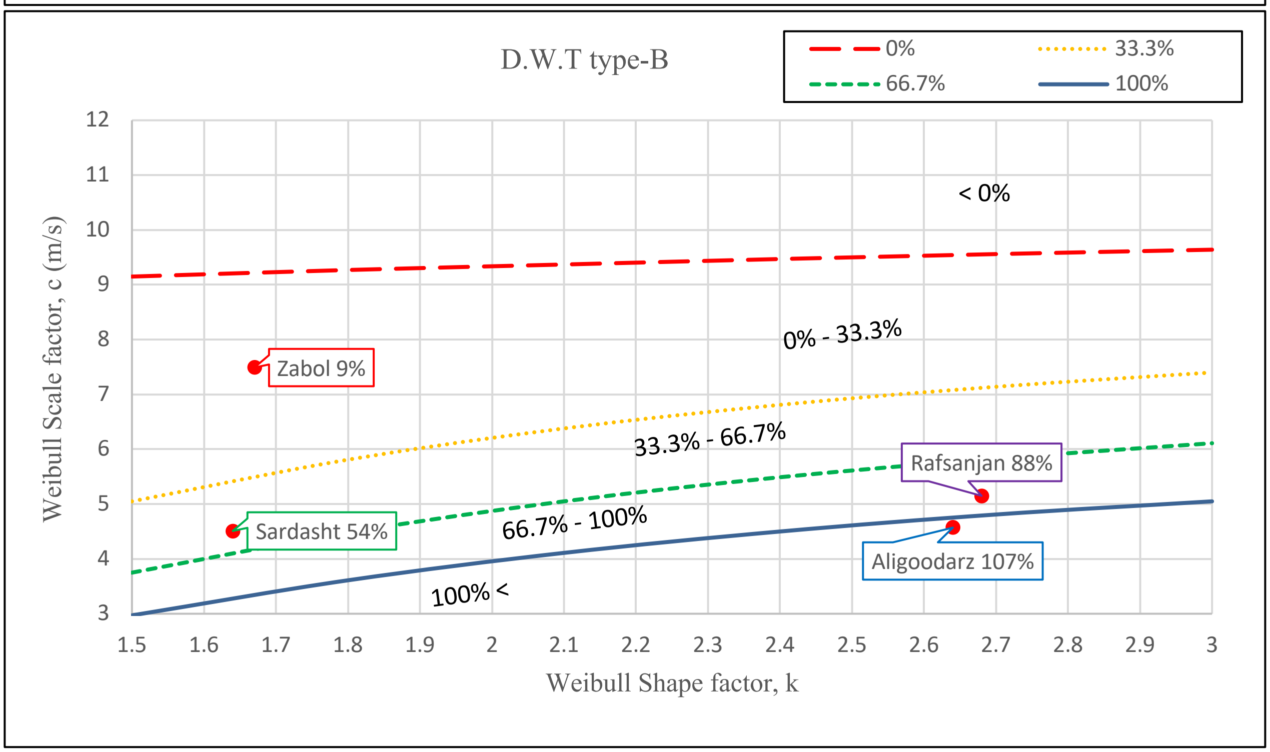


Figure 10. Duct efficiency for all areas.

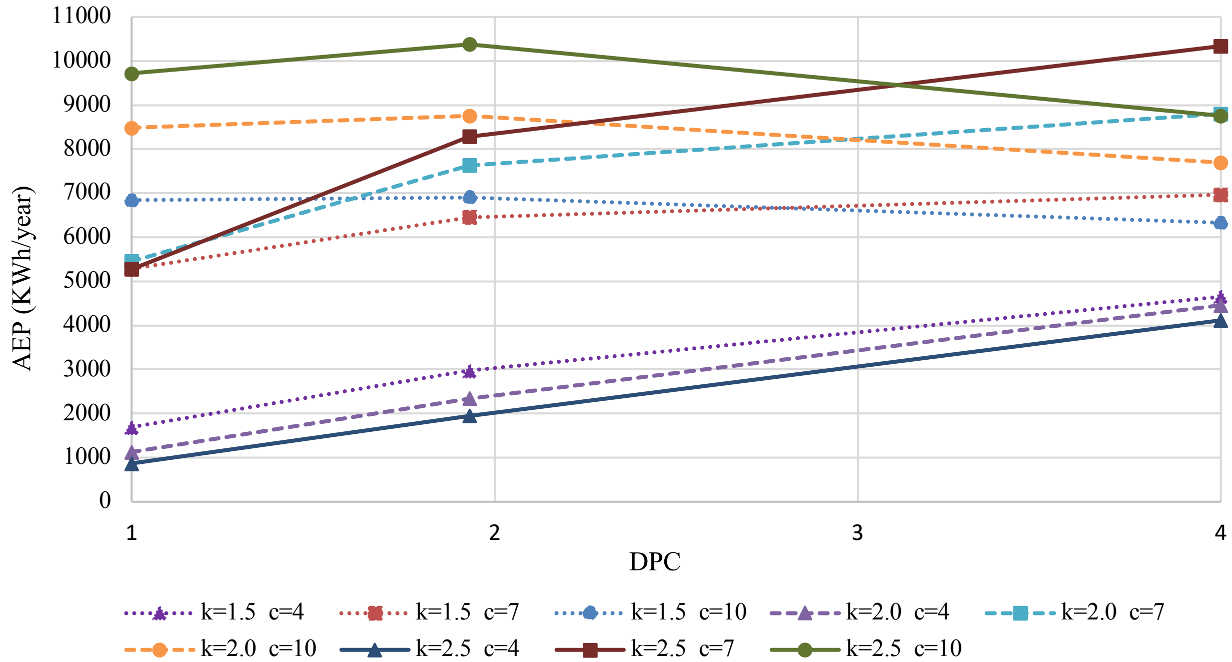


Figure 11. AEP to DPC for Ductless W.T, D.W.T type-A and type-B in different Weibull parameters

Levelized cost of energy (LCOE)

In the method of Levelized cost of energy (LCOE), an approach is used, which is the same as the present value method. The costs become uniform in this method to the annual payment. In other words, LCOE well-defined as a fixed income for selling a single product that can cover all the project lifetime costs (Cassedy, 2000). According to equation (22), LCOE can be calculated:

$$LCOE = \frac{(R\times C)+(M\times C)}{AEP} \tag{22}$$

Where LCOE is levelized cost of energy ($/kWh); (R) is capital recovery factor; (M) is the fraction of total cost for maintenance, M in this paper is 0.02 (Nouni et al., 2007); (C) is initial capital cost ($); AEP is annual energy production (kWh). The capital recovery factor (R) and the initial capital cost (C) can be calculated using equations (23) and (24).

$$R = \frac{d(1+d)^n}{(1+d)^n - 1} \tag{23}$$

$$C = C_{duct} + C_{turbine} + C_{inverter} + C_{tower} + C_{civil} + C_{miscellaneous} \tag{24}$$

Where (n) is useful lifetime (year), in this paper n=25 years; d is discount rate (%), for Iran d=16%.

The duct economic properties for Ductless W.T, D.W.T type-A, and type-B are shown in Table 4. Aluminum sheets with 0.5 mm thickness and a rectangular steel tube (20*10 mm) with 2 mm thickness of the materials needed for ducts construction (see Figure 4). Steel round tube with 15 cm diameter, 3mm thickness and 9 m length is used for the tower. Also, the economic properties are shown in Table 5.

Table 5 shows the economic calculations for turbines based on equations (23) and (24). By obtaining LCOE, Figure 12 is drawn for turbines in DPC different for all areas.

Table 4. Duct economic properties

Properties		Unit	Ductless W.T	D.W.T Type-A	D.W.T Type-B
Aluminum sheets-0.5mm thickness	Area	m^2	0	12.04	105.1
	2700 Kg/m^3	Kg	0	16.25	141.88
	3 $/Kg	$	0	48.75	425.65
Rectangular tube - steel (20*10 mm)	Length	m	0	44.77	86.79
	0.94 Kg/length	Kg	0	42.08	81.58
	0.5 $/Kg	$	0	21.04	40.79
Manufacture	Roll, Weld, paint & …	$	0	30	60
Duct	Sum	$	0	~ 100	~ 525

Table 5. Economic calculations

Properties			Unit	Ductless W.T	D.W.T Type-A	D.W.T Type-B
Duct	C_{duct}		$	0	100	525
Wind Turbine 2KW 48V	$C_{turbine}$		$	460	460	460
Inverter (Efficiency 90%)	$C_{inverter}$		$	200	200	200
Tower	C_{tower}		$	60	60	60
Civil Work	C_{civil}		$	50	50	50
Miscellaneous	$C_{miscellaneous}$		$	100	150	150
Total Cost	C		$	870	1020	1445
Maintenance (0.02*C)	(M*C)		$	17.4	20.4	28.9
Capital recovery factor	R		$	0.164	0.164	0.164
Annual cost	(R*C) + (M*C)		$	160.1	187.7	265.9
Annual Energy Production (with inverter efficiency)	AEP	Zabol	KWh	5126	6244	6585
		Sardasht	KWh	1641	2846	4321
		Aligoodarz	KWh	1005	2149	4224
		Rafsanjan	KWh	1588	3205	5761
levelized cost of energy	LCOE	Zabol	$/KWh	0.031	0.030	0.040
		Sardasht	$/KWh	0.098	0.066	0.062
		Aligoodarz	$/KWh	0.159	0.087	0.063
		Rafsanjan	$/KWh	0.101	0.059	0.046

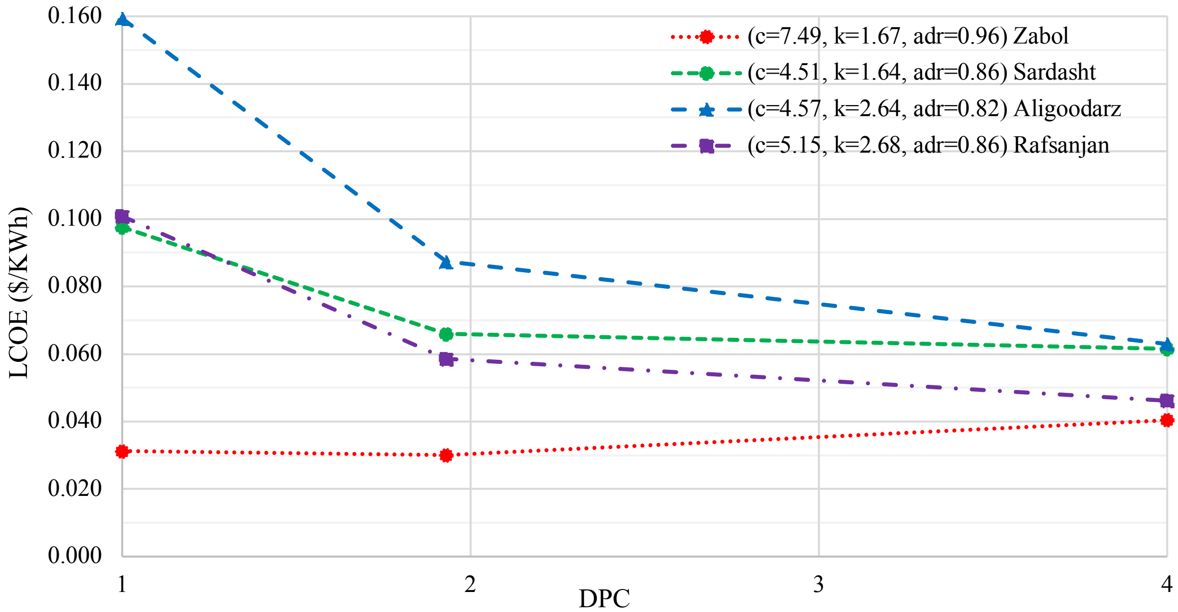


Figure 12. LCOE to DPC for all areas

Following results can be obtained by constructing ducts and calculating the economics of the turbines in different areas:

1. The lowest LCOE in Zabol with duct type-A will be done (0.03 S/KWh).
2. Due to the low wind speed in the Aligoodarz, the LCOE is reduced by up to 2.5 times.
3. Except for Zabol, the DPC to the LCOE in other areas is inversely related.

Conclusion

This study adds ducts to maximize AEP and minimize the LCOE, which are discussed. The following information was applied in this study:

1. Wind and geographic characteristics of Zabol, Sardasht, Aligoodarz, and Rafsanjan Areas in Iran are used.
2. Information of Wuxi Ruifeng 2KW 48V wind turbine, the (S ii), and the prototype ducts are applied.

The following results are to be obtained by this research:

1. Ducts in low-wind speed areas can reduce LCOE up to 2.5 times or even more.
2. The effect of ducts in areas with extreme wind speeds is reduced.
3. If the duct is not selected according to the turbine and the area's wind conditions, it may not increase the AEP and reduce it.
4. Adding ducts in wind turbines is recommended for urban or low and medium wind areas.

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