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Technical Note

A sensitivity analysis for the design of small-scale hydropower plant: Kayabogazi case study

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Abstract

In this study, the feasibility of hydroelectric power generation from the Kayabogazi dam, which was built by The State Hydraulic Works of Turkey (DSI) in 1987 in the town of Tavsanli, Kutahya, for irrigation and flood control purposes is investigated. Since a certain amount of water is supplied from the dam to the town of Tavsanli as drinking water, that amount is deducted from the total and is not allowed to be used in the process of electric power generation. By evaluating the amount of incoming water to the Kayabogazi dam in the period of 1995 and 2003 years, the most agreeable turbine type and size is decided for a small hydropower plant (SHP). In this purpose, seven different cases have been taken into consideration. As a conclusion, the case used three turbines which one of them is installed to utilize from the higher flow rates has been determined as the best configuration. In this study, a power generation ranging between 0.313 and 4.997 MW has been achieved in the viewpoint of installed capacity for Kayabogazi dam. Hence, it has been estimated an electricity generation up to 10,579 MWh per annum.

Keywords: Electricity; Sensitivity analysis; Small hydropower plant; Turkey

1. Introduction

In recent years due to the harmful effects of conventional power stations to the environment, installations utilizing renewable energy sources have been subject to renewed interest both in developing and in industrially developed countries. Hydroelectric power as a proven and well-advanced technology providing 19% of the world's electric power from both large and small power plants [1]. Small hydropower plants (SHPs), in the most cases, constructed as "run-of-river", with no dam. An SHP requires a sizable flow and an adequate head of water, which is available without building elaborate and expensive facilities. SHPs can be developed at existing dams and can be constructed in connection with water level control of rivers, lakes and irrigation schemes. By using existing structures, only minor new civil engineering work is required; therefore, the initial investment costs are considerably reduced. In addition, they do not have negative effects to the environment such as replacement of settlements, loss of historical sites and agricultural fields, destruction of ecological life. Although there is no universally agreed definition for "small hydro", the upper limit varies between 2.5 and 25 MVA and a maximum of 10 MW is the most widely accepted value worldwide. The terms mini- and micro-hydro are also used to refer to groupings of capacity below the "small" designation. Generally in industrial terms, mini- and micro-hydro typically refer to schemes below 2 MW and below 500 kW, respectively [1]. These are arbitrary divisions and many of the principles involved apply to both smaller and larger schemes [1,2].

In literature [3–10], many studies are present in which hydropower is evaluated. Houri [3] in his study, evaluated the hydropower in the electricity generation aspect for Lebanon. Mamlook et al. [4] have used neuro-fuzzy programming method to evaluate different electricity generation options for several energy sources in Jordan and found out that the hydropower is the best system

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Nomenclature

D	diameter of penstock, m
H_f	friction losses, m
H_{net}	net head, m
H_{sum}	total losses, m
L	length of penstock, m
Q	flow rate, m^3/s
Z	gross head, m
b	width between bars, mm
g	gravitational constant, m/s^2
k_b	coefficient of bend losses
k_e	coefficient of entrance losses
k_v	coefficient of valve losses
k_{scr}	coefficient of screen losses
n	Manning coefficient
t	bar thickness, mm

Greek letters

Φ	angle of inclination from horizontal, rad
v	velocity of the flow, m/s

combined with solar and wind systems. Mungwena [5] evaluated the Zimbabwe's hydropower potential in major dams using the general technique. Egre and Milewski [6] have exposed the diversity of hydropower projects; hence, they have determined that there is a wide variety of hydroelectric projects, each providing different types of services and generating environmental and social impacts of different nature and magnitude. Castellarin et al. [7] using flow–duration curves, have determined the reliability of the ungauged basins in Italy. Dudhani et al. [8] in their study, evaluated the potential of small hydropower. In this regard, they have used the remote sensing data taken from satellite in India. Kishor et al. [9] have made a review study on hydropower models and controls; hence, they exposed the importance of controlling mechanisms in the viewpoint of a hydropower plant structure. Kaldellis et al. [10] have evaluated the SHPs of Greece in the techno-economical aspect. They have used a sensitive analysis method for this aim.

In Turkey, the sources suitable for SHPs are generally used for agricultural irrigation purposes. Having 433 billion kWh gross theoretical hydro-potential, Turkey has a share of 1% of world hydro-potential and with its 125 billion kWh economically exploitable potential, this share is about 15% in European hydropower potential [2,11]. The total number of hydropower stations with less than 10 MW installed capacity is 93. Of these 89 are run-of-water and the others are dam or lake hydropower schemes with total installed capacity of only 83.8 MW [11].

2. Material and method

Kayabogazi dam was built by The State Hydraulic Works of Turkey (DSI) on Kocacay River for irrigation and flood control purposes in 1987. It is located 34 km east of town of Tavsanli of Kutahya province. As can be seen from Fig. 1, it is an earth- and rock-filled dam with height (from the river bed) of 38 m and with a volume of 628,000 m^3.

At normal water elevation, the area of the reservoir is 3.00 km^2 with a volume of 38.00 hm^3. By using the water from this dam, 7000 ha of agricultural land is irrigated per annum. The modeling of the Kayabogazi hydroelectric power station is based on generation of power from 130 million m^3 of water currently used for agricultural irrigation only. For this reason, the data related to the water flow rate recorded by DSI between the years of 1994 and 2003 is evaluated. To take into account the effects of another dam, which was commissioned before the Kayabogazi dam on the same river bed in 1994, the data before that was not taken into account.

From the records between the years 1994 and 2003, it is seen that the maximum altitude of water hardly exceeded 918 m. The maximum level of water was regulated at 917 m by DSI and in this study the maximum level of water was assumed to be 918 m. The monthly average rate of water flow to the dam as total and production values is given in Fig. 2. As seen from the figure, the incoming flow rate is highly time dependent and not stable. The amount of monthly average of flow varied from 0.056 to 18 m^3/s. The total volume of the reservoir is 34.4 million m^3 and rather small. While in some years with relatively more rain fall, the total amount of incoming river flow was higher than 200 million m^3/year, in the year 2001 which was the driest of all the years investigated the total water volume remained at a record low of 57 million m^3. In general, the average annual rate of flow has been 130 million m^3. Since the physical size of the reservoir is not adequate in dry seasons, the volume of water cannot be regulated for more than a few months. In this case, the electric power to be

Fig. 1. The Kayabogazi dam.

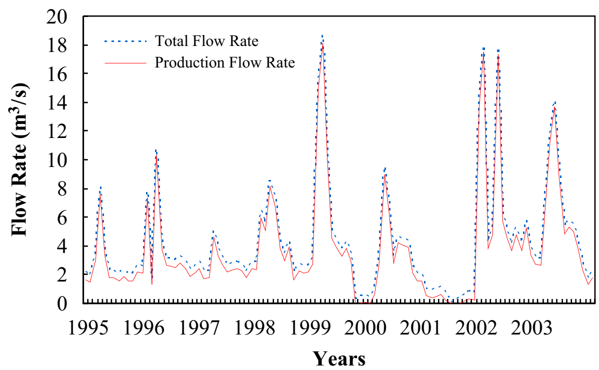

Fig. 2. The average flow to Kayabogazi dam.

produced will be highly dependent on the incoming water flow to the dam and will be subject to variations.

In this study, by evaluating the amount of incoming water to the Kayabogazi dam in the period of 1995 and 2003 years (since a certain amount of water is supplied from the dam to the town of Tavsanli as drinking water, that amount is deducted from the total and is not allowed to be used in the process of electric power generation), it has been targeted to get the most available power plant design. In this purpose, seven different cases have been taken into consideration. These cases are as follows:

Case I describes the present situation of the dam. In this case, it has been considered that the turbine is located at the end of the existing penstock which has a diameter of 1.0 m and a length of 270 m (see Fig. 3). In this case, the gross head is 18 m.

Case II is the developed form of Case I where it is considered that the turbine is located at the 10^{th} m of the penstock.

Hence, it is aimed to decrease the penstock losses since it has approximately a horizontal position (see Fig. 4). For this case, the gross head has been determined as 16 m.

Case III is the new configuration plant. In this case, the plant has been redesigned; therefore, it has been targeted to increase the gross head to 33 m. In this scheme, the diameter of penstock has been chosen as 1.5 m to decrease the losses. Although the head is increased, the length of penstock, about a length of 60 m, is less in comparison with Cases I and II. By investigating five different configurations (Cases IIIa, b, c, d, e), the effect of multiple turbine employment on power generation has been determined. In Fig. 5, the considered configurations are illustrated.

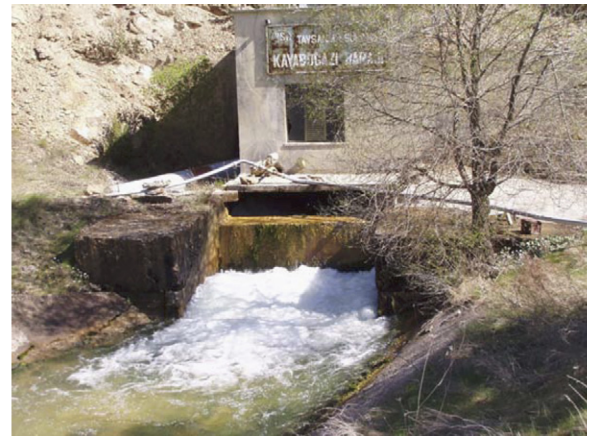

Fig. 3. Considered location of turbine for Case I.

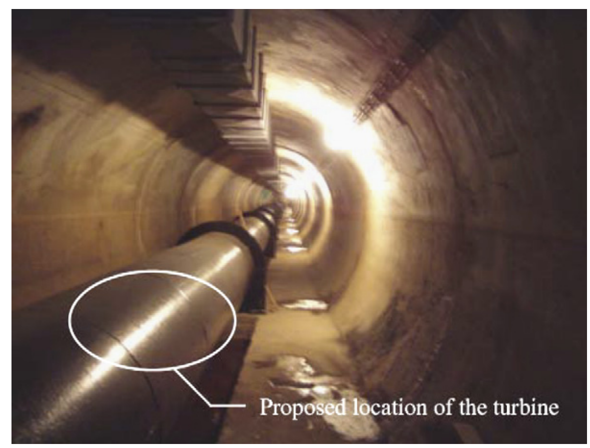

Fig. 4. Considered location of turbine for Case II.

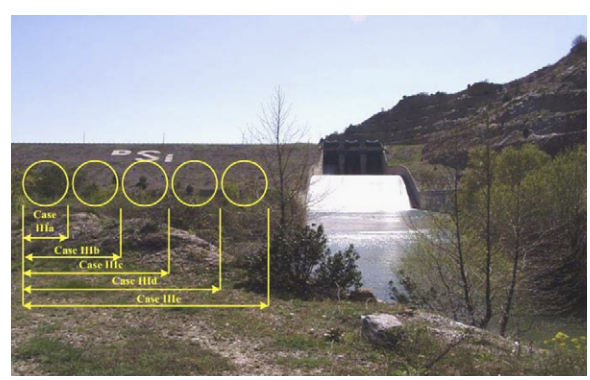

Fig. 5. Penstock locations for Case III.

2.1. Determining net available head

For a sensitive analysis, the losses in the process must be calculated carefully to determine the net available head. In a hydropower plant, the most important losses are commonly friction losses, H_{f}. A few empirical formulas have been developed for this purpose in the literature. One of these formulas widely used to estimate the friction losses in the flow in open channels, but also applicable to closed pipes, is that developed by Manning [12]:

$$H_{\mathrm{f}} = \frac{10.29 n^2 Q^2}{D^{5.333}} L, \tag{1}$$

where D is the diameter of the penstock, L is the length of penstock and n is the Manning coefficient.

Additionally, a few losses depended on the velocity of flow occur in a hydro system. These losses can be enumerated as screen losses (H_{scr}), entrance losses (H_{e}), bend losses (H_b), and valve losses (H_v). The sum of these losses (H_{sum}) can be calculated with the following formulate [13,14]:

$$H_{sum} = \left(k_{scr}\left(\frac{t}{b}\right)^{4/3}\sin\phi + k_e + k_b + k_v\right)\left(\frac{v^2}{2g}\right). \quad (2)$$

So, the net available head is given as follows:

$$H_{net} = Z - (H_f + H_{sum}), \quad (3)$$

where Z is the gross head. The values used in the determination of losses are given in Table 1. The variation of net head versus years has been given in Fig. 6. In this figure, the net head values have cumulated in two groups due to difference between the gross heads of the cases studied.

As seen in Fig. 6, the net head values are varied from 22 to 33 m for the new design and from 11 to 18 m for the present case designs considered. In the new design conditions, particularly for Cases IIIb–e, the change of net head is rather small.

2.2. Determination of turbine types

Since every region has a unique characteristics in SHP applications, it is very important to determine the most suitable turbine type. In this study, the flow rate—net head chart given in Ref. [13]—is used to determine the turbine types. In this purpose, the data of Kayabogazi dam and the calculated net head values have been sensitively marked on this chart; so, the agreeable turbine types have been designated as seen in Figs. 7–13.

According to Figs. 7–13, the best agreeable turbine types are Crossflow, Francis and semi-Kaplan turbines for all cases. Since the dam studied has variable flow rates of incoming water and the semi-Kaplan turbine, depending on adjustable guide vanes, has poor part-flow efficiency, only Crossflow and Francis types have been considered in this study.

Table 1
The parameters used in the calculations [13]

Parameter	Symbol	Unit	Value
Manning coefficient	n	–	0.012
Coefficient of screen losses	k_{scr}	–	1.8
Bar thickness	t	mm	3
Width between bars	b	mm	10
Angle of inclination from horizontal	Φ	rad	1.22
Coefficient of entrance losses	k_e	–	0.5
Coefficient of bend losses	k_b	–	0.14
Coefficient of valve losses	k_v	–	0.05

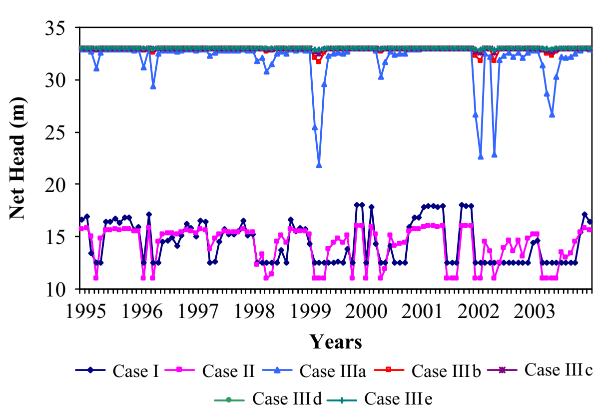

Fig. 6. Net head for considered cases.

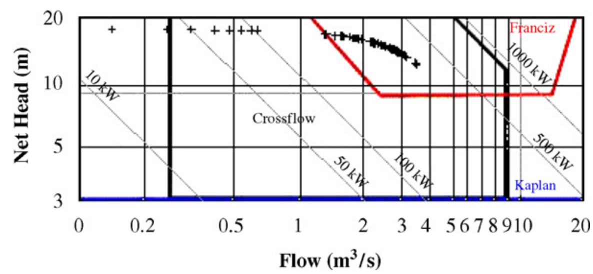

Fig. 7. Head-flow ranges of hydro turbines for Case I.

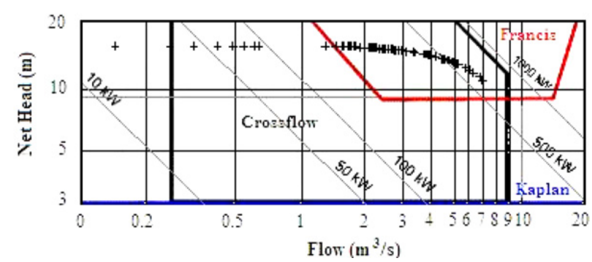

Fig. 8. Head-flow ranges of hydro turbines for Case II.

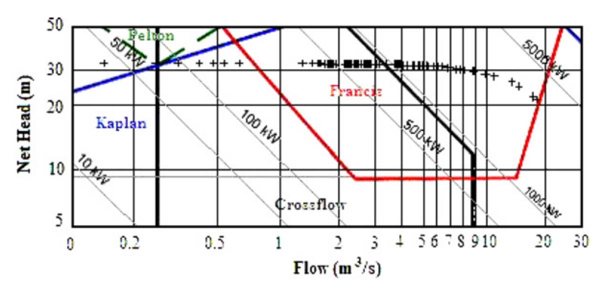

Fig. 9. Head-flow ranges of hydro turbines for Case IIIa.

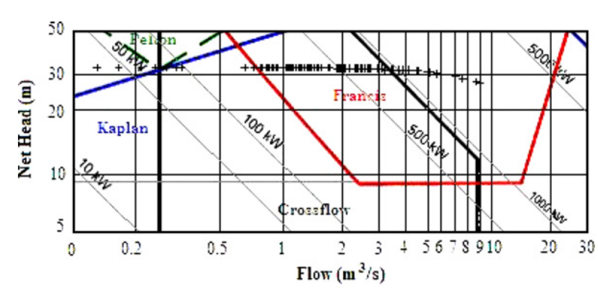

Fig. 10. Head-flow ranges of hydro turbines for Case IIIb.

2.3. Determination of turbine efficiencies

The turbine efficiencies change depending on both the design points (DPs) and reduced flow rates. Therefore, when one needs to determine the efficiency of a turbine, a relative efficiency must be taken into consideration. Paish [1] has presented a chart for typical turbines in which the efficiency change versus rated flow is illustrated. Based on this chart, to determine relative efficiency, different DPs for each case have been chosen. In this study, three DPs have been determined taking the data of Figs. 7–13 into consideration for both Crossflow and Francis turbines. These points have been selected for the minimum and maximum data within the limits of these two turbine types and for the data where it has a more density as shown in Table 2.

For the Crossflow turbine, the efficiencies range from 49% to 82% when the power generation is capable. It varies from 2% to 91% for the Francis turbine. The detailed values for each case and DPs have been shown in Table 3.

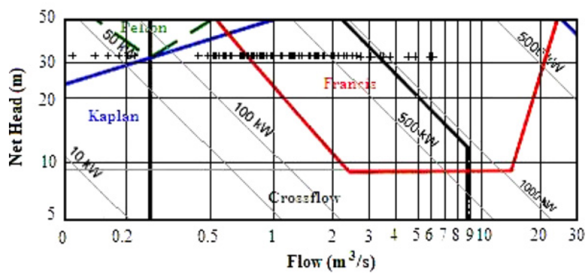

Fig. 11. Head-flow ranges of hydro turbines for Case IIIc.

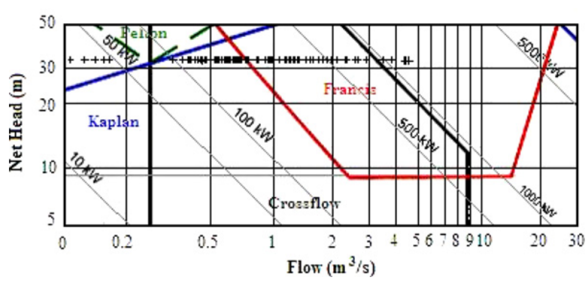

Fig. 12. Head-flow ranges of hydro turbines for Case IIId.

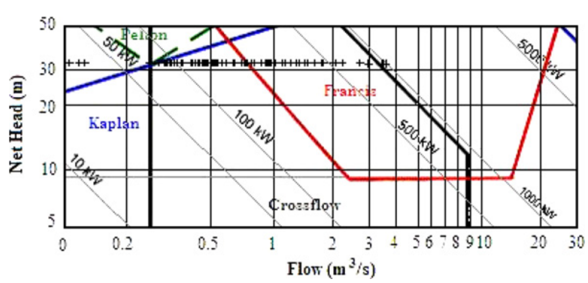

Fig. 13. Head-flow ranges of hydro turbines for Case IIIe.

2.4. Determining available power

The energy approximation is the best way to calculate available power generation in a turbine. So, it is given by the following equation:

$$P = \eta \times \rho \times g \times H \times Q, \tag{4}$$

where η, ρ, g, H and Q are the turbine efficiency, water density, gravitation constant, net available head and the flow rate, respectively.

In Case I, the highest power generation is achieved as 366 kW for DP3 with a Francis turbine. But this highest generation is not sustainable due to fluctuations of water supplied. Therefore, a power generation could be attained ranging from 123 to 366 kW for the DP3 with a Francis turbine. For the DP1 and DP2 with Francis turbine, this range is from 19 to 186 kW and from 11 to 312 kW, respectively. For the Crossflow turbine, the power generation ranges from 13 to 35 kW, from 26 to 281 kW and from 34 to 325 kW for DP1, DP2 and DP3, respectively. In Case II, the highest power production is achieved as 664 kW for DP3 with a Francis turbine. For this case, although the maximum power generation is higher in comparison to Case I, since the fluctuations in power generation are larger, the sustainability of power generation is lower. Therefore, a power generation could be attained ranging from 46 to 592 kW for the DP3 with a Crossflow turbine. For the DP1 and DP2 with Francis turbine, this range is from 22 to 195 kW and from 125 to 385 kW, respectively. This power generation ranges from 11 to 31 kW and from

Table 2
The design points for flow rates

Design point (m^3/s)	Case I	Case II	Case IIIa	Case IIIb	Case IIIc	Case IIId	Case IIIe
Crossflow							
DP1	0.25	0.25	2.20	1.20	0.80	0.70	0.50
DP2	2.40	3.00	2.70	2.00	1.30	1.00	0.90
DP3	3.35	6.90	3.40	3.30	3.30	2.80	3.00
Francis							
DP1	1.30	1.45	2.70	2.00	1.30	0.80	0.75
DP2	2.40	3.00	3.80	3.70	2.00	1.00	0.90
DP3	3.35	6.90	17.50	9.00	6.00	4.30	3.70

Table 3
The efficiency values

Efficiency (%)	Case I		Case II		Case IIIa		Case IIIb		Case IIIc		Case IIId		Case IIIe	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Crossflow														
DP1	79	81	79	81	64	82	60	82	60	82	49	82	60	82
DP2	60	82	64	82	49	82	60	82	64	82	60	82	49	82
DP3	60	82	49	82	60	82	60	82	67	82	65	82	49	82
Francis														
DP1	52	87	10	91	20	91	45	91	47	91	59	91	50	91
DP2	12	91	6	91	34	89	3	91	7	91	45	91	37	91
DP3	56	91	4	91	21	88	2	91	2	91	3	91	3	90

32 to 349 kW for DP1 and DP2 with a Crossflow turbine, respectively.

In Case IIIa, the highest power production is achieved as 3413 kW for DP3 with a Francis turbine. For this case, although the maximum power generation is higher in comparison to the other DPs, a continual power generation is not available during the whole year. Therefore, neglecting the small power generations in this case, ranging from 144 to 1054 kW for the DP2 with a Francis turbine, more sustainable power generation can be achieved. For the DP1 with Francis turbine, this range is from 35 to 755 kW. This power generation ranges from 52 to 560 kW, from 37 to 685 kW and from 62 to 847 kW for DP1, DP2 and DP3 with a Crossflow turbine, respectively. In Case IIIb, the highest power production is achieved as 4865 kW for DP3 with a Francis turbine. For this case, although the maximum power generation is higher in comparison to the other DPs, a continual power generation is not available during the whole year as in Case IIIa. Therefore, neglecting the small power generations in this case, it is more sustainable to obtain a power generation ranging from 62 to 2069 kW for the DP2 with a Francis turbine. For the DP1 with Francis turbine, this range is from 191 to 1123 kW. At this DP, the concerned curve has continuity in the viewpoint of sustainable power generation. The power generation ranges from 49 to 613 kW, from 80 to 1021 kW and from 95 to 1687 kW for DP1, DP2 and DP3 with a Crossflow turbine, respectively. The highest power production is achieved as 4997 kW for DP3 with a Francis turbine in Case IIIc. A continual power generation is not available during the whole year for this case, either. Neglecting the small power generations in this case, it is more sustainable to obtain a power generation ranging from 282 to 2536 kW for the DP3 with a Crossflow turbine. For the DP1 and DP2 with Francis turbine, this range is from 198 to 1097 kW and from 31 to 1687 kW, respectively. The power generation ranges from 49 to 614 kW and from 85 to 997 kW for DP1 and DP2 with a Crossflow turbine, respectively. In Case IIId, the highest power production is achieved as 4845 kW for DP3 with a Francis turbine. Neglecting the small power generations in this case, it is more sustainable to obtain a power generation ranging from 274 to 2863 kW for the DP3 with a Crossflow turbine. For the DP1 and DP2 with Francis turbine, this range is from 247 to 901 kW and from 191 to 1126 kW, respectively. The power generation ranging is from 40 to 716 kW and from 80 to 1022 kW for DP1 and DP2 with a Crossflow turbine, respectively. The highest power production is achieved as 5089 kW for DP3 with a Francis turbine in Case IIIe. Neglecting the small power generations in this case, it is more sustainable to obtain a power generation ranging from 206 to 3821 kW for the DP3 with a Crossflow turbine. For the DP1 and DP2 with Francis turbine, this range is from 209 to 1056 kW and from 154 to 1267 kW, respectively. The power generation ranging is from 49 to 639 kW and from 65 to 1151 kW for DP1 and DP2 with a Crossflow turbine, respectively. The annual average power generation for considered DPs and cases has been shown in Table 4.

2.5. Cost analysis

With respect to the nature of SHPs (lower than 5 MW), the costs are evaluated to be approximately US$500 per kW (including turbines, generators, governors, gates, control systems, power substation, electrical and mechanical auxiliary equipment, etc.) of power installation [15]. In this view of point, the costs belong to considered design options have been given in Table 5.

3. Results and discussion

In the evaluation of the present case (Case I), the most agreeable case is Francis-DP3 as seen in Fig. 14. In this case, the highest annual energy generation is about 3021 MWh in 2002 and the minimum one has been attained as 2082 MWh in 1995 except for 2001, due to extraordinary climatic conditions. However, the stable energy production has been attained as 228 MWh on an average in the Crossflow-DP1, although the generation capability is very low.

For Case II, the best option is the Crossflow-DP3 (see Fig. 15) with the highest generation of 4278 MWh. The most stable case is also Crossflow-DP1 as in Case I with

Table 4
Annual average power generation for considered options (kW)

Years	Turbine type	Design point	Considered cases						
			Case I	Case II	Case IIIa	Case IIIb	Case IIIc	Case IIId	Case IIIe
1995	Crossflow	DP1	30.23	29.39	475.60	493.35	493.75	518.04	500.15
		DP2	229.68	239.82	506.55	559.17	557.95	559.91	568.16
		DP3	249.27	263.37	539.20	599.51	606.56	595.81	561.93
	Francis	DP1	173.10	187.75	453.06	505.28	509.92	528.59	515.91
		DP2	243.84	238.02	418.48	344.46	413.29	506.06	484.70
		DP3	237.01	150.30	83.90	123.51	124.07	128.24	123.41
1996	Crossflow	DP1	28.40	28.35	525.13	570.08	570.97	623.56	587.42
		DP2	251.28	280.01	600.70	695.69	692.79	697.42	717.52
		DP3	287.99	335.62	648.33	794.71	869.39	875.24	849.08
	Francis	DP1	162.64	180.08	624.58	695.86	698.48	694.17	699.47
		DP2	274.30	300.88	589.47	643.07	660.34	697.74	688.64
		DP3	300.44	258.95	245.60	326.24	328.50	343.18	326.28
1997	Crossflow	DP1	29.20	29.62	534.32	569.67	569.99	602.99	580.89
		DP2	258.74	282.75	592.81	638.45	637.19	638.95	646.85
		DP3	281.30	292.46	621.85	638.92	618.00	608.01	576.93
	Francis	DP1	167.23	189.20	607.25	616.22	621.98	650.88	630.02
		DP2	284.10	301.53	513.06	383.12	489.22	616.74	590.39
		DP3	288.82	191.87	31.69	30.85	30.90	35.50	29.90
1998	Crossflow	DP1	27.02	27.38	539.82	586.92	587.85	650.95	604.65
		DP2	246.92	287.60	622.63	800.70	792.52	802.57	847.47
		DP3	300.10	400.05	710.88	978.69	1007.49	999.71	971.18
	Francis	DP1	154.75	174.86	655.03	835.16	828.58	759.65	815.17
		DP2	272.40	310.78	738.49	889.32	913.94	837.21	866.50
		DP3	318.70	357.63	296.06	367.42	368.80	395.16	363.58
1999	Crossflow	DP1	19.69	20.47	386.79	455.77	458.73	535.31	479.00
		DP2	178.99	232.13	474.70	698.56	693.46	704.75	751.11
		DP3	242.69	351.26	572.34	875.87	1083.22	1144.95	1293.05
	Francis	DP1	107.46	124.77	522.77	766.28	760.88	663.98	744.27
		DP2	197.11	256.65	661.73	893.98	864.47	773.08	813.12
		DP3	267.96	341.72	751.92	1002.01	1021.10	1031.70	1026.93
2000	Crossflow	DP1	25.52	25.70	445.72	484.00	484.77	543.17	499.94
		DP2	204.50	243.21	518.33	669.10	661.32	670.67	701.81
		DP3	251.13	323.34	592.59	776.50	812.38	808.59	784.62
	Francis	DP1	137.26	152.34	527.02	682.29	675.86	615.52	663.85
		DP2	216.97	254.20	604.58	669.67	704.25	684.01	706.92
		DP3	257.24	275.10	247.11	287.89	289.28	312.48	284.77
2001	Crossflow	DP1	23.92	21.33	95.12	105.99	106.74	112.74	108.74
		DP2	49.67	43.69	100.08	120.67	120.25	122.26	130.75
		DP3	51.13	53.13	102.40	148.66	210.56	238.56	297.43
	Francis	DP1	49.83	25.62	58.28	91.75	90.80	74.80	87.79
		DP2	24.96	24.01	72.16	169.73	139.69	93.49	105.35
		DP3	29.79	54.01	232.11	317.64	322.41	327.76	323.22
2002	Crossflow	DP1	24.47	26.24	524.50	608.84	612.04	713.55	638.80
		DP2	234.90	312.67	643.56	964.36	953.13	971.07	1049.38
		DP3	323.69	487.71	789.13	1198.03	1328.55	1379.05	1520.15
	Francis	DP1	140.12	167.60	708.89	1063.42	1051.74	891.04	1024.15
		DP2	258.69	344.89	947.82	1204.41	1237.92	1070.81	1146.08
		DP3	356.35	487.37	818.84	1035.44	1056.02	1071.81	1061.45
2003	Crossflow	DP1	26.37	25.96	510.65	574.73	576.94	652.56	597.38
		DP2	234.90	273.84	603.34	848.48	836.81	853.09	928.55
		DP3	299.96	447.22	709.32	1145.60	1341.56	1390.78	1435.03
	Francis	DP1	150.99	164.91	636.34	896.82	885.96	775.15	863.88
		DP2	255.64	294.59	786.27	1169.50	1115.77	901.89	971.59
		DP3	318.74	431.89	721.63	967.18	976.12	1014.53	971.44

Table 5
Costs of considered designs (US$)

Design point	Case I	Case II	Case IIIa	Case IIIb	Case IIIc	Case IIId	Case IIIe
Crossflow							
DP1	22,500	22,500	320,000	370,000	420,000	520,000	475,000
DP2	190,000	210,000	392,500	500,000	600,000	720,000	850,000
DP3	210,000	312,500	462,500	900,000	1,410,000	1,620,000	2,025,000
Francis							
DP1	130,000	130,000	392,500	500,000	600,000	640,000	700,000
DP2	140,000	210,000	550,000	990,000	787,500	720,000	850,000
DP3	210,000	312,500	2,075,000	2,890,000	3,240,000	3,260,000	2,500,000

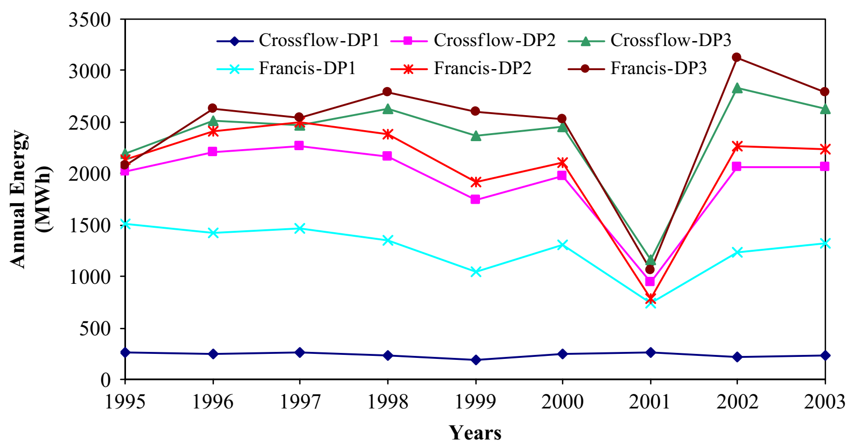

Fig. 14. Annual energy generation for Case I.

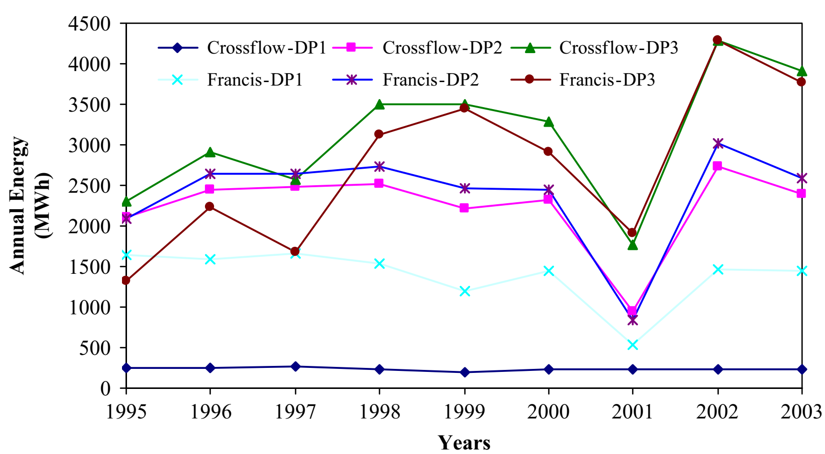

Fig. 15. Annual energy generation for Case II.

generation of 228 MWh on an average. Since Case II is the improved one of Case I, it could be understood that the friction losses is the most effective parameter that affects the energy generation. Hence, by changing the location of turbine, the energy generation has been increased by 106%.

In Case IIIa (see Fig. 16), the highest energy generation has been attained as 8295 MWh for Francis DP2, and excluding the year 2001, the lowest generation for Francis DP2 is estimated as 3680 MWh. Therefore, it can be concluded that this design is more stable for power generation. If the total energy generation is considered between the years of 1995 and 2003, the energy generation for Francis-DP2 and Crossflow-DP3 are so close to each other with the values of 46,692 and 46,320 MWh, respectively; hence, it would be a better option to select Crossflow-DP3, since the stability of this case is more agreeable.

In Case IIIb (see Fig. 17), the highest energy generation has been achieved as 10,579 MWh for Francis DP2. The lowest generation for Francis DP2 is 3019 MWh. For

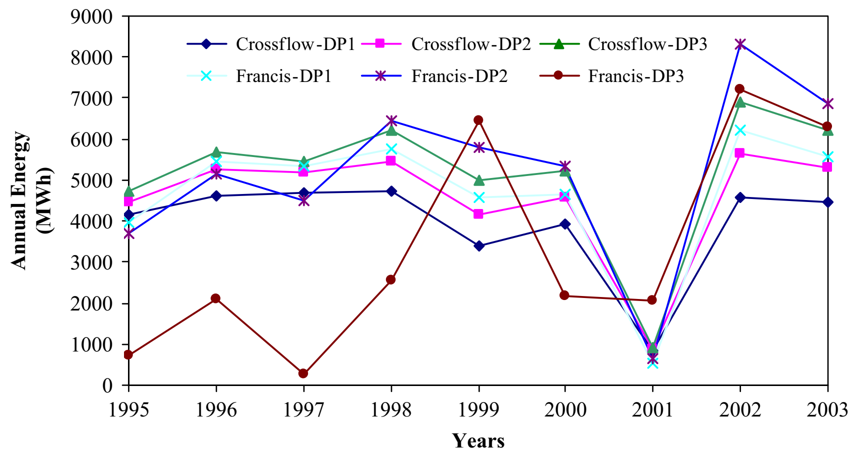

Fig. 16. Annual energy generation for Case IIIa.

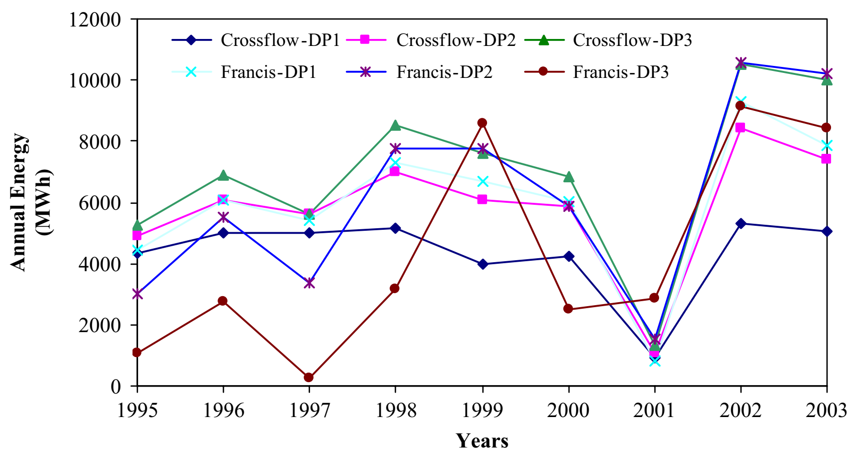

Fig. 17. Annual energy generation for Case IIIb.

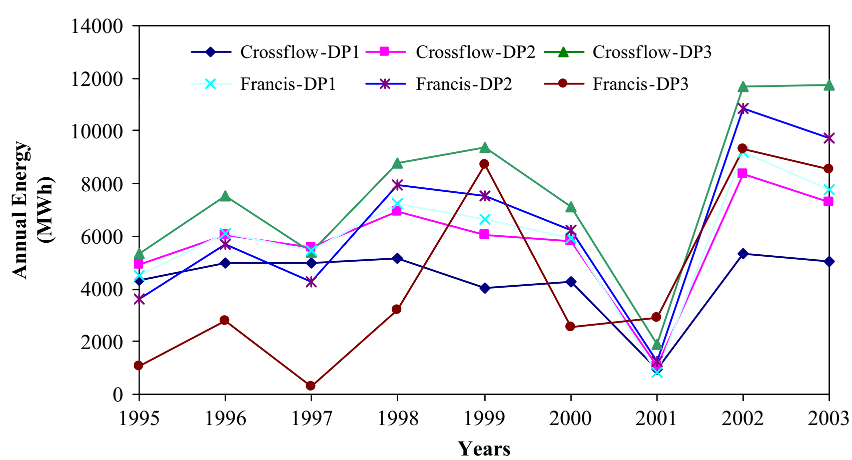

Fig. 18. Annual energy generation for Case IIIc.

Crossflow-DP3, the highest and lowest generations are, respectively, 10,512 and 5255 MWh (except for the year 2001).

The total generations for Case IIIb between the years of 1995–2003 are 55,573 and 62,577 MWh for Francis DP2 and Crossflow-DP3, respectively. Hence, the Crossflow-DP3 is the best option for this case, in the viewpoint of stability.

For Case IIIc (see Fig. 18), it is clear that the best design is Crossflow-DP3 with the highest generation of

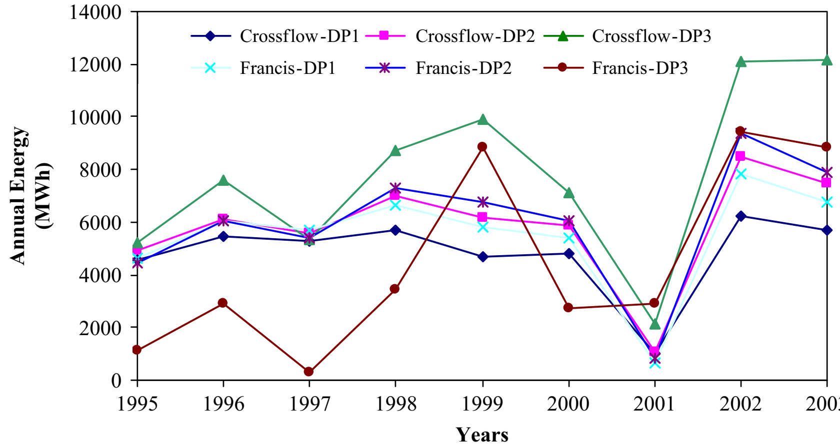

Fig. 19. Annual energy generation for Case IIId.

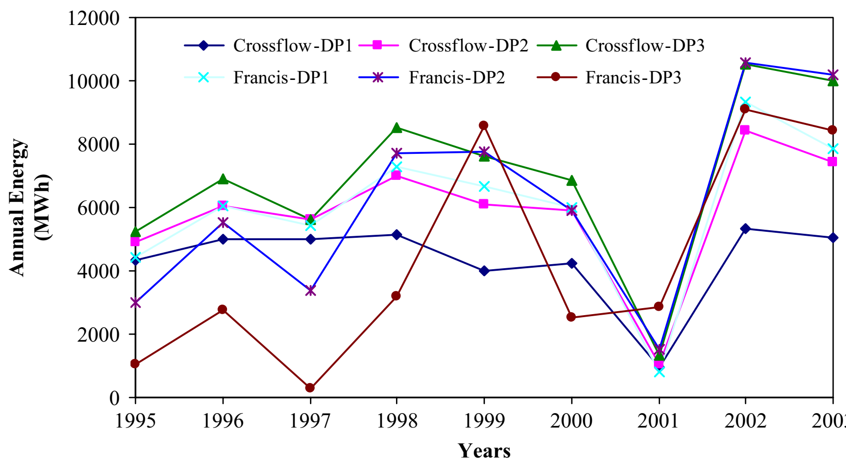

Fig. 20. Annual energy generation for Case IIIe.

11,725 MWh and the lowest generation of 5313 MWh except for the year 2001. The total generation from 1995 to 2003 for this case is 68,833 MWh.

As can be seen from Figs. 19 and 20, the best DPs are that of Crossflow-DP3. The highest and lowest generations for Case IIId are 12,158 and 5219 MWh, respectively. The total energy generation for this case from 1995 to 2003 is 70,251 MWh. The highest and lowest generations for Case IIIe are 13,343 and 4923 MWh, respectively. The total energy generation in this case is 72,393 MWh.

In the viewpoint of energy generation, it can be concluded that the most agreeable case is the Crossflow-DP3 for all cases except for Cases I and II.

4. Conclusions

In the present century in which the development level of the nations is evaluated with the energy consumptions per person, the most valuable thing is energy generation. In this regard, it has primary importance to get it by the clean and sustainable ways, since the global concerns such as global warming and energy scarcity, related to this generation, increase rapidly. Therefore, the renewable energy sources such as hydro, wind, geothermal and solar energy must be utilized as an alternative to fossil fuels. In this aspect, the small hydropower with its potential all over the world attracts attention amongst the other renewable energy resources.

In this study, a sensitivity analysis has been realized for Kayabogazi dam in Kutahya, Turkey. In the analysis, different cases have been evaluated to get the best design. In this aim, seven different cases have been studied. The first case is the present case in which the existing penstock is used. The second case is the improved case of the first one. The third one, which includes five different configurations, is completely the newest case. As a conclusion of the present study, the Crossflow turbine has been the most agreeable turbine type, since it is relatively more efficient despite the variable flow rates. In the study, it is also determined that the best design is obtained at the DP3. In Case III, energy generation increases in amount of 35.1% with the addition of the second turbine. With the addition of the third turbine, this rate is about 9.9%; hence, the overall investment cost increases in an amount of 50%. So, it is the best to design a plant with two turbines (Case IIIb). In addition to this, a Francis turbine can be added to the system as a third unit to exploit the high flow rates. Therefore, it is suggested to use an automatic control system to maximize the power generation from the dam.

Considering the installation of $2 \times 900\,\mathrm{kW}$ Crossflow turbines, the initial investment cost is estimated around US$0.9 million (excluding civil and power transmission line costs since the plant will be connected to the local power distribution network at 34.5 kV level). The corresponding price for the electricity production sold to the national grid is assumed equal to US$0.05 kWh (excluding the taxes). It is anticipated that with the implementation of option IIIb which has been explained above the SHP will pay back the initial investment costs in a period of 2.7 years.

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