Optimal Installation Capacity of Medium Hydro-Power Plants Considering Technical, Economic and Reliability Indices

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OPTIMAL INSTALLATION CAPACITY OF MEDIUM HYDROPOWER PLANTS CONSIDERING TECHNICAL, ECONOMIC AND RELIABILITY INDICES

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Abstract

One of the most important issues in planning the reservoir type of Medium Hydro-Power Plants (MHPP) is to determine the optimal installation capacity of the MHPP and estimate its optimal annual energy value. In this paper, a method is presented to calculate the annual energy. A computer program has been developed to analyze energy calculation and estimation of the most important economic indices of an MHPP using the sensitivity analysis method. Another program, developed by Matlab software, calculates the reliability indices for a number of units of an MHPP with a specified load duration curve using the Monte Carlo method. Ultimately, comparing the technical, economic and reliability indices will determine the optimal installation capacity of an MHPP. By applying the above-mentioned algorithm to an existing MHPP named "Bookan" (located in the west-north of Iran); the optimal capacity of 30MW is obtained.

Key Words: Medium Hydro-Power Plant (MHPP), Economic analysis, Monte Carlo method, Optimized installation capacity

1. Introduction

MHPPs have found special importance due to their relatively low administrative and executive costs and a short construction time compared to large power plants. These MHPPs are in the "reservoir" (annual or seasonal regulation reservoir) category with a domain capacity from 10MW to 100MW. The generated capacity is based on the accumulation of water reservoir and consists of a reservoir dam, penstock, power house, and tailrace structure of the body of the MHPP as well as other electrical and mechanical equipments. Seasonal regulation of the water volume in the headpond is used to get maximum power from the MHPP during peak and base hours. The amount of energy generated during different daily hours and/or different seasons of the year are the most important issues worthy of study in the reservoir type of MHPP studies. In other words, calculating the optimal installation capacity is one of the most important factors in planning MHPPs.

2. Determination of the optimal installation capacity

To determine the optimal installation capacity of MHPPs all technical, economic and reliability indices are considered in a trade-off relation. Using this approach, the amount of annual energy is determined by using categorized statistics of the output and overflow volume of water in different months or even days. Then, after specifying the income and costs of the plant, the economic indices of different alternatives are extracted. The reliability indices are then calculated and ultimately, through comparison of the technical, economic and reliability indices, a superior alternative can be selected, determining the optimal installation capacity.

2.1 Method of energy calculation

The calculation of energy is based on the status table of the output and overflow of the accessible water in month and daily, as well as the net level of water recorded in different years. The net height of the reservoir is a function of the input of water into reservoir and also the level of the water in the reservoir. Therefore, the height is not fixed in the different month. The useful net height can be extracted from the subtraction of the level of water in the reservoir and the level of axis of the turbine.

Due to considering the above-mentioned items in different months and also days, the maximum efficiency of MHPP and the earned energy can be calculated. Ultimately, the mean gained energy can be estimated. It should be noted that due to the section type of the turbine according to the USBR standard, and the other constraints of the turbine in the output and the net height of the reservoir the calculations are being done. Fig. 1 [See Fig. 1] shows the energy calculation algorithm.

In addition, with respect to the by-laws of the Ministry of Energy regarding energy purchases, energy generation in a day must be divided into three different types: peak load (4 hours), normal load (12 hours) and low load (8 hours). The high value of energy is categorized based on the peak, normal and low loads respectively, so the planner can choose different alternatives with the highest energy generation relative to the load. While coordinating between energy in peak and base states, the technical indices such as the plant factor of an MHPP should be within a reasonable and acceptable limit. With respect to the role of an MHPP in the load power system network, the recommended range should be 29% to 45%. [1].

2.2 Economic calculation method

In this section, the method of evaluation of income and costs and ultimately, the economic analysis of MHPPs are described [2]. The costs of the project are divided into two categories: investment and annual costs. Investment costs include civil costs, electro-mechanical equipment, power transmission line, and other indirect costs. Annual costs include the depreciation of equipment, operating and maintenance, and replacement costs. The income of the project is based solely on the sale of electrical energy.

2.2.1 Investment costs

Civil costs consist of the construction and hydro-structural costs of the project, including a reservoir dam, the water penstock structure, the power house, the tailrace structure, the access road and any future unpredicted costs taken from the preliminary designs of a feasibility study.

Electro mechanical equipment costs include turbines, generators, governors, gates, control systems, a power substation, electrical and mechanical auxiliary equipment, etc. With respect to the nature of MHPPs, the costs are evaluated to be approximately US$400/kW of power installation. [2-3].

Power transmission line costs include a power transmission line for delivering generated energy from power plant to power transmission network. The transmission line cost depends on the location, type of existing system (overhead line or cable system), and capacity of MHPP as well as length of transmission lines, which have a very high affect on project costs.

Indirect costs include: 1.Engineering & Design (E&D) 2.Supervision and Administration (S&A) 3.Inflation costs during the construction period.

1. E&D costs: These costs are affected by many parameters, such as type, size and the location where the project is being constructed. The E&D costs are usually expressed as a percentage of construction costs, including civil and equipment costs, and the amount of this percent differs from one location to another. Recently, a case study on these MHPPs has shown that this figure could range from 5% for small and medium sized projects, to 8%, for very large sized projects. [4-5].

2. S&A costs: These costs include the purchase of land, management, inspection and supervision costs, and other miscellaneous costs in the region. Similar to the E&D costs, the S&A costs are expressed as a percentage of the construction costs. A recent case study on MHPPs has shown that this figure could be anywhere from 6% to 8%. [4-5].

3. Inflation costs during construction: To precisely calculate the investment cost of a project, it is necessary to take into consideration the inflation rate during the course of the project and adjust the

investment cost with respect to the inflation rate. The inflation rate of future years should be determined by obtaining the average of previous years' inflation rate.

2.2.2 Annual costs

To obtain the net benefit of a project, annual costs, in addition to investment costs should be calculated. Annual costs include depreciation of equipment, Operating & Maintenance (O&M), and replacement and renovation costs.

Depreciation of equipment: In the economic analysis of the project, depreciation and other factors affecting the equipment should be considered.

O&M costs include salary/wages of personnel, labor, insurance, tax, duties, landscape, and consumable materials. These costs are increased only by the annual inflation coefficient. A 5% inflation rate is used in the economic calculations. The costs which are related to the salary/wage and consumable materials make up one percent of annual investment costs, and insurance, tax, duties, charges and unpredicted cases are also taken as one percent of annual investment costs. It should be noted that to calculate investment costs, the interest rate during construction should also be considered. [1], [5-6].

Replacement and renovation costs: The main parts of the MHPP, such as generator windings, turbine runners and other parts will eventually need replacement and renovation. To estimate the costs for large and medium sized power plants, the percentage of wear should be determined for different sections separately. [2-3].

2.2.3 Income & benefits

There are two benefits for the MHPPs: Tangible benefits, and Intangible benefits. The tangible benefit is the sale of electrical energy. Based on approval by Iranian regulators, the purchase of electrical energy from MHPPs has been guaranteed by the Ministry of Energy. Based on this approval, the purchase will be done from four sectors: 1. The governmental sector without transmission lines; 2. The governmental sector with transmission lines; 3. The private sector without transmission lines; and, 4. The private sector with transmission lines. In each, the electrical energy purchasing rates are being provided in different months of the year based on the peak load (4 hours a day), normal load (12 hours a day) and low load (8 hours a day). Meanwhile, for the private sector, different purchase rates are being presented with four options, namely, 100%, 75%, 50% and 25% of private investment.

Due to peak hours of energy consumption, the purchasing rate would be more attractive for the producer of energy. The annual inflation-purchasing rate is being considered to be 5% in the calculation. The intangible benefits cover the positive environmental effects, flood control, agriculture and irrigation, fish farm pools, camps and recreation centers, etc. which eventually turn into quantitative values. The intangible benefits are not included in this economic analysis of the project, but naturally a more desirable result will be obtained for the economic indices when taking these factors into account. [3].

2.2.4 Financial and time specifications and methods of capital distribution

Capital depreciation period for construction costs:	50 years
Replacement and renovation of electro-mechanical equipment:	25 years
Duration of construction:	3 years
Annual interest rate:	10 %
Annual inflation rate:	5%

Table 1 shows the capital distribution during the investment period. This table presents construction time from one to six years [3-4]. In this table, the construction costs are expensed in the relevant subsequent years. Thus, with the effects of interest and inflation, the costs of the subsequent years can be predicted. Social and economic factors could also be included in this calculation. When execution activities begin, the annual payments should be expensed in the midyear, in order to lessen the effect of inflation, thus lowering the investment value. For example, according to Table 1, for a three-year construction project, the percentages of the cost in each year are as followings: 37% of capital in the middle of the first year, 56% in the middle of the second year and 7% in the middle of the third year.

2.3 Reliability calculations

The reliability index of Loss of Load Expectation (LOLE) is calculated by using the Monte Carlo method. [7-8]. The Monte Carlo algorithm is one of the strongest engineering tools that enable us to perform a statistical analysis of the uncertainties involved in engineering problems. This method is very applicable in solving complicated problems where many random variables are involved in non-linear equations. The Monte Carlo analysis can be imagined as a simulation method, which replaces a practical execution with a computer simulation. The basis of the Monte Carlo analysis is to produce a series of random numbers. The produced homogenous random numbers retain the same characteristics of the probability of their occurrences in the selected domain between 0 and 1. In this method, first, "n" random numbers are produced for each one of the existing random parameters in the given equation and this equation is then solved for each single random selected number. Finally, "n" values are obtained for the concerned equation by using the related relations to obtain the statistical information of the histogram sample. It should be noted that as the number of iterations increase, the answer would more closely approach the real value. With a decreasing probability of not supplying electricity to subscribers (customers) there is a direct relation to an increase in the number of generation units (generators) and as a result, an increase in investment design status and/or utilization. More investment will definitely lead to an increase in utilization costs, which should be reflected in the tariff of energy sale. Subsequently, economic limitations would lead to a decrease in the reliability of the system. Therefore, there could be a compromise between reliability and economic restrictions that could lead to difficult management decisions in both the design and operational stages. [7],[9]. In general, a study of the reliability of the three sections of generation, transmission and distribution of power systems should be done. In this paper, only generation reliability is being considered to meet the load demands. The transmission and distribution reliability have been assumed to be perfect (reliability=100%). The LOLE calculation algorithm, using the Monte Carlo method, is in Fig. 1. [8].

3. Case study

The case study of the MHPP "Bookan" (medium hydro-power plant) is presented. This MHPP is located in the West Azarbaijan Province of Iran. The MHPP is reservior type and the object is to determine the optimal installation capacity.

3.1 Energy calculation of the Bookan MHPP

The simulation has been done for a period of 33 years according to the data extracted from 1964 to 1997. In this case, the monthly net output (output plus overflow) in reservoir and net height in the reservoir for the different months (the difference between the level of water in reservoir and the level of axis of the turbine have been extracted in these periods) have been extracted in this duration. According to the special specification of the plant and the feasibility study, the different alternatives, based on the expertise judgment have been considered. In these alternatives, the calculated energy is based on the different number of the vertical Francis turbines. Ultimately, the annual energy is being drawn after getting mean value of them [10].

The maximum level of water in the reservoir is about 1421 meter, and the installation level of turbines is about 1380 meter. Therefore the max height of the MHPP is about 41 meter. According the given recommendations in USBR standards the constraints of vertical Francis turbine are as below:

The minimum admitted flow of turbine is about 40% of the designed rated flow;

The maximum admitted flow of turbine is about 110% of the designed rated flow;

The minimum operational height of turbine is about 65% of the designed operational height;

The maximum operational height of turbine is about 125% of the designed operational height;

According to the above-mentioned points, the following results have been extracted:

The minimum height is about 21.5 meter;

The nominal height of is about 32.5 meter;

The maximum permanent overloads of the generators are about 10%

The accessibility of the MHPP has been considered to be 98%.

Then the results of the calculations for different alternatives have been given in Table 2.

3.2 Economic calculations of the Bookan MHPP

The calculated civil, equipment and total investment costs of the Bookan MHPP have been extracted from the feasibility study. These costs for a mean duration of MHPP is about US$1000/kW (US$600/kW for civil works and US$400/kW for the equipments).

The economic analysis has been carried out considering costs and obtained incomes, according to the given algorithm. The economic basis is considered so that the investor may receive a loan from a financial source and pay it back with a specific interest rate through annual installments during the utilization stage. The economic analysis has been calculated for fully governmental, fully private and governmental-private financings, then the economic indices including benefit to cost ratio (B/C), the net present value (NPV) and US$/kWh of energy have been calculated. The interest rate has been settled as 8% & 10% in order to attract foreign investment in developing countries. This rate is considered a normal rate by global financial institutes for economic feasibility studies of water resource development. , and the results have been presented in Tables 3. In any case, the effect of interest rate changes is studied by sensitivity analysis

3.3 Calculation of the reliability of the Bookan MHPP

To study the affect of an increase in the number of generation units and subsequently, an increase in the cost on the LOLE index, the various combinations of generation units are being used for the Bookan MHPP, each with the following specifications:

P_G = 10 & 15 [MW] rated capacity of generating units

N = 50 [years] MHPP's life time

$\lambda = 1/25$ [f/ years] rate of failures

$\mu = 2$ [r/ years] rate of repairs

The minimum and maximum load values are considered based on the loads in different years. The specifications of the loads are as follows (a sensitivity analysis has also been performed on the load values for more assurance):

{PL_{max} = 35 [MW] average maximum of load

{PL_{min} = 5 [MW] average minimum of load

There are 2,000 iterations for calculating the LOLE in the Monte Carlo algorithm (iterations = 2,000). Installing different numbers of generation units created the following possible options:

Option 1. 2x20 MW

Option 2. 2 x 12.5 MW

Option 3. 2 x 15 MW

Option 4. 3 x 10 MW

LOLE calculation with the Monte Carlo method for option 4 has shown in Fig. 4. The results of these calculations are listed in Table 4.

3.4 Results of the analysis

With respect to the results presented in Tables 2, 3 and 4 and studying the technical, economic and reliability indices, the alternative No. 11 is clearly the best option, with a 30 MW installation capacity,

an annual energy of 99.40 GWh, a plant factor (PF) of 38%, a B/C that equals 1.49 (for inflation rate equal 8%) , an NPV that equals US$17.08 million, a USCent/kWh that equals 2.60 and the suitable LOLE index of 10 days/year. By increasing the installed capacity, the LOLE decreases so that even with a 3x10MW installation capacity (option 4) the failure will reach minimum and will even become a zero value; it should be noted that with such a situation, more expense for generating a kWh electrical energy is required, obviously not desirable. Furthermore, the PF and the economic indices are also not suitable. With an installation capacity of 2x15MW, the number of failures, PF and other economic indices are very relatively proportional and the costs of a kWh energy is also at an acceptable limit.
Furthermore, considering only alternative 11, a sensitivity anlysis of interst rate from 6% to 20% have been calculated and the results are given in Tables 5.

4. Conclusion:

1. One of the most important issues in designing an MHPP is to determine the optimal installation capacity. In this paper, the methods of energy and the economic and reliability calculation have been presented and finally, the above-mentioned algorithm has been studied for a sample MHPP.

2. The economic indices have been calculated based on an algorithm (by using Excel software) and by the application of sensitivity analysis.

3. The reliability indices have been calculated by employing the Monte Carlo method based on an algorithm (by using Matlab software).

4. The optimal installation capacity has been obtained by establishing a compromise between the technical, economic and the reliability indices.

5. The aforementioned method has been applied to a sample MHPP named “Bookan” by comparing the plant factor (PF), the B/C, NPV, USCent/kWh, and the reliability index LOLE, so the optimal installation capacity of 30 MW has been obtained.

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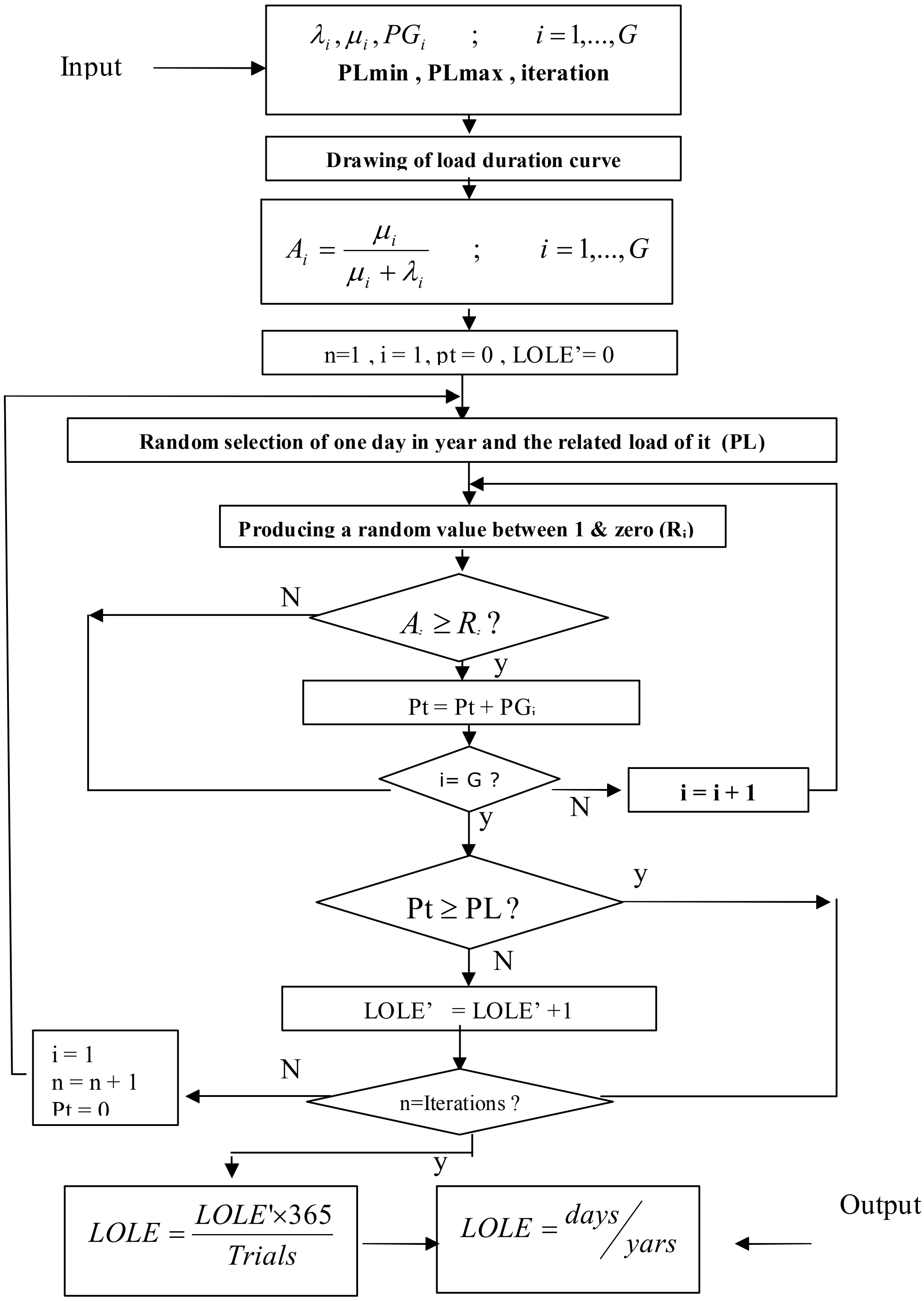

Figure 1. The LOLE calculation algorithm, using the Monte Carlo method

Table 1
Distribution of costs versus construction years

Construction years	1 [%]	2 [%]	3 [%]	4 [%]	5 [%]	6 [%]
1	100	-	-	-	-	-
2	77	23	-	-	-	-
3	37	56	7	-	-	-
4	16	62	18	4	-	-
5	9	49	30	9	3	-
6	6	31	40	15	6	2

Table 2
Obtained annual energy for different alternatives of Bookan MHPP

Alternative No	The rated power & number of units [NxMW]	The rated power [MW]	The mean annual energy [GWh]	Plant Factor (PF) [%]
1	2 x 2.5	5	25.33	0.58
2	2 x 3.75	7.5	36.80	0.56
3	2 x 5	10	47.23	0.54
4	2 x 6.25	12.5	57.67	0.53
5	2 x 7.5	15	67.26	0.51
6	2 x 8.75	17.5	76.03	0.50
7	2 x 10	20	83.41	0.48
8	2 x 11.25	22.5	89.20	0.45
9	2 x 12.5	25	93.19	0.43
10	2 x 13.75	27.5	96.52	0.40
11	2 x 15	30	99.40	0.38
12	3 x 10	30	99.73	0.38
13	2 x 16.25	32.5	101.71	0.36
14	2 x 17.5	35	103.65	0.34
15	2 x 18.75	37.5	105.31	0.32
16	3 x 12.5	37.5	107.99	0.33
17	2 x 20	40	107.64	0.31
18	4 x 10	40	110.85	0.32
19	2 x 22.5	45	112.52	0.29
20	3 x 15	45	115.40	0.29
21	2 x 25	50	116.14	0.27
22	4 x 12.5	50	119.80	0.27
23	3 x 17.5	52.5	120.28	0.26
24	3 x 20	60	124.55	0.24
25	4 x 15	60	127.43	0.24

Table 3
Economic indices of different alternatives with private section contribution for Bookan MHPP
(the inflation rate is 0.2% for sales of energy and is 5% for annual cost)

Alternative No	The rated power & number of units [NxMW]	The rated power [MW]	Interest rate = 8%			Interest rate = 10%		
			Final costs [USCent/kWh]	B/C	NPV [US$million]	Final costs [USCent/kWh]	B/C	NPV [US$million]
1	**2 x 2.5**	5	1.70	2.28	7.41	2.11	1.82	4.63
2	**2 x 3.75**	7.5	1.76	2.21	10.49	2.17	1.76	6.46
3	**2 x 5**	10	1.82	2.12	13.02	2.25	1.70	7.86
4	**2 x 6.25**	12.5	1.87	2.07	15.57	2.31	1.66	9.28
5	**2 x 7.5**	15	1.93	2.02	17.67	2.37	1.61	10.34
6	**2 x 8.75**	17.5	1.99	1.95	19.34	2.45	1.56	11.08
7	**2 x 10**	20	2.07	1.87	20.20	2.55	1.50	11.19
8	**2 x 11.25**	22.5	2.18	1.78	20.41	2.69	1.43	10.78
9	**2 x 12.5**	25	2.31	1.68	19.59	2.86	1.34	9.58
10	**2 x 13.75**	27.5	2.45	1.58	18.43	3.04	1.26	8.11
11	**2 x 15**	**30**	**2.60**	**1.49**	**17.08**	**3.21**	**1.19**	**6.50**
12	**3 x 10**	30	2.60	1.49	17.08	3.21	1.19	6.50
13	**2 x 16.25**	32.5	2.75	1.41	15.34	3.40	1.12	4.58
14	**2 x 17.5**	35	2.92	1.33	13.45	3.60	1.06	2.54
15	**2 x 18.75**	37.5	3.05	1.27	11.78	3.76	1.02	0.68
16	**3 x 12.5**	37.5	3.05	1.27	11.78	3.76	1.02	0.68
17	**2 x 20**	40	3.17	1.23	10.44	3.90	0.98	-0.92
18	**4 x 10**	40	3.17	1.23	10.44	3.90	0.98	-0.92
19	**2 x 22.5**	45	3.40	1.14	7.25	4.20	0.91	-4.53
20	**3 x 15**	45	3.40	1.14	7.25	4.20	0.91	-4.53
21	**2 x 25**	50	3.65	1.06	3.54	4.51	0.85	-8.55
22	**4 x 12.5**	50	3.65	1.06	3.54	4.51	0.85	-8.55
23	**3 x 17.5**	52.5	3.76	1.03	1.83	4.64	0.82	-10.44
24	**3 x 20**	60	4.11	0.94	-3.88	5.07	0.75	-16.58
25	**4 x 15**	60	4.11	0.94	-3.88	5.07	0.75	-16.58

Table 4
Index of reliability for the Bookan MHPP

LOLE index [day/year]				Min. Load [MW]	Max. Load [MW]
Option 1	**Option 2**	**Option 3**	**Option 4**		
101	10	7.2	6.9	5	25
132	9.5	10	6.5	10	25
180	100	10	12.6	10	30
230	130	11	15	15	30

Table 5

Economic analysis results on alternative No. 11 with different interest rates

(the inflation rate is 0.2% for sales of energy and is 5% for annual cost)

Interest rate (%)	Unit	6	8	10	12	14	16	18	20
Energy Cost	[USCent/kWh]	2.02	2.60	3.21	3.84	4.47	5.11	5.75	6.39
Benefit Cost Ratio (B/C) & (P/t=1)		1.94	1.49	1.19	0.98	0.83	0.72	0.64	0.57
Benefit Cost Ratio (B/C) & (P/t=0.75)		1.78	1.37	1.09	0.9	0.77	0.66	0.58	0.52
Benefit Cost Ratio (B/C) & (P/t=0.5)		1.62	1.25	1	0.82	0.7	0.6	0.53	0.47
Benefit Cost Ratio (B/C) & (P/t=0.25)		1.46	1.13	0.9	0.74	0.63	0.55	0.48	0.43
Benefit Cost Ratio (B/C) & (P/t=0)		0.73	0.56	0.45	0.37	0.31	0.27	0.24	0.21
Net Present Value (NPV) & (P/t=1)	[US$million]	34.17	17.08	6.50	-0.51	-5.42	-9.04	-11.80	-13.99
Net Present Value (NPV) & (P/t=0.75)	[US$million]	28.41	12.84	3.20	-3.18	-7.66	-10.96	-13.49	-15.49
Net Present Value (NPV) & (P/t=0.5)	[US$million]	22.64	8.60	-0.10	-5.86	-9.90	-12.89	-15.18	-16.99
Net Present Value (NPV) & (P/t=0.25)	[US$million]	16.88	4.35	-3.40	-8.53	-12.15	-14.81	-16.86	-18.49
Net Present Value (NPV) & (P/t=0)	[US$million]	-9.74	-15.23	-18.62	-20.88	-22.50	-23.71	-24.65	-25.41

Notice: P/t = Ratio of private section investment to total in percent
B/C= Benefit Cost Ratio
NPV= Net Present Value

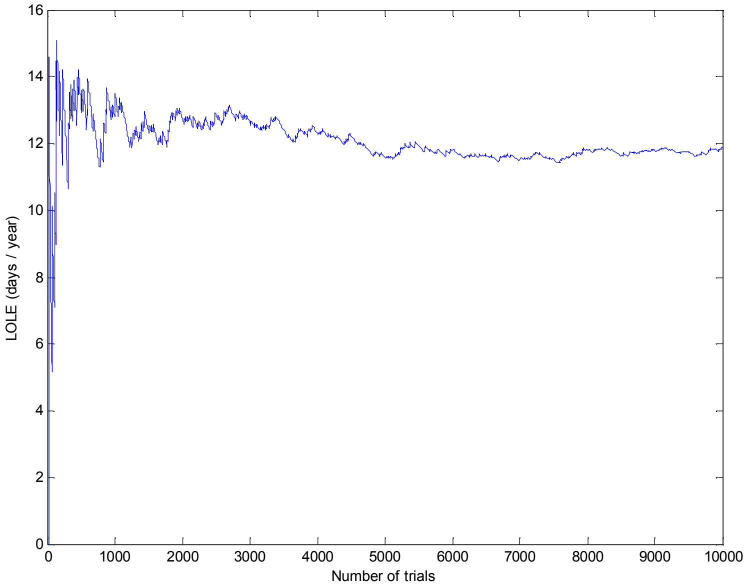

Figure 2. The graf of calculated LOLE with the Monte Carlo method for option 4
(min. & max. load between 10 - 30 MW)

Biographi

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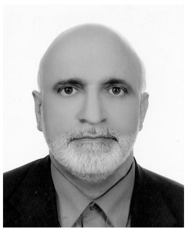

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