

Capacity and Availability Analysis of Power Plants in Kuwait

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Abstract

In recent years, reliability, availability, and capacity have become critical issues in power plants industries. It is also becoming a challenge to meet the demand without the expansion of aged power plants. This paper presents availability analysis of the power generation systems in cogeneration plants situated in Kuwait. Furthermore, an overview of the current situation about Kuwait power plants and their availability, demand for electricity, and installed capacity are presented. Stochastic availability analysis of one power plant with concentration on steam turbine units is illustrated using empirical data for one year. The results are extrapolated to other power plants to determine expected power output under different operational conditions.

Keywords

Power plants, operational availability, reliability, power forecast, capacity, preventive maintenance.

1. Introduction

Cogeneration methods of electrical power generation and fresh water production has been utilized by utility companies for many years as a reliable, efficient and economic means of generating power and simultaneously desalting sea water [1]. Cogeneration power plant is a complex process engineering system consisting of various subsystems to achieve the goal of maximum power generation. It is required to run various units of the plant failure free for a long period of time. Maintenance, which is defined as combinations of several functions needed to keep in or restore the equipment to a designated operational state [2], is an essential activity in complex systems. Maintenance costs are known to be the increasing portion of operational costs, and therefore, can be seen as a major opportunity for operational improvement. An asset that continues to perform its intended function is considered as reliable [3]. The process used to ensure that any physical asset continues to do what it is designed and instructed to do is known as reliability-centered maintenance [4]. Reliability is "the probability of a device or system performing its purpose adequately for a period of time intended under the operating conditions encountered" [5]. It is a mean of cost effectiveness and normally measured as the mean time between failures (MTBF). Availability is "the ability of equipment to successfully perform its required function at a stated instant of time over a stated period of time" [6]. Any failure which occurs in any unit in the cogeneration plant will affect the overall availability and the reliability of the system. Therefore, evaluating reliability and availability of a unit plays an important role for determining its performance, capability, and limitations. It will also help in planning and deciding periodical maintenance activities and replacing or repairing when failures occur [7].

Optimization and modeling of reliability and availability in different systems of a complex industrial plant is of great interest as the plant economy strongly depends on reliability and availability. Different studies have been carried out

to model and study different aspects of reliability and availability. Tsai, et al. [8] studied preventive maintenance in simultaneously considering three actions, mechanical service, repair and replacement for a multi-components system based on availability. Whereas, Borges and Falcão [9] presented a methodology for optimally distributed generation (DG) allocation and sizing in distribution systems, in order to minimize the electrical network losses and to guarantee acceptable reliability level and voltage profile. They used a combination of genetic algorithms (GA) techniques with methods to evaluate DG impacts in system reliability, losses and voltage profile. Kancev and Cepin [10] showed that testing and maintenance improve the reliability of safety systems and components in nuclear power plants, which is of special importance for standby systems. Sanchez, et al. [11] studied two types of models, i.e. deterministic and probabilistic, and considered them to simulate the impact of testing and maintenance activities on equipment unavailability and the cost involved. Marseguerra and Zio [12] presented an optimization approach based on the combination of a Genetic Algorithm maximization procedure with a Monte Carlo simulation. Haghifam and Manbachi [13] proposed a combined heat and power reliability and availability model based on the state space and the continuous Markov method with electricity-generation, fuel-distribution and heat-generation subsystems. Eti et al. [4] presented a survey of the performance of gas-turbine plants in Afam Thermal-Power Station and showed that the financial impact of lost generation (through non-availability) exceeded within a few years, the initial purchase price of the power plants and associated equipment. Proctor et al. (14) presented reliability modeling of a gas turbine standby system operating under dusty conditions. Based on the historical data, they developed a Markov model and analyzed the system to determine the steady state availability. This paper discusses the availability analysis of the power generation systems in cogeneration plants situated in Kuwait. The study presents an overview of the current situation of Kuwait power plants, their availability, the demand for electrical power, installed capacity, and estimated requirements for the future. Furthermore, one of the seven power plants is selected and a stochastic model is developed to analyze its reliability and steady state availability. The results are extrapolated to other power plants to estimate expected total power output from all plants in Kuwait.

2. Power Generation and Distribution Structure in Kuwait

Power generation in Kuwait depends primarily on the cogeneration-desalination power plants. There are 6 power plants in Kuwait, namely: *Doha East, Doha West, Shuaiba, Al-Zour South, Sabiya,* and *Shuwaikh* as shown on the Kuwait map in figure 1. These power plants employ both thermal steam turbines and gas turbines for power generation. The installed capacity is shared between thermal steam turbines and thermal gas turbines. While thermal steam turbines constitute 85% of power generation capacity, thermal gas turbines provide only 15% of the total capacity. The Ministry of Electricity and Water (MEW) is responsible for supplying power and water to the population. The MEW has met the 700% growth in demand for electricity and water during the past 25 years by the construction of a system of cogeneration plants, now totaling 12,880 MW of power and 423.1 MIGD (Million Imperial Gallons of Water per Day) [15]. These plants are identical in layout but different in size and installed capacity.



Number	Name of the power plants
1	Sabiya
2	Doha West
3	Doha East
4	Shuwaikh
5	Shuaiba
6	Az-zour south

Figure 1. Kuwait map with location of power plants

The Kuwait plants are typical in that each plant has a boiler, a turbo-generator, and a distiller as shown in figure 2. The boilers produce high pressure steam from fuel; the turbo-generators produce electric power from high pressure steam and the distillers produce desalinated water from salt water using low pressure steam. A common steam header connects the boilers of a plant so that steam from a boiler in one unit can be used by a distiller in another unit. The water produced is stored in reservoirs which are used to meet the predicted demand at each time period of planning horizon. The plants should also satisfy the demand for electric power and water during each time period.

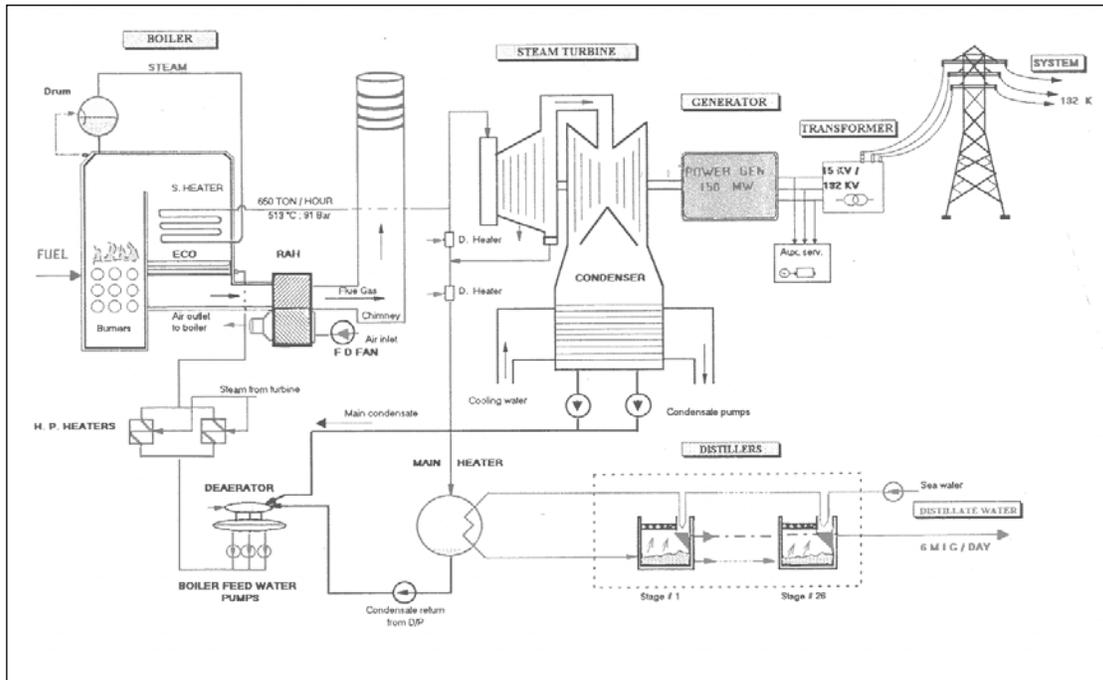


Figure 2: Elements of the units of a typical cogeneration plant in Kuwait

Under normal conditions, total power generation is achieved through the utilization of only the thermal steam turbines that convert the thermal energy into mechanical energy and then to electrical energy. On the other hand, thermal gas turbines are used only in emergencies and times of peak loads. The installed capacities of the power plants, including steam turbine and gas turbine plants in Kuwait, are shown in Table 1 below. Different types of fossil fuels are available in Kuwait, such as natural gas, heavy fuel oil, crude oil, and gas oil, which are utilized for power generation in these plants. Kuwait population has tripled during the past three decades. The increasing consumption of electricity is shown in Table 2 for the past 34 years to illustrate the trend in the consumption as well as capacity expansion. As it is seen from table 2, population has increased from 1,107,633 to 3,484,881, which is an increase of about 215% in 34 years. However, installed capacity has increased from 1,868 MW to 12,879 MW, an increase of about 590%. The last column in table 2 shows that the trend in power consumption is much higher than the trend in population increase. Also, per capita consumption shows an increase of about 177%, which is an indication of the increase in quality of life in Kuwait. This high consumption of electricity per capita presents a real challenge to the Ministry of Water and Electricity to satisfy the demand with no power interruptions or restrictions.

Table 1. Installed capacity of power plants in Kuwait.

Stations	Steam Turbine MW	Gas Turbine MW
Shuwaikh Station	-	252
Shuaiba Station	720	660
Doha East Station	1050	108
Doha West Station	2400	112.8
Al-Zour South Station	2400	1976
Sabiya Station	2400	500.2

Table 2. Increase in Kuwait population and installed capacity of power plants

Year	Population	Installed Capacity MW	Per Capita Consumption KWh/Person
1977	1107633	1868	4825
1979	1332611	2578	5656
1987	1926328	6696	8054
1989	2097570	7411	8606
1997	1837450	6898	12442
1999	2148032	8289	12552
2007	3399637	10481	12527
2009	3484881	12879	13372

3. Demand Forecasting for Electrical Power Usage in Kuwait

Power stations are operated according to the demand. Therefore, the stations are not necessarily operated in full capacity. Table 3 shows the power generation at each station over the past 19 years. Total power generation, which depends on the total demand, is also shown in the last column of the table. Based on the annual demand, which shows a linearly increasing trend as shown in figure 3, a regression model is developed to establish a simple model for estimating future need for electrical power. The regression model is as follows:

$$P_t = -4,123,168 + 2078.428 * Y_t \quad (1)$$

Where P_t = Demand for Electrical Power in year t

Y_t = Year t

For example, using equation (1) above, the demand for years 2011 through 2015 could be estimated as given in table 4. It gives an indication of the demand for power in the future.

Table 3. Annual demand for electrical power at each station and total demand (million KWh)

Period	Shuwaikh Station	Shuaiba South Station	Doha East Station	Doha West Station	Al-Zour South Station	Sabiya Station	Total (M.kWh)
1992	0	1627	2745	5548	6965	0	16885
1993	0	2147	3599	7110	7322	0	20178
1994	0	3070	3650	8062	8020	0	22802
1995	0	3021	4067	8881	7755	0	23724
1996	0	3085	4135	9229	9026	0	25475
1997	0	3032	4219	10271	9202	0	26724
1998	0	3272	4630	11010	10212	860	29984
1999	0	3354	3927	10600	10215	3480	31576
2000	0	3050	3652	10091	9293	6237	32323
2001	0	3220	3977	9647	9929	7526	34299
2002	0	3421	4152	10640	9832	8317	36362
2003	0	3333	4160	11239	10464	9381	38577
2004	0	3446	4592	11880	12355	8984	41257
2005	0	3840	4793	11726	13686	9689	43734
2006	0	4058	5128	12066	16173	10180	47605
2007	835	3255	4875	11316	16895	11578	48754
2008	1345	3602	4853	11770	17549	12630	51749
2009	325	4290	4769	12086	19055	12691	53216
2010	868	3872	5114	11036	20537	12907	54334

Table 4. Demand forecasting for power consumption using regression model

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Demand (MillionKWh)	54505	56587	58668	60749	62830	64911	66992	69073	71155	73236	75317

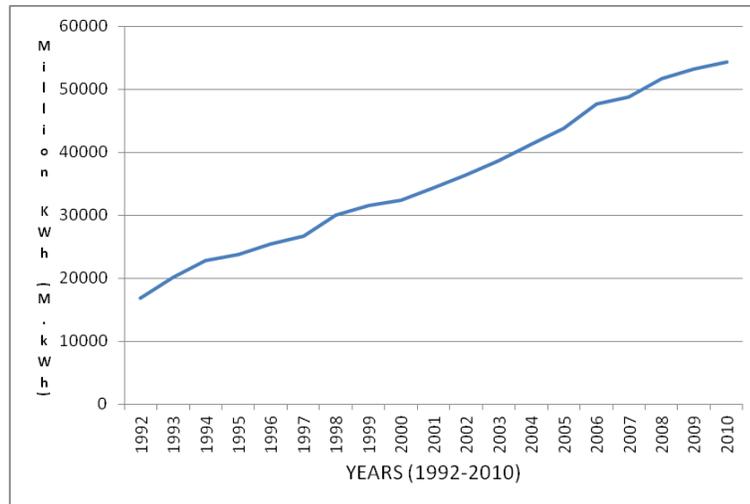


Figure 3. Trend of annual demand for electrical power

4. Availability Calculations of Power Stations

As it was mentioned in the previous section, availability and reliability are crucial issues in power plants. Therefore, management needs to estimate availability of each plant in order to plan for future maintenance activities based on equipment availabilities. Maintenance is essential in the power plants and needs to be well planned in order to avoid power generation shortages. Generally there are three types of availability calculations:

i. Inherent Availability (A_i): It is defined as the probability that an equipment (or system) will operate satisfactorily when used under ideal support environment (i.e. tools, spares, and personnel for corrective maintenance are all readily available). It excludes preventive maintenance, scheduled maintenance, logistic delays and administrative delays etc. It is calculated as below.

$$A_i = MTBF_u / (MTBF_u + M_{ct}) \quad (2)$$

Where, $MTBF_u$ = Mean time between failures (unscheduled) for the power station.

M_{ct} = Mean corrective time or mean repair time due to failures.

If there are more than one failure type, mean corrective time is a weighted average of all mean corrective times based on failure rate of each failure type, λ_i . The following formula is used to calculate average corrective maintenance time if k types of failures is involved.

$$M_{ct} = \left(\sum_{i=1}^k \lambda_i M_{cti} \right) / \sum_{i=1}^k \lambda_i \quad (3)$$

ii. Achieved Availability (A_a): The probability that a system or equipment, when used under ideal conditions will operate satisfactorily when needed at a point in time, provided that necessary preventive maintenance actions are carried out on the equipment. This definition (A_a) is similar to that of A_i . However, scheduled PM is included. It excludes logistic and administrative delays and is calculated as below.

$$A_a = MTBM / (MTBM + M) \quad (4)$$

Where,

$MTBM$ = Mean time between maintenances combined

M = Mean Active Maintenance Time

$MTBM$ and M are functions of corrective and preventive maintenance actions, which are defined as follows.

$$MTBM = \frac{1}{(1/MTBM_u) + (1/MTBM_s)} \quad (5)$$

$$M = \frac{(\lambda)(M_{ct}) + (\beta)(M_{pt})}{\lambda + \beta} \quad (6)$$

Where,

$MTBM_u$ = Mean time between unscheduled (failure) maintenances (corrective)

$MTBM_s$ = Mean time for scheduled maintenances (preventive).

M_{ct} = Mean corrective time as defined above by equation (3).

M_{pt} = Mean preventive time as calculated based on several preventive maintenances carried out on the same

equipment, each with specific rate β_i for n types of maintenances. $M_{pt} = \frac{\sum_{i=1}^n \beta_i M_{pti}}{\sum_{i=1}^n \beta_i}$ (7)

iii. **Operational Availability (A_o):** Probability that a system or equipment, when used under stated conditions in an actual operational environment will operate satisfactorily when called upon, provided that PM and other delays due to spare part availability and administrative/logistic delays are taken into consideration. It is calculated as below.

$$A_o = \frac{MTBM}{MTBM + MDT} \quad (8)$$

Where,

$MDT = M + LDT + ADT$

MDT = Mean Maintenance Down Time

L_{dt} = Logistic delay time due to spare parts unavailability and delays.

A_{dt} = Administrative delay time due to any administrative reasons.

Supplier has no control over the operational environment in which the equipment will function. A_a and A_i are the appropriate figures against which the supplier's equipment could be assessed. To assess a system in a realistic operational environment, one has to use A_o as a figure of merit or performance measure. Based on the historical data, we have calculated the operational availability measures for the 6 power stations in Kuwait. Calculations are made separately for steam turbine (ST) units and gas turbine (GT) units and the results are given in table 5. In order to see the general trend for power generation from all six power stations, we have analyzed the monthly power generation during 2005-2010 for 60 months. In particular, power output trend is shown in three categories in figure 4. First, total power generation in million MWh is shown as Total Gen./Hr. in the figure. This is the actual power generated based on demand. Maximum productions shown as the top line in the figure are possible maximum output that could be achieved if no maintenance is performed. Maximum production with maintenance is the middle line in the figure, which is the total monthly output that could be achieved if maintenance is taken into consideration.

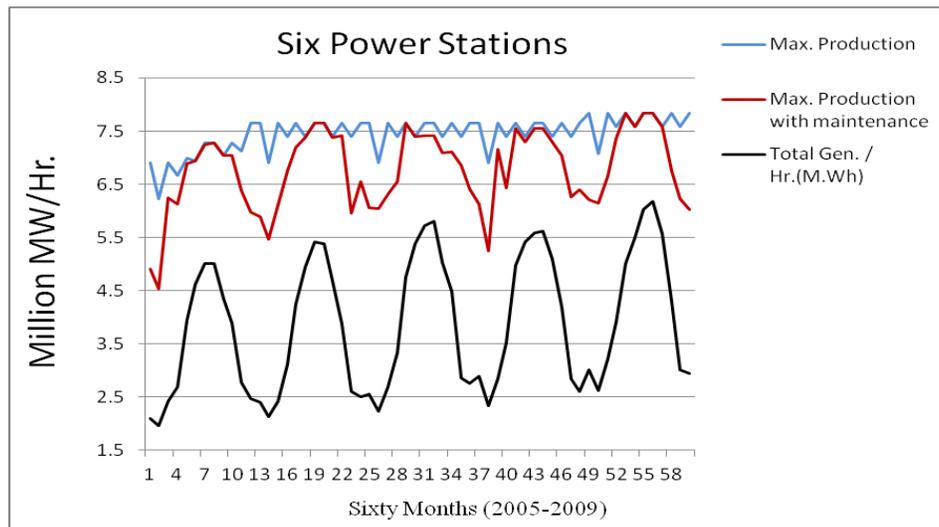


Figure 4. Monthly power generation and usage in Kuwait from all 6 stations (2005-2010)

During winter months more maintenance is scheduled since the demand is lower and thus the output would be lower. This figure illustrates the general trend in power consumption and output from Kuwait power stations.

Table 5. Monthly Operational Availability of 6 power plants in Kuwait in 2009.

Period 2009	Shuwaikh Station		Shuaiba South Station		Doha East Station		Doha West Station		Al-Zour South Station				Sabiya Station	
	Operational Availability		Operational Availability		Operational Availability		Operational Availability		Operational Availability				Operational Availability	
	ST	GT	ST	GT	ST	GT	ST	GT	ST	GT	New GT	E. GT	ST	GT
January		54.9	72.1		65.8	81.9	77.5		75	100	100	100	66.9	
February		2.4	65.2		57.1	76.5	76.6		100	100	100	100	67.6	
March		82	52.3		56.3	74	73.5		100	100	100	100	67	
April		93.6	73.8		57.5	93.8	75.2		75	100	75	100	71.8	
May		97.9	96		79.6	94.9	93.9	57.8	79	100	75	100	90.7	
June		97.6	98.7		93.2	99.9	100	88.7	92	100	87	100	97.9	
July		98.2	99.2		99.8	100	98.7	37.7	100	100	100	100	97.6	
August		99.4	99.4		99.8	100	97.8	72.3	100	100	100	100	98.8	
Sept.		99.6	96.9		98.4	100	93.5	70.1	95.9	100	100	100	93	
October		99.9	83		80.7	81.5	75.9	56.3	81.9	100	61.6	65	76.2	
Nov.		75	69		63	88.7	79.3	51.1	80.7	100	100	100	73.6	
Dec.		71.1	58.1		57.2	86.5	76.8	78.7	75	100	75	100	63.1	

5. Stochastic Modeling of the Availability of East Doha Power Plant

In this section, we present the reliability and availability calculations for one specific power plant, for which failure and repair data were available. In particular, Doha East Power Plant, which had 7 steam turbines, each with 150 MW power capacities was selected for the analysis. Based on the historical data up to 2009 given in table 6, Weighted Mean Time Between Failures (MTBF) was found to be 1466.30 hours, while Weighted Mean Time to Repair (MTTR) each failure was found to be 42.48 hours for all turbines. Using the weighted MTBF and MTTR, related mean failure rates and mean repair rates are calculated as: $\lambda=1/\text{MTBF}=0.000682$ failures/hour and $\alpha=1/\text{MTTR}=0.02354$ repairs per hour. A stochastic model was then used to evaluate steady state system availability.

Table 6. Availability analysis for steam turbine units on Doha East Station for one year

	Steam Turbine 1	Steam Turbine 3	Steam Turbine 4	Steam Turbine 5	Steam Turbine 6	Steam Turbine 7
MTBF	3688.07	0	1532.01	986.38	950.24	1118.07
Availability	0.9930	1	0.9406	0.9967	0.8086	0.8701
Number of Failures	2	0	4	2	5	5
MTTR	13.050	0	24.175	1.625	44.983	33.397

Figure 5 shows the system state transition flow diagram, for which the notations are described as follows:

- λ = mean failure rate of the steam turbine units
- m = total number of steam turbine units in the system ($m=7$ in this case)
- i = number of failed steam turbine units; $i=0, 1, 2, \dots, m$
- α = mean repair rate of each steam turbine unit.

In this transition flow diagram, it is assumed that there is only one repair crew engaged in the repair of a turbine. If there are two or more turbines failed, only one can be repaired at a time.

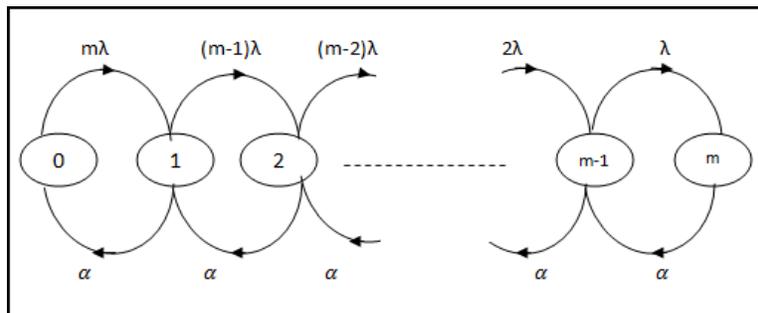


Figure 5. Portability transition flow diagram for m turbines with a single repair crew

For each state, a differential equation can be written based on the rate of change for that state, which is rate of flow in minus rate of flow out as follows.

$$\begin{aligned} \frac{dP_0(t)}{dt} &= \alpha P_1(t) - m\lambda P_0(t) \\ \frac{dP_1(t)}{dt} &= m\lambda P_0(t) + \alpha P_2(t) - [\alpha + (m-1)\lambda]P_1(t) \\ &\dots \\ \frac{dP_m(t)}{dt} &= \lambda P_{(m-1)}(t) - \alpha P_m(t) \end{aligned} \quad (9)$$

When the system reaches steady state (as time goes to infinity; $t \rightarrow \infty$), rate of change $\frac{dP_i(t)}{dt} \rightarrow 0$ and therefore flow in = flow out. Thus the differential equations take the form of difference equations, which can be solved as a set of linear equations as below.

$$\begin{aligned} \alpha P_1(t) &= m\lambda P_0(t) \rightarrow P_1(t) = \frac{m\lambda}{\alpha} P_0(t) \\ m\lambda P_0(t) + \alpha P_2(t) &= [\alpha + (m-1)\lambda]P_1(t) \\ &\dots \\ (m-i+1)\lambda P_{i-1} + \alpha P_{i+1} &= [(m-i)\lambda + \alpha]P_i \\ \lambda P_{m-1} &= mP_m \end{aligned} \quad (10)$$

Using the fact that $\sum_{i=0}^m P_i = 1$, the following recursion formula is obtained for P_0 , probability of being in state 0.

$$P_0 = \frac{1}{\sum_{i=0}^m (m)_i \left(\frac{\lambda}{\alpha}\right)^i} \quad (11)$$

$$\text{Where, } (m)_i = m(m-1)(m-2)\dots(m-i+1) = \frac{m!}{(m-i)!}$$

$$\text{and an equation is obtained for probability of each state as: } P_i = \left(\frac{\lambda}{\alpha}\right)^i (m)_i P_0 \quad (12)$$

Steady state operational readiness probability or 100% availability is obtained by P_0 , which is calculated by the equation given above. Average number of turbines down, N_{td} and average down time, T_{td} , would be calculated by the following equations.

$$N_{td} = m - (\alpha / \lambda)(1 - P_0) \quad (13)$$

$$T_{td} = N_{td} / \bar{\lambda} \quad (14)$$

Where, $\bar{\lambda}$ is the average failure rate obtained from failure rates at each state n (denoted as λ_n) as follows.

$$\bar{\lambda} = \sum_{n=0}^{\infty} \lambda_n P_n = \lambda(m - N_{td}) \quad (15)$$

By using the equations above, several questions related to power plant availability can be answered. In the case example considered (East Doha Station), there are 7 steam turbines. Table 7 shows the calculation results for the number of turbines down at any time. Probability that all turbines would be operational at any time in the steady state would be 80.398% and the probability that 6 out of seven would be operational while one being down would be

16.305%. Since the power output for each turbine is 150 MW, total output would be $7 \times 150 = 1050$ MW if all turbines operated. In the long run, the chance of having 1050 MW power output from this station would be about 80.4%.

Table 7. Probability calculations for the number of turbines being down in East Doha Station

Number of Turbines Shut Down	0	1	2	3	4	5	6	7
Probability	0.80398	0.16305	0.02834	0.00411	0.00048	0.000037	0.0000023	0.000007

Using the equations for average number of turbines shut down (N_{id}) and the average down time for the turbines under repair (T_{id}) are calculated as: $N_{id}=0.2342$ units and $T_{id}=50.75$ hours. Thus expected number of turbines operating at any time would be $1-N_{id}=7-0.2342=6.7658$. This implies that expected power output would be 6.7656 Turbines*150 MW/Turbine=1014.87 MW from East Doha Steam Turbine Power Station. It should be noted that in these calculations only random failures and repairs are taken into considerations. Preventive maintenances, which are usually scheduled during winter times, are not taken into consideration. The availability calculations above indicate that for the case of Doha East Power Station, if the station is kept fully operational except for the forced down failures, it would produce at 96.65% of its installed capacity ($1014.87/1050=96.65\%$). If this result is extrapolated and generalized to all stations in Kuwait, which have a total power generation capacity of about 12880 MW, the expected output would be $12880 \times 0.9665 = 12448$ MW. This is the expected power output if they are all operated with full capacity except for forced shut downs due to failures. This figure does not take into account the preventive maintenances which are implemented during the winter months when the demand for power consumption is low. The first column in table 8 shows the performance measures for the single repair crew case in all stations.

In order to see effects of repair capacity on the availability of power stations, we have considered the same model with more than one repair crew. If only one repair crew is assigned to the power station with 7 turbine units, there is a possibility that a unit may fail while another unit is being repaired by the repair crew. In this case the second unit will wait for the repair to start. We looked at the case when two repair crews are assigned, which could work collectively or individually. If they work together, the same stochastic model above can be used with new repair rate of $2\alpha=2 \times 0.02354 = 0.04708$. When this rate is utilized, system performance measures for two repair crews are obtained as given in the second column of table 8 under the heading of 2 crews.

Table 8. Performance measures of power stations for different numbers of repair crews

Performance Measure\Repair Crews	1	2	3	4	5	6	7
100% Availability, P_0	80.40	90.02	93.31	94.97	95.97	96.64	97.12
Expected number of turbines shut down due to failures, N_{id}	0.2342	0.1090	0.0710	0.0526	0.042	0.035	0.0296
Expected down time of failed units, T_{id}	50.75	23.20	15.013	11.095	8.798	7.298	6.222
Expected number of units operating any time in East Doha	6.7658	6.8910	6.929	6.947	6.958	6.965	6.9704
Expected power output from East Doha Steam Turbine Stations	1014.82	1033.65	1039.4	1042	1043.7	1045	1045.56
Expected power output from all stations in Kuwait (MW)	12448	12679.4	12749	12782	12803	12819	12825.5
Increase in power output due to additional repair crews (MW)	-	231.44	301	334	355	371	377.54

If the repair crews work independently, only one repair crew would work on the system when one unit is down. In this case, the stochastic model needs to be modified slightly. The rates of flow in figure 5 from states $m, m-1, \dots, 2$ would be 2α , while the flow from state 1 to state 0 would be α . If this model is solved, the following results would be obtained: 100% Availability, $P_0=81.85\%$; Expected number of turbines shut down due to failures, $N_{id}=0.1982$ units; Expected down time, $T_{id}= 42.73$ hours; Expected number of turbine units operating any time = $7-N_{id}=6.8018$; Expected power output from East Doha Steam Turbine Stations= $150 \times 6.8018 = 1020.27$ MW; Expected power output from all stations in Kuwait = $(1020.27/1050) \times 12880 = 12515.31$ MW. There is an increase of 67.31 MW (12515.31-12448) due to an additional repair crew working independently. As it can be seen from these results, if an additional repair crew is added, the crews should work together in order to get a meaningful increase in the expected power output. More than two repair crew would only increase the system availability and expected power output if

the crew members work together. For example, if there are three crews and only one turbine is down, all would work together on the unit with a repair rate of $3(0.02354)=0.07062$. The performance measure results for 1 to 7 repair crews working collectively are summarized in table 8. Power output can be increased by as much as 377.54 MW if 7 repair crews are assigned to the system instead of 1 repair crew. This is equivalent to more than 2.5 turbine units operated in Doha East Power station each with 150 MW capacities. Cost calculations can also be performed to see if additional capacity gained justifies additional repair crews.

6. Conclusions

This paper has presented a detailed analysis of capacity and availability of electrical power stations in Kuwait. The analysis show that as Kuwait population has increased over the past 34 years by more than 3 times, the demand for power consumption has increased by almost 7 times. This indicates a high increase in per capita power consumption due to increase in quality of life and income level. The ministry of electricity has been coping with this increase by installing more and more power units over the past decades. Models were developed to analyze the availability of seven power stations. It was found that most of the preventive maintenances were scheduled during the winter months when the demand for power was low due to air conditioning requirements. While operational availability was very high in some stations, the figure was very low for some other stations possibly due to inappropriate PM schedules. In general, the demand was met with the current availability levels. A stochastic model was used, based on queuing analysis and available data from one of the power stations with 7 steam turbines, to determine expected number of turbines that would be operational in the steady state. The model was used to determine expected power output from all stations in the long run assuming that all stations had similar failure rates as the selected station. Furthermore, effects of the number of repair crews and level of repair on the system availability as well as the expected power output was estimated based on the stochastic analysis. The results indicated that increasing repair rates by additional repair crews considerably increased system availability and the expected power outputs. Models and analysis presented in this paper can be used by operation managers and maintenance engineers to study the systems under consideration for further improvements.

References

1. Alardhi, M., R.G. Hannam, and A.W. Labib, *Preventive maintenance scheduling for multi-cogeneration plants with production constraints*. Journal of Quality in Maintenance Engineering, 2007. 13(3): p. 276-292.
2. Duffuaa, S., et al., *Planning and control of maintenance systems: modeling and analysis*. 1999: John Wiley & Sons Inc.
3. Eti, M., S. Ogaji, and S. Probert, *Integrating reliability, availability, maintainability and supportability with risk analysis for improved operation of the Afam thermal power-station*. Applied Energy, 2007. 84(2): p. 202-221.
4. Eti, M.C., S. Ogaji, and S. Probert, *Reliability of the Afam electric power generating station, Nigeria*. Applied Energy, 2004. 77(3): p. 309-315.
5. Carter, A.D.S., *Mechanical reliability*. 1986: Wiley.
6. Institute, B.S., *Glossary of General Terms Used in Maintenance Organization, BS 3811*. 1984.
7. Majeed, A. and N. Sadiq, *Availability & Reliability Evaluation of Dokan Hydro Power Station*, in *Transmission & Distribution Conference and Exposition: Latin America*. 2006. p. 1-6, 15-18
8. Tsai, Y.T., K.S. Wang, and L.C. Tsai, *A study of availability-centered preventive maintenance for multi-component systems*. Reliability Engineering & System Safety, 2004. 84(3): p. 261-270.
9. Borges, C.L.T. and D.M. Falcao, *Optimal distributed generation allocation for reliability, losses, and voltage improvement*. International Journal of Electrical Power & Energy Systems, 2006. 28(6): p. 413-420.
10. Kancev, D. and M. Cepin, *The price of risk reduction: Optimization of test and maintenance integrating risk and cost*. Nuclear Engineering and Design, 2010.
11. Sanchez, A., et al., *Addressing imperfect maintenance modelling uncertainty in unavailability and cost based optimization*. Reliability Engineering & System Safety, 2009. 94(1): p. 22-32.
12. Marseguerra, M. and E. Zio, *Optimizing maintenance and repair policies via a combination of genetic algorithms and Monte Carlo simulation*. Reliability Engineering & System Safety, 2000. 68(1): p. 69-83.
13. Haghifam, M.R. and M. Manbachi, *Reliability and availability modelling of combined heat and power (CHP) systems*. International Journal of Electrical Power & Energy Systems. In Press, Corrected Proof.
14. Proctor, C.L., El-Tamimi, A. and Savsar, M., "Reliability Modeling of a Gas Turbine Standby System", *Proceedings of the IASTED International Conference on Reliability and Quality Control*, June 24-26, 1987, Paris, France, 125-128.
15. Kuwait Ministry of Electricity and Water (MEW) Report No. 20, 2010.