be noted, however, that in the case of non-linear regression, more data (observations) will be required, as the data covering only ten years between 1981 and 1990 is apparently not sufficient.[3] Non-linear, extrapolating lines could invite substantial over- or under-estimation of demand. Thus, our trend extrapolation forecasting is limited to the one on the basis of linear trend. The results of this forecasting are summarized in Table 5.4.1 (see also Figure 5.4.3).

Table 5.4.1 Summary of extrapolation forecasting for water consumption

Description	Equation	r^2	Year 2000 (Projected)	Year 2010 (Projected)
Average daily water consumption (cu m/d)				
Private water consumption	Y = -7204056.6 + 3643.073 x X	0.982	82,089	118,520
Government water consumption	Y = -8116080.867 + 4101.63 x X	0.931	81,179	128,195

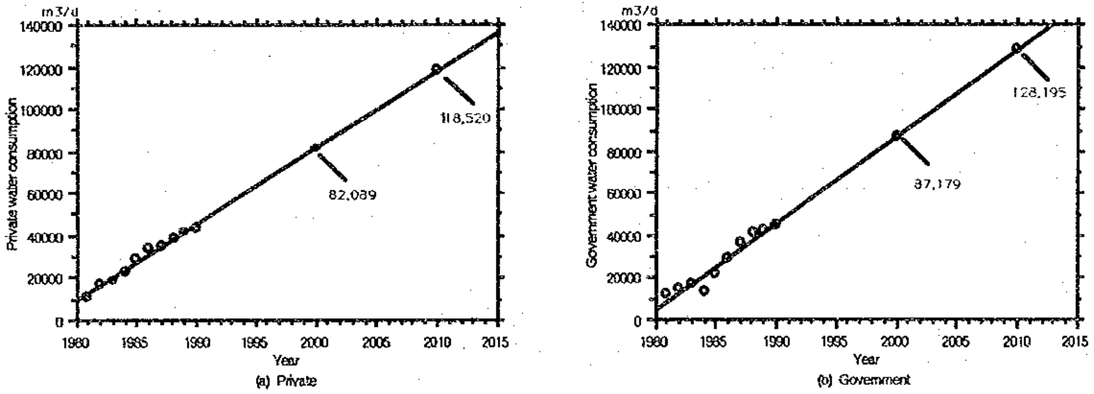


Figure 5.4.3 Extrapolated average daily water consumption

5.4.3 Micro forecasting method

Our micro forecasting is conducted separately for major consumers (government consumers only) and others. The latter are further divided into two groups, "domestic" or households, and "non-domestic", which includes "government" and "commercial" (see Figure 5.4.4). Demand projection is made not only for the Muscat Governorate, where MEW water is already served, but also for the South Batinah Region, where the Project is located and no piped water is yet provided.

---

[3] In actuality, non-linear lines fit better in the trends appearing in the figure than linear lines. For example, r^2 of the least-square, non-linear equation for private water consumption, Y(m^3/d) = 623,337,377.517 + 624,277.281X(year) - 156.292X3(year) is 0.993, which is higher than the counter figure of 0.982 for the linear equation Y=-7,204,056.6+3,643.073X(year).

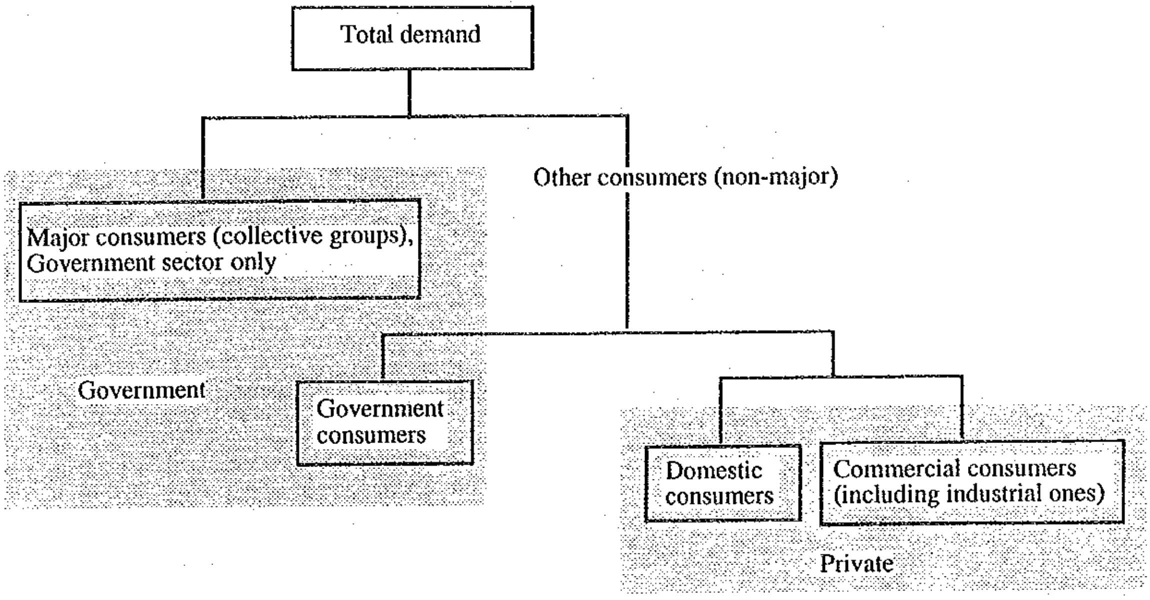


Figure 5.4.4 Water consumer groups

(1) Major consumers

The Master Plan identifies large water consumers and their levels of consumption. According to the plan, 279 largest water users comprising 188 government and 91 private consumers, collectively consumed 46,000 m^3/d or 52% of the total consumption in 1990. Those government consumers, while they represented only 8.8% of all the 2,128 public consumers, consumed 85% of the total public consumption. Similarly, but to a lesser degree, those private customers consumed 23% of the total private consumption, although they accounted for less than 3% of all the private consumers of 37,852.

Table 5.4.2 lists collective groups comprising most of the above-mentioned 279 largest water users. Estimated annual growth rates are also exhibited in the table, which are derived also from the Master Plan, and are based on an extensive study including direct inquiries to the respective consumers. In our demand forecasting, all of the four collective groups of the public sector will be regarded as major consumers and their consumption will be projected based on the estimated growth rates the Master Plan provides, separately from other consumers, as their collective share in the total government consumption is significantly high.[4]

None of the collective consumers in the private sector are treated separately as major consumers in our forecasting. The share of any of the collective consumers to the total private consumption is not significantly high, so that it appears not necessary to make projections separately from other private consumers.

Table 5.4.2 High water consumers (collective groups) (1990)

Collective group	Average consumption (m^3/d)	% of consumption in respective sectors	% of total consumption	Estimated annual growth rate (%) by 2010
Government sector				
Diwan Royal Court	8,620	20.0	9.5	2.0
Royal Oman Police	6,798	15.8	7.5	1.0
Public Irrigation	6,009	13.9	6.7	3.5
Min. of Defense	5,527	12.8	6.1	3.7
Total	26,954	62.5	29.8	10.2
Private sector				
Hotels	2,159	5.2	2.4	2.0
Company accommodations*	1,837	4.4	2.0	2.5
Industries excluding Rusayl Ind. Estate	1,529	3.7	1.7	3.0
Rusayl Ind. Estate	861	2.1	1.0	3.9
Total	6,386	15.4	7.1	11.4

* All the four groups are in the commercial category except the company accommodations, 48% of which, including labor camps, are in the commercial category, and the rest in the domestic category.

Source: Ministry of Electricity and Water, Sultanate of Oman, "Water Supply Master Plan for Muscat", Final Report, Vol. II of Main Report, June 1993.

(2) Increase in the number of connections

1) Muscat Area

a. Domestic connections

Table 5.4.3 exhibits the water consumption, the number of connections, and the unit consumption by type of users for the last six years except 1991 and 1992. According to the Master Plan, as in 1990, 261,000 residents were served with piped water, and the estimated average number of persons per connected household was 6.7. These two figures suggest that there were approximately 39,000

---

[4] The total number of the consumers of the four collective groups in the table is estimated at 140. The estimated growth rates appeared in the table take into account the future increase in the number of connections as well as the unit consumption growth.

domestic connections in 1990. The corresponding figure in the table, which was derived from a different reference source, is somewhat similar.

According to the 1993 census, the Muscat Area comprised 622,506 people and 92,298 families, as compared to 41,474 domestic connections indicated in Table 5.4.3. These figures suggest that only 45% of the population in the Muscat Area were covered by the piped water system in 1993. It is apparent that a large potential demand for piped water exists in the area.

In the current fourth development plan (1991-1995), an annual amount of 150,000 R.O. was appropriated for the extension of the water distribution network to areas in the Muscat Governorate. If the planned investment is realized and if the current level of investment for that purpose is maintained, it is estimated that the number of domestic connections will increase in the future by 2,000 annually, by the same increment experienced during the three years between 1990 and 1993 (see Table 5.4.3). The estimated numbers of domestic connections under this scenario are 55,500 for the year 2000 and 75,500 for 2010, as compared to 103,400 and 129,400 for the estimated total numbers of families for the respective years.[5] Under the scenario, the piped water system would cover only 53.7% of the area's population in 2000, and 58.3% in 2010. Knowing that providing piped water to every town and village with 500 inhabitants or more is one of the important socio-economic objectives of the government, the scenario needs to be reconsidered.

---

[5] The total population of the Muscat Governorate was approximately 623,000 in 1993. The estimated population growth rate was 3.5% annualy. No change in the average household size of 6.7 in 1993 is assumed.

Table 5.4.3 Water consumption, connections, and unit consumption by type of users (1987-1990 and 1993)

Description	Consumption (m^3/d)									
Consumer classification	1987		1988		1989		1990		1993	
	m^3/day	%	m^3/day	%	m^3/day	%	m^3/day	%	m^3/day	%
Domestic	24,121	35.9	27,415	36.8	30,257	37.9	33,615*	39.1	40,546	41.0
Commercial	8,214	12.2	8,283	11.1	8,708	10.9	9,164	10.7	9,555	9.7
Private total	32,335	48.1	35,698	47.9	38,965	48.8	42,779	49.8	50,101	50.6
Government	34,846	51.9	38,858	52.1	40,863	51.2	43,145	50.2	48,821	49.4
Total	67,181	100.0	74,556	100.0	79,828	100.0	85,924	100.0	98,922	100.0

Description	Number of accounts									
Consumer classification	1987		1988		1989		1990		1993	
		%		%		%		%		%
Domestic	N/A	N/A	N/A	N/A	N/A	N/A	35,954	89.9	41,474	91.4
Commercial	N/A	N/A	N/A	N/A	N/A	N/A	1,889	4.7	2,321	5.1
Private total	31,534	93.9	33,950	94.5	35,478	94.5	37,843	94.7	43,795	96.5
Government	2,057	6.1	1,983	5.5	2,053	5.5	2,134	5.3	1,572**	3.5
Total	33,591	100.0	35,933	100.0	37,531	100.0	39,977	100.0	45,367	100.0

Description	Unit consumption (m^3/d per connection)				
Consumer classification	1987	1988	1989	1990	1993
	m^3/day	m^3/day	m^3/day	m^3/day	m^3/day
Domestic	N/A	N/A	N/A	0.9	1.0
Commercial	N/A	N/A	N/A	4.9	4.1
Private total	1.0	1.1	1.1	1.1	1.1
Government	16.9	19.6	19.9	20.2	N/A
Total	2.0	2.1	2.1	2.1	2.2

* Including the tanker water of 3,903 m^3/day, which was consumed not only by domestic consumers but also by non-domestic ones.

** Counted by a new counting method.

N/A: Not available.

Source: Data obtained at MEW. Data for 1987-1990 and for 1993 were derived from different documents. Data for 1987-1990, which seemingly do not include tanker water, are slightly different from those used in the Master Plan.

The water consumption has been suppressed almost chronically, because of the insufficient capacity of water production. The Master Plan estimated the level of the suppressed consumption in 1990 at 2,600 m^3/day, or 7.8% of the total domestic consumption of that year. It is reported that the condition has become worse since then. We expect that the current shortage of supply will be solved with the implementation of the fifth-stage expansion plan (approximately 27,400 m^3/d) at the Ghubrah Plant. Operation of the new desalination unit is expected to start in 1996. Until that time, we assume, the annual increase in the number of connections will remain at the current level. Once the production capacity is expanded, substantial increase in the number of connections will become possible. Giving consideration only to the production capacity, and assuming that the new demand after the year 1999 will be handled by the Project, an annual connection increase of 4,000 or more would be feasible in 1997 and 1998. We assume the annual number of increase during the period will be 3,500.

Assumptions can be arbitrary with regard to the connection increase after the completion of the Project's first phase. In this respect, therefore, we take two scenarios. In one scenario (Scenario 1), considerably brisk investment is made in water transmission and distribution facilities and as a result, domestic connections increase in the number by 5,000 annually. In the other (Scenario 2), while investment in those facilities is active, the annual connection increase is at most 3,500. Under both scenarios, larger investment capital will generally be required in transmission and distribution facilities, as the supply area is expanded into rural and less populated areas.

Based on the assumptions discussed above, the annual increase in the number of domestic connections in the Muscat Area is projected as follows: (Projected numbers of domestic connections and ratios of population served are also shown.)

Annual increase in the number of domestic connections

Description/Year	1994 - 1996	1997 - 1998	1999-2004	2005-2010
Scenario 1	2,000	3,500	5,000	4,500
Scenario 2	2,000	3,500	3,500	3,200

Domestic connections and the ratio of population served

	1993 (actual)	2000	2010
Scenario 1			
connections	41,474	64,474	111,474
service ratio	45%	55%	67%
Scenario 2			
connections	41,474	61,474	94,674
service ratio	45%	52%	57%

b. Non-domestic connections

The per-connection cost for the provision of transmission and distribution facilities is comparatively high, particularly when the piped distribution network is expanded into remote areas. As the geographical expansion into different jurisdiction is slow, the average annual increase in the number of government consumers is expected to be low. In fact, the average annual increase was only 26 during the intervening three years between 1987 and 1990. Our projections for the increase in government connections under scenarios 1 and 2 are as follows:

Annual increase in the number of government connections

Description/Year	1994 - 1996	1997 - 1998	1999-2004	2005-2010
Scenario 1	10	18	26	23
Scenario 2	10	18	18	16

Percentage changes in the above annual increments (from 1993-1996 to 2005-2010) are the same as in the case of domestic connections. Government connections are projected to increase in number from the actual figure of 1,994 in 1990 to 2,134 in 2000 and 2,376 in 2010 under Scenario 1, and to 2,126 and 2,294, respectively, under Scenario 2.

The annual rate of increase in the number of commercial connections was 7.1% between 1990 and 1993. New connections for commercial uses occur in the area already served as well, and therefore commercial connections tend to increase at a higher rate than the rate of expansion of the service area. The difference in the annual increase rate between the two scenarios is expected to be low, as shown below.

Annual increase rate of the number of commercial connections

Description/Year	1994 - 1996	1997 - 1998	1999-2004	2005-2010
Scenario 1	5%	6%	7%	6%
Scenario 2	5%	6%	6%	5%

2) South Batinah

a. Domestic connections

MEW has a plan to provide piped water to some areas in South Batinah in conjunction with the Project. Those areas cover the Wilayats of Barka, Al-Masnaah, Rustaq, Nakhal, Al-Awabi, and Wadi Al-Maawil. The population of each wilayat is shown in Table 4.4.3. With respect to the supply water service in South Batinah, we make the following assumptions:

(a) The wiyalats' population will increase at an average annual rate of 3.5%, from 198,000 in 1993 to approximately 251,000 in 2000--a year after the Project is expected to complete its first phase including the construction of a desalination plant--and to 355,000 in 2010.

(b) The average household size in the region will not change from the current level of 7.9 and thus the total household number will be approximately 32,000 in 2000, and 45,000 in 2010.

(c) The ratio of the population served with piped water will reach 60% in 2005, and thereafter domestic connections will increase in number by 3.5% annually, which corresponds to a projected population growth rate of the wilayats.

(d) Between 1999 and 2005, due to the expansion of the service area, government and commercial connections will increase in number annually by 60 and 580, respectively.[6] The numbers will increase thereafter at an average yearly rate of 2% for government connections and 5% for commercial connections.

---

[6] We assume that by the year 2005, 400 government offices and 4,000 commercial establishments will be provided with piped water.

Table 5.4.4 exhibits estimated changes in the number of connections between 1999 and 2010.

Table 5.4.4 Projected number of water consumers in South Batinah 1999-2010

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1. Population		251,000					299,000					355,000
2. Number of families		32,000					38,000					45,000
3. Domestic connections	3,200	6,400	9,600	12,800	16,000	19,200	22,400	23,184	23,995	24,835	25,705	26,604
4. Government connections	60	120	180	240	300	360	420	428	437	446	455	464
5. Commercial connections	580	1,160	1,740	2,320	3,480	4,060	4,263	4,476	6,843	7,401	8,004	8,656
6. Total (Items 3 to 5)	3,840	7,680	11,520	15,360	19,780	23,620	27,083	28,088	31,275	32,682	34,164	35,724

(3) Unit consumption

a. Domestic consumption

According to the Master Plan, the per capita consumption of water by individuals living in villas, flats, or Arab/traditional houses was 2201 ℓ/day, 110 ℓ/day, or 80 ℓ/day, respectively, in 1990. This finding suggests that, regardless of the type of dwelling, an average person served by the MEW's piped water consumed 136 ℓ/day in 1990, as of the total housing units in 1990, 33% were villas, 40% flats, and 27% Arabic. Table 5.4.3 indicates that the domestic unit consumption was 0.9 m^3/day in 1990 and 1.0 m^3/day in 1993. We also know that the average family size in Muscat in 1993 was 6.7. From these figures and with an assumption that the average household size in 1990 was also 6.7, the per-capita domestic consumption in 1990 and that in 1993 are estimated to have been at 134 ℓ/day and 149 ℓ/day, respectively. The figure for 1990 and the corresponding figure suggested in the Master Plan are almost identical.

More precise values of 0.9 m^3/day for 1990 and 1 m^3/day for 1993 are 0.935 m^3/day and 0.978 m^3/day, respectively. These figures represent an annual growth rate of 1.5%. The growth of unit consumption will be limited, as the supply area is expanded into rural towns. We, however, assume that an average annual increase in unit consumption will be at 2% until 2010, taking into account the fact that water consumption was, to some extent, suppressed during the three years. With this growth rate, the unit consumption among domestic users is projected at 1.37 m^3/d for 2010, which is approximately 1.4 times higher than the current level.

A high growth rate of 4% is applied to the corresponding rate for South Batinah between 2000 and 2010. It is expected that once piped water becomes available, water usage per capita will substantially increase. As the dwelling units in Barka are predominantly of traditional Arabic style, we assume that the per capita consumption in Barka in 1990, if piped water had been available there, would have been 50 ℓ/day, as compared to the corresponding figure of 80 ℓ/day in Muscat Area. Based on the actual average family size of 7.9, the unit consumption in South Batinah in 1990 can be computed at 0.4 m^3/day.

Thus, the future domestic unit consumption is projected as shown below:

Year	1993	2000	2010
Muscat Area			
Unit consumption (m^3/day)	0.98	1.09	1.37
Annual growth rate	2.0%--1994 to 2010		
South Batinah			
Unit consumption (m^3/day)	(0.4--1990)	0.51	0.75
Annual growth rate	(2.0%)--1990 to 1999 4.0%--2000 to 2010		

b. Non-domestic consumption

The unit consumption of government users (including major consumers) increased from 16.9 m^3/day in 1987 to 20.2 m^3/day in 1990, at an average annual rate of 6.1%. Part of this high growth rate is believed to have been attributed to a sharp increase for the use of public irrigation. The unit consumption for 1990 is calculated at 8.1 m^3/day, if the consumption by the earlier-mentioned collective consumers is excluded.[7] The average consumption by commercial users decreased from 4.9 m^3/day in 1990 to 4.1 m^3/day in 1993.

As the existing transmission network will be extended more frequently into rural areas in the future, the unit consumption by non-domestic users may decline. Without suppression of consumption or any other constraints, however, the average consumption should increase in the long run. We expect that the unit consumption by both government and commercial users will increase at small rates. We assume that the levels

---

[7] 8.1 m^3/d = (43,145 m^3/d - 26,954 m^3/d) ÷ (2,1434 connections - 140 connections)
See Tables 5.4.2 and 5.4.3.

of unit consumption for South Batinah for 1990, if water had been available there, would be 4.0 m^3/day for government users and 1.0 m^3/day for commercial users.[8] Table 5.4.5 exhibits our estimates regarding the non-domestic unit consumption.

Table 5.4.5 Unit consumption by non-domestic users

	Year	2000	2005	2010
	Unit consumption:			
1.	Government (m^3/d)			
	Muscat	10.8	12.1	13.4
	South Batinah	5.0	6.0	7.1
2.	Commercial (m^3/d)			
	Muscat	4.7	5.2	5.6
	South Batinah	1.2	1.4	1.7
	Year	1993(1990)-1998	1999-2004	2005-2010
3.	Government			
	Muscat	3.0%	2.5%	2.0%
	South Batinah	(2%)	3.5%	3.5%
4.	Commercial			
	Muscat	2.0%	2.0%	1.5%
	South Batinah	(2.0%)	3.0%	3.0%

(4) Total water consumption

Based on all the assumptions discussed above, the total water consumption is projected as shown in Tables 5.4.6 and 5.4.7. The projected total consumption for the year 2000 and that for 2010 are approximately 152,000 m^3/d and 297,000 m^3/d under Scenario 1 and 148,000 m^3/d and 269,000 m^3/d under Scenario 2. The domestic consumption in the Muscat Area will constitute a large portion to the total, 51.6% under Scenario 1 and 48.4% under Scenario 2 in 2010, as compared to the actual ratio of 41.8% in 1993. This projection reflects an anticipation that the service area will be expanded so as to increase the household service ratio significantly, and conversely, that the government is willing to make large investments in water transmission and distribution facilities. The water demand in the six walayats concerned in South Batinah is estimated at approximately 32,000 m^3/d. Unless water distribution networks are build in the walayats, the demand will remain only as a potential demand. We

---

[8] According to the Master Plan, there were 17 accounts with the water consumption of over 100 m^3/d. Their total consumption was 4,621 m^3/d. The unit consumption of the commercial consumers excluding those high consumers was 2.4 m^3/d [=(9,164 m3/d - 4,621 m^3/d) ÷ (1,889 connections -17 connections)]. We assume that there would be no consumers with the consumption level at 100 m^3/d or larger in South Batinah.

assume that the distribution networks will be built at such a rapid pace that 60 percent of the residents in the walayats can be served by the year 2005.

(5) Comparison of forecasting results

Table 5.4.8 compares the demand projections by the trend extrapolation and the micro approach as well as the MEW forecast indicated in the Master Plan. The MEW forecast does not cover any demand in South Batinah. All the projections are similar.

Table 5.4.8 Comparison of forecasting results

Description Year	2000	2010	(m^3/d)
Master plan (MEW)	-	245,496	
Trend extrapolation	163,268	246,715	
Micro approach			
Including the demand in South Batinah			
Scenario 1	151,503	296,762	
Scenario 2	147,724	268,855	
Average	149,614	282,809	
Excluding the demand in South Batinah			
Scenario 1	146,214	264,860	
Scenario 2	142,435	236,953	
Average	144,325	250,907	

Table 5.4.9 compares the demand by consumer group projected by different methods. The percentage share of the domestic use is clearly higher in the Master Plan forecast than in other results. The Master Plan estimated a 2.5% annual increase for the domestic consumption in the Muscat Area, whereas the micro forecasting adopted a 2.0% increase. This is the primary cause of the percentage share difference between the two forecasts. In the micro forecasting, the consumption by commercial users is expected to grow at a comparatively higher rate of speed, with an anticipation of moderate economic activities and thus larger increases in the number of connections and the unit consumption. Results by the trend extrapolation are unlikely to be accurate, as they appear to have reflected unusually sharp increases in the public use in recent years.

Table 5.4.6 Projected Consumption of Water - Scenario 1

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Muscat Area																					
1. Major consumers	26,954	27,609	28,283	28,977	29,692	30,427	31,184	31,963	32,765	33,591	34,442	35,318	36,220	37,149	38,106	39,093	40,109	41,155	42,234	43,345	44,491
a. Diwan Royal Court	8,620	8,792	8,968	9,148	9,331	9,517	9,708	9,902	10,100	10,302	10,508	10,718	10,932	11,151	11,374	11,601	11,833	12,070	12,311	12,558	12,809
% change		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
b. Royal Oman Police	6,798	6,866	6,935	7,004	7,074	7,145	7,216	7,288	7,361	7,435	7,509	7,584	7,660	7,737	7,814	7,892	7,971	8,051	8,131	8,213	8,295
% change		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
c. Public Irrigation	6,009	6,219	6,437	6,662	6,895	7,137	7,387	7,645	7,913	8,190	8,476	8,773	9,080	9,398	9,727	10,067	10,420	10,784	11,162	11,552	11,957
% change		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
d. Min. of Defence	5,527	5,731	5,944	6,163	6,392	6,628	6,873	7,128	7,391	7,665	7,948	8,242	8,547	8,864	9,192	9,532	9,884	10,250	10,629	11,023	11,430
% change		3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%
2. Domestic				40,546	43,351	46,253	49,253	53,941	58,798	65,479	72,403	79,579	87,012	94,711	102,683	110,316	118,213	126,382	134,831	143,566	152,598
connections				41,474	43,474	45,474	47,474	50,974	54,474	59,474	64,474	69,474	74,474	79,474	84,474	88,974	93,474	97,974	102,474	106,974	111,474
% change of connections					4.8%	4.6%	4.4%	7.4%	6.9%	9.2%	8.4%	7.8%	7.2%	6.7%	6.3%	5.3%	5.1%	4.8%	4.6%	4.4%	4.2%
unit consumption				1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.4
% change of unit consumption					2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
combined % change					6.9%	6.7%	6.5%	9.5%	9.0%	11.4%	10.6%	9.9%	9.3%	8.8%	8.4%	7.4%	7.2%	6.9%	6.7%	6.5%	6.3%
3. Government	16,191	16,719	17,307	17,915	18,543	19,193	19,866	20,641	21,445	22,255	23,091	23,956	24,849	25,772	26,726	27,540	28,375	29,233	30,114	31,019	31,947
connections	1,994	2,004	2,014	2,024	2,034	2,044	2,054	2,072	2,090	2,116	2,142	2,168	2,194	2,220	2,246	2,269	2,292	2,315	2,338	2,361	2,384
% change of connections		0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.9%	0.9%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
unit consumption	8.1	8.3	8.6	8.9	9.1	9.4	9.7	10.0	10.3	10.5	10.8	11.0	11.3	11.6	11.9	12.1	12.4	12.6	12.9	13.1	13.4
% change of unit consumption		3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
combined % change		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.9%	3.9%	3.8%	3.8%	3.7%	3.7%	3.7%	3.7%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
4. Commercial				9,555	10,192	10,915	11,690	12,640	13,666	14,915	16,278	17,766	19,390	21,162	23,096	24,849	26,735	28,765	30,948	33,297	35,824
connections				2,321	2,437	2,559	2,687	2,848	3,019	3,230	3,456	3,698	3,957	4,234	4,531	4,802	5,091	5,396	5,720	6,063	6,427
% change of connections					5.0%	5.0%	5.0%	6.0%	6.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
unit consumption				4.1	4.2	4.3	4.4	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.3	5.4	5.5	5.6
% change of unit consumption					2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
combined % change					7.1%	7.1%	7.1%	8.1%	8.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	7.6%	7.6%	7.6%	7.6%	7.6%	7.6%
5. Total (Items 1 to 4)				96,993	101,778	106,788	111,992	119,185	126,674	136,239	146,214	156,618	167,471	178,794	190,611	201,797	213,432	225,535	238,127	251,227	264,860
South Batinah																					
6. Domestic										1,560	3,244	5,061	7,018	9,123	11,386	13,815	14,870	16,006	17,229	18,545	19,962
connections										3,200	6,400	9,600	12,800	16,000	19,200	22,400	23,184	23,995	24,835	25,705	26,604
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	3.5%	3.5%	3.5%	3.5%	3.5%
unit consumption	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
combined % change											108.0%	56.0%	38.7%	30.0%	24.8%	21.3%	7.6%	7.6%	7.6%	7.6%	7.6%
7. Government										291	602	935	1,291	1,670	2,074	2,504	2,644	2,791	2,947	3,111	3,284
connections										60	120	180	240	300	360	420	428	437	446	455	464
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	2.0%	2.0%	2.0%	2.0%	2.0%
unit consumption	4.0	4.1	4.2	4.2	4.3	4.4	4.5	4.6	4.7	4.9	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.1
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
combined % change											108.0%	56.0%	38.7%	30.0%	24.8%	21.3%	6.1%	6.1%	6.1%	6.1%	6.1%
8. Commercial										700	1,442	2,228	3,059	3,939	4,869	5,850	6,327	6,843	7,401	8,004	8,656
connections										580	1,160	1,740	2,320	2,900	3,480	4,060	4,263	4,476	4,700	4,935	5,182
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	5.0%	5.0%	5.0%	5.0%	5.0%
unit consumption	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.6	1.7
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
combined % change																					
9. Total (Items 6 to 8)										2,551	5,289	8,224	11,368	14,732	18,328	22,170	23,841	25,640	27,576	29,660	31,902
10. Grand total (items 5 and 9)				96,993	101,778	106,788	111,992	119,185	126,674	138,790	151,503	164,842	178,839	193,526	208,940	223,967	237,273	251,176	265,703	280,887	296,762

Assumptions for South Batinah:

1 Projected number of households in 2000: 32,000
2 % of households to be connected by 2005: 60% (22,000)
3 New domestic connections each year between 1999 and 2005: 3,200
4 Government connections by 2005: 400
5 Commercial connections by 2005: 4,000

Table 5.4.7 Projected Consumption of Water - Scenario 2

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Muscat Area																					
1. Major consumers	26,954	27,609	28,283	28,977	29,692	30,427	31,184	31,963	32,765	33,591	34,442	35,318	36,220	37,149	38,106	39,093	40,109	41,155	42,234	43,345	44,491
a. Diwan Royal Court	8,620	8,792	8,968	9,148	9,331	9,517	9,708	9,902	10,100	10,302	10,508	10,718	10,932	11,151	11,374	11,601	11,833	12,070	12,311	12,558	12,809
% change		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
b. Royal Oman Police	6,798	6,866	6,935	7,004	7,074	7,145	7,216	7,288	7,361	7,435	7,509	7,584	7,660	7,737	7,814	7,892	7,971	8,051	8,131	8,213	8,295
% change		1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
c. Public Irrigation	6,009	6,219	6,437	6,662	6,895	7,137	7,387	7,645	7,913	8,190	8,476	8,773	9,080	9,398	9,727	10,067	10,420	10,784	11,162	11,552	11,957
% change		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
d. Min. of Defence	5,527	5,731	5,944	6,163	6,392	6,628	6,873	7,128	7,391	7,665	7,948	8,242	8,547	8,864	9,192	9,532	9,884	10,250	10,629	11,023	11,430
% change		3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%
2. Domestic				40,546	43,351	46,253	49,253	53,941	58,798	63,827	69,034	74,424	80,002	85,773	91,743	97,545	103,543	109,742	116,147	122,764	129,600
connections				41,474	43,474	45,474	47,474	50,974	54,474	57,974	61,474	64,974	68,474	71,974	75,474	78,674	81,874	85,074	88,274	91,474	94,674
% change of connections					4.8%	4.6%	4.4%	7.4%	6.9%	6.4%	6.0%	5.7%	5.4%	5.1%	4.9%	4.2%	4.1%	3.9%	3.8%	3.6%	3.5%
unit consumption				1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.4
% change of unit consumption					2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
combined % change					6.9%	6.7%	6.5%	9.5%	9.0%	8.6%	8.2%	7.8%	7.5%	7.2%	7.0%	6.3%	6.1%	6.0%	5.8%	5.7%	5.6%
3. Government	16,191	16,719	17,307	17,915	18,543	19,193	19,866	20,641	21,445	22,171	22,919	23,691	24,487	25,308	26,155	26,872	27,608	28,362	29,135	29,928	30,741
connections	1,994	2,004	2,014	2,024	2,034	2,044	2,054	2,072	2,090	2,108	2,126	2,144	2,162	2,180	2,198	2,214	2,230	2,246	2,262	2,278	2,294
% change of connections		0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.9%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
unit consumption	8.1	8.3	8.6	8.9	9.1	9.4	9.7	10.0	10.3	10.5	10.8	11.0	11.3	11.6	11.9	12.1	12.4	12.6	12.9	13.1	13.4
% change of unit consumption		3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
combined % change		3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.9%	3.9%	3.4%	3.4%	3.4%	3.4%	3.4%	3.3%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%
4. Commercial				9,555	10,233	10,960	11,738	12,691	13,722	14,836	16,041	17,343	18,751	20,274	21,920	23,362	24,898	26,535	28,279	30,139	32,120
connections				2,321	2,437	2,559	2,687	2,848	3,019	3,200	3,392	3,596	3,811	4,040	4,282	4,497	4,721	4,957	5,205	5,466	5,739
% change of connections					5.0%	5.0%	5.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
unit consumption				4.1	4.2	4.3	4.4	4.5	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.4	5.5	5.6
% change of unit consumption					2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%
combined % change					7.1%	7.1%	7.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	6.6%	6.6%	6.6%	6.6%	6.6%	6.6%
5. Total (Items 1 to 4)				96,993	101,819	106,833	112,040	119,237	126,730	134,425	142,435	150,776	159,460	168,504	177,924	186,871	196,157	205,794	215,795	226,177	236,952
South Batinah																					
6. Domestic										1,560	3,244	5,061	7,018	9,123	11,386	13,815	14,870	16,006	17,229	18,545	19,962
connections										3,200	6,400	9,600	12,800	16,000	19,200	22,400	23,184	23,995	24,835	25,705	26,604
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	3.5%	3.5%	3.5%	3.5%	3.5%
unit consumption	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
combined % change											108.0%	56.0%	38.7%	30.0%	24.8%	21.3%	7.6%	7.6%	7.6%	7.6%	7.6%
7. Government										291	602	935	1,291	1,670	2,074	2,504	2,644	2,791	2,947	3,111	3,284
connections										60	120	180	240	300	360	420	428	437	446	455	464
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	2.0%	2.0%	2.0%	2.0%	2.0%
unit consumption	4.0	4.1	4.2	4.2	4.3	4.4	4.5	4.6	4.7	4.9	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.1
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
combined % change											108.0%	56.0%	38.7%	30.0%	24.8%	21.3%	6.1%	6.1%	6.1%	6.1%	6.1%
8. Commercial										700	1,442	2,228	3,059	3,939	4,869	5,850	6,327	6,843	7,401	8,004	8,656
connections										580	1,160	1,740	2,320	2,900	3,480	4,060	4,263	4,476	4,700	4,935	5,182
% change of connections											100.0%	50.0%	33.3%	25.0%	20.0%	16.7%	5.0%	5.0%	5.0%	5.0%	5.0%
unit consumption	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.6	1.6	1.7
% change of unit consumption		2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
combined % change																					
9. Total (Items 6 to 8)										2,551	5,289	8,224	11,368	14,732	18,328	22,170	23,841	25,640	27,576	29,660	31,902
10. Grand total (items 5 and 9)				96,993	101,819	106,833	112,040	119,237	126,730	136,976	147,724	159,600	170,828	183,236	196,253	209,041	219,998	231,434	243,372	255,837	268,855
11. Average total (Scenarios 1 & 2)				96,993	101,799	106,810	112,016	119,211	126,702	137,883	149,614	161,921	174,823	188,361	202,596	216,504	228,636	241,305	254,537	268,362	282,309

Assumptions for South Batinah:

1 Projected number of households in 2000: 32,000
2 % of households to be connected by 2005: 60% (22,000)
3 New domestic connections each year between 1999 and 2005: 3,200
4 Government connections by 2005: 400
5 Commercial connections by 2005: 4,000

Table 5.4.9 Comparison of projected consumer-wise demand (2010)

Description	Domestic	Commercial	Government	Tanker water
Master plan (MEW)	157,737 (64%)	15,536 (6%)	70,698 (29%)	1,525 (1%)
Trend extrapolation	118,520 (48%)		128,195 (52%)	
Micro forecasting (Muscat Area)				
Scenario 1	152,598 (58%)	35,824 (14%)	76,438 (29%)	
Scenario 2	129,600 (54%)	32,120 (14%)	75,233 (32%)	
Average of two scenarios	141,099 (56%)	33,972 (14%)	75,836 (30%)	

We support the forecasting results by our macro approach, and we adopt in this study the average of the projections under the two scenarios. The Master Plan provides similar forecasts. We believe, however, that the demand by commercial consumers will be much higher than the Master Plan's projection, because of the government's continuous efforts for economic development. The Private Sector including manufacturing industries must provides more jobs to the increasing population, thus consuming larger quantities of water in the future. Figures 5.4.5 and 5.4.6 exhibit the changes in the projected demand which is adopted for this study, and those in the composition of the demand.

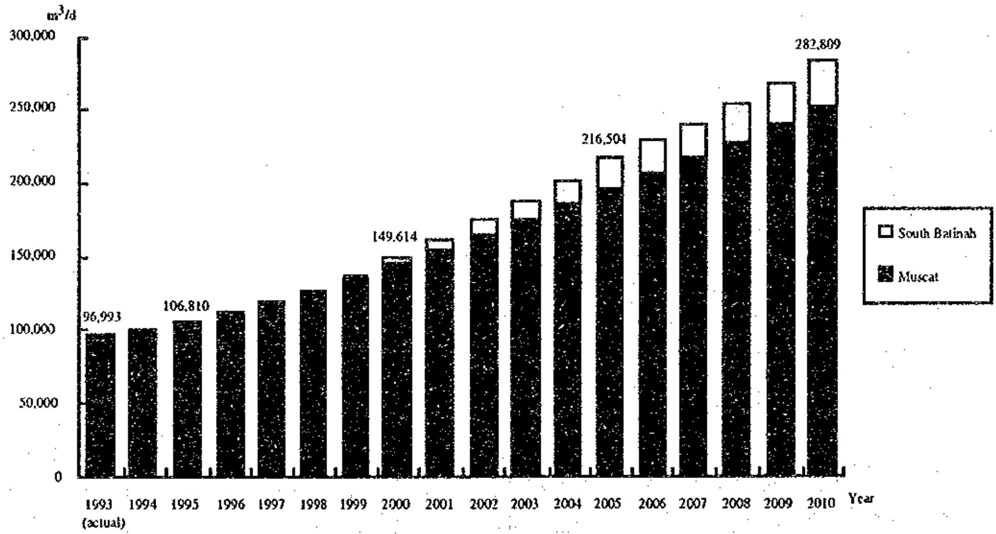
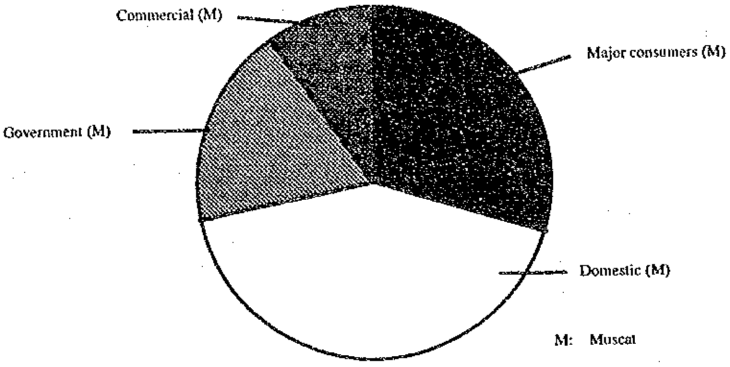
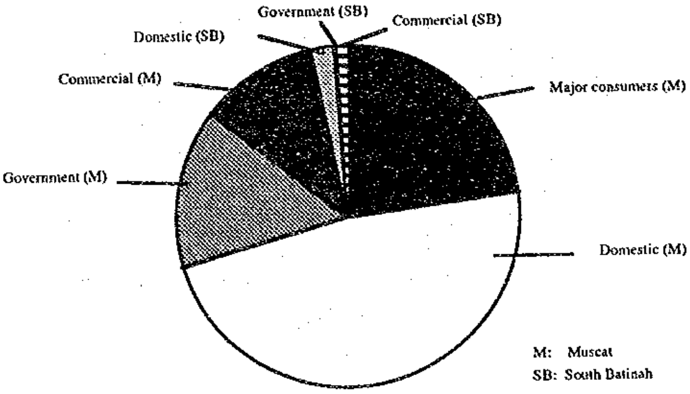


Figure 5.4.5 Changes in water consumption (projected)
1993-2010

(1) Year 1993 (actual)



(2) Year 2000 (projected)



(3) Year 2010 (projected)

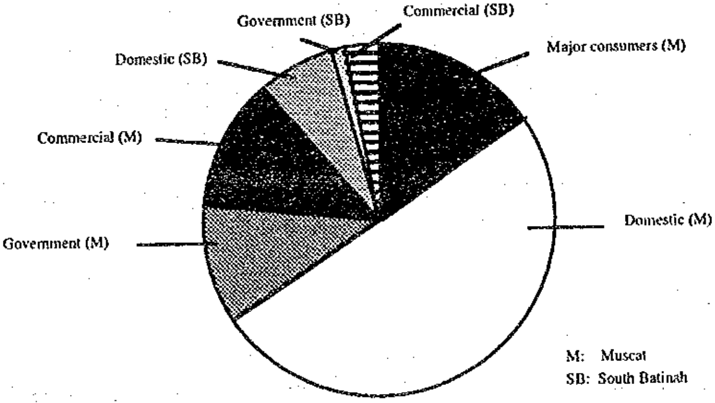


Figure 5.4.6 Changes in the composition of the water consumption

5.5 Barka Water Resource Development Plan

5.5.1 "The Master Plan"

According to Master Plan, the feasibility study has been undertaken with classification of water resources into:(1) underground water, (2) surface water, (3) desalination. Aspect of the study can be deployed as the followings:

(1) Underground water

Water extraction from the Eastern, Central and Western Wellfield has already exceeded the control level, 20,000 m^3/d. Measures should be taken to ensure that this extraction rate does not increase. Underground water is often used for agricultural and domestic purposes in areas outside Muscat. The capacity and quality of this water supply is neither appropriate nor sufficient for the needs of Muscat area.

(2) Surface water

Wadi Dayqah, about 90 km southeast of Muscat, is the only source of surface water which can be used in the Muscat area. Although there have been proposals to use surface water for domestic or agricultural purposes since the early 1980s, no such plans have yet been finalized. While the Wadi Dayqah project has been extensively assessed since 1991, including a site survey, environmental investigation and economic evaluation, many issues remain unsolved. It will probably take several years to prepare more specific plans. MEW is of opinion that the Wadi Dayqah development project does not need to be a consideration in the Barka project. It is believed that the Wadi Dayqah water source will be capable of supplying 40,000 to 50,000 m^3/d atmost after development.

(3) Desalination

The deteriorating quality of underground water is of concern, and has resulted in limits being placed on drawing water from wells. Desalination will become a focus for meeting the anticipated growth in water demand.

1) Ghubrah Desalination Plant

Section 5.2.1 has already indicated that the 22,730 m^3/d (5 MGPD) Ghubrah Desalination Plant facility was firstly constructed in 1976, and then through three construction stages the plant currently operates five MSF units with a total capacity of 131,930 m^3/d (29 MGPD). The fifth phase of construction should be completed by 1996, providing a further 27,300 m^3/d (6 MGPD).

MEW's 1990 study assessed the re-development of the Ghubrah Power Generation and Desalination Plant. The study was designed to ascertain the maximum expansion capacity at Ghubrah. The results revealed that capacity could be expanded by a further 300,000 m^3/d. However, the study was limited to the Ghubrah plant and does not discuss the re-development issue from the perspective of ensuring a safe and reliable water system for whole of Oman.

2) Barka Desalination Plant

The Barka Desalination Plant was assessed by JICA in 1985 with a feasible forecasting. And the development project is envisaged by the Oman Government to commence during the 5th five year plan (1996 - 2000).

5.5.2 Scope of Development Plan

This development plan is provided, under the agreement between MEW and JICA, to construct a desalination plant in Barka, capable to supply for both water demands in Muscat and South Batinah area in 2010.

Presupposition of this development plan consists of:

(1) The Ghubrah Desalination Plant would be maintained with its current capacity plus No. 6 Unit. Even in case required its plant renewal, it should be covered by an extension stage of the Barka Plant to bear such water demands as long as possible, then the Ghubrah Plant should be set on renewal schedule.

(2) Supply capacity of well water shall be assumed 20,000 m^3/d as constant or average, and it should be acceptable with seasonal and/or annual variation from it.

(3) Existing capacity of wells in South Batinah would be neglected as there is no data available.

5.5.3 Prospect of Supply Capacity

(1) Supply capacity before Barka plant development

The Ghubrah Desalination Plant as of the end of 1993 provides the supply capacity of 131,930 m^3/d. The No. 6 plant is also scheduled to come on line in 1996. This will increase the Muscat region's supply capacity as shown in Table 5.5.1.

Table 5.5.1 Muscat Region Water Supply Capacity in 1998

Source	Capacity m^3/d	Note
Desalination plant	159,230	* Pumping Capacity is about 100,000 m^3/d, but restricted below 20,000 m^3/d
Well water	20,000*	
Oil Refinery	1,000	
Total	180,230	

(2) Expected life of existing desalination plant

The No. 1 unit of Ghubrah Desalination Plant began operations in 1976, and has been extended up to current scale during its lifetime. Such plants are normally designed to last about 20 years, and the materials for principal components are selected accordingly. The depreciation period for this plant in Oman is set at 20 years, but this only indicates that using a desalination plant for 20 years is possible. A desalination plant could continue to operate for more than 20 years, assuming such operation was economically rational. Economic indices which would suggest replacement are:

1) When plant renewal is more economical because maintenance costs have increased and availability have dropped as a result of increasingly frequent failures, or

2) When the efficiency of new technologies improves sufficiently to lower desalination costs.

Ghuburah No. 1 and No. 2 units are single purpose MSF plants with high fuel consumption rates. By the year 2010 these units will have been in service for 34 years and 27 years respectively. We anticipate these units will be replaced.

The steam source for No. 3 and No. 4 units is being switched from the boiler using natural gas to heat recovery boiler, of gas turbine.
These plants are expected to be in use in 2010.

5.5.4 Presupposition of Plant Capacity Determination

(1) Demand forecasting

Concerning the water demand in Muscat and South Batinah in 2010, it shall be used the averaged value of Scenario 1 and Scenario 2 as aforementioned in §5.4.3. That is to say:

Water demand in 2010 : 282,809 m^3/d

(2) Conversion to supply capacity

The value discussed in §5.3.3 shall be used, as follows:

Total design capacity required = $(282,809 \div 0.85) \times 1.2^*$
= 399,260 m^3/d

* 0.85 = Revenue ratio
1.2 = Design capacity ratio

(3) Unit capacity

Here, we applied the unit capacity 7 MGPD (31,800 m^3/d).

The reason comes from the followings:

1) In the Middle East, desalination capacity is usually nominated as "MGPD" and rounded up such as 5 MGPD for Ghubrah No. 1 Unit, and 6 MGPD for the No. 2 to No. 5 Unit.

2) According to the records ordered with MSF process plant in 1990 to 1991, their median were represented 7 MGPD.

3) As it is sure the more capacity of the unit the more economical, application of 7 MGPD is reasonable including the result of previous feasibility study by JICA as 30,000 m^3/d (nearly 7 MGPD).

Such selection of a larger size for the Barka Plant to the Ghubrah meets the current plant/unit scale planning.

The Barka Desalination Plant should be also constructed two unit as set, considering combination with power station plan.

5.5.5 The Barka Water Resource Development Plan

(1) Desalination facilities required in 2010

Subtracting the capacity 180,230 m^3/d of current Ghubrah Desalination Plant from the total design capacity 399,260 m^3/d required in Muscat and South Batinah area, it is resulted in remaining 219,030 m^3/d as shortage.

This shortage may be covered by four sets with two units, which has capacity of 31,800 m^3/d/unit, of expected the Barka Plant. That is to say:

The Barka Plant capacity required in 2010 = 31,800 x 2 x 4
= 254,000 m^3/d (approx.)

(2) Construction schedule

Based on forecasting the annual water demand, a construction schedule is introduced with Table 5.5.2 and Fig. 5.5.1

(3) Reserve capacity

Unlike electricity, desalination facilities enable storage. At present, the reservoir has the capacity to stock one day's reserve. To date, repairs have been carried out during winter when demand drops and there is little reserve capacity. Water taken from wells helps stabilize demand. However, reserve capacity will be required in 2010 for the following reasons:

(a) Six units will be in operation at Ghubrah and eight at Barka, a total of 14 units. This will mean a longer maintenance period. It takes one month to maintain one existing unit, so that five months are required even now to complete all maintenance work. However, by 2010, it is possible that repairs will need to be carried out year-round, excluding the peak period during summer.

(b) The oldest unit at present is 18 years old. Most units are being used for ten years at most. However, by 2010, Ghubrah Plant will have been in operation for another 16 years. This means a greater possibility that frequency of failures will increase.

In this study, however, it is not taken account of the reserve capacity. Because it is expectable to operate the plant, in case RO process as §9.2 without long term shutdown, and maintain monthly each unit by turns except June to August for seasonal peak load in conjunction with adjustment of well water pumping.

Table 5.2.2 Development Plan

Year	Design Demand	Existing Cap.	Barka Project	Supply Capacity	Differrece
	m3/D	m3/D	m3/D	m3/D	m3/D
1986	122,984	125,630		125,600	2,616
1987	129,700	125,630		125,600	-4,100
1988	135,678	125,630		125,600	-10,078
1989	143,305	125,630		125,600	-17,705
1990	145,884	125,630		125,600	-20,284
1991		125,630		125,600	
1992		125,630		152,900	
1993	155,189	152,930		152,930	-2,259
1994	162,878	152,930		152,930	-9,948
1995	170,896	152,930		152,930	-17,966
1996	174,570	152,930		152,930	-21,640
1997	181,080	180,230		180,230	-850
1998	187,707	180,230		180,230	-7,477
1999	199,349	180,230	63,600	243,830	44,481
2000	211,220	180,230	63,600	243,830	32,610
2001	228,582	180,230	63,600	243,830	15,248
2002	246,823	180,230	127,200	307,430	60,607
2003	265,950	180,230	127,200	307,430	41,480
2004	286,018	180,230	127,200	307,430	21,412
2005	305,653	180,230	127,200	307,430	1,777
2006	322,780	180,230	198,000	378,230	55,450
2007	340,666	180,230	198,000	378,230	37,564
2008	359,346	180,230	198,000	378,230	18,884
2009	378,864	180,230	254,400	434,630	55,766
2010	399,260	180,230	254,400	434,630	35,370

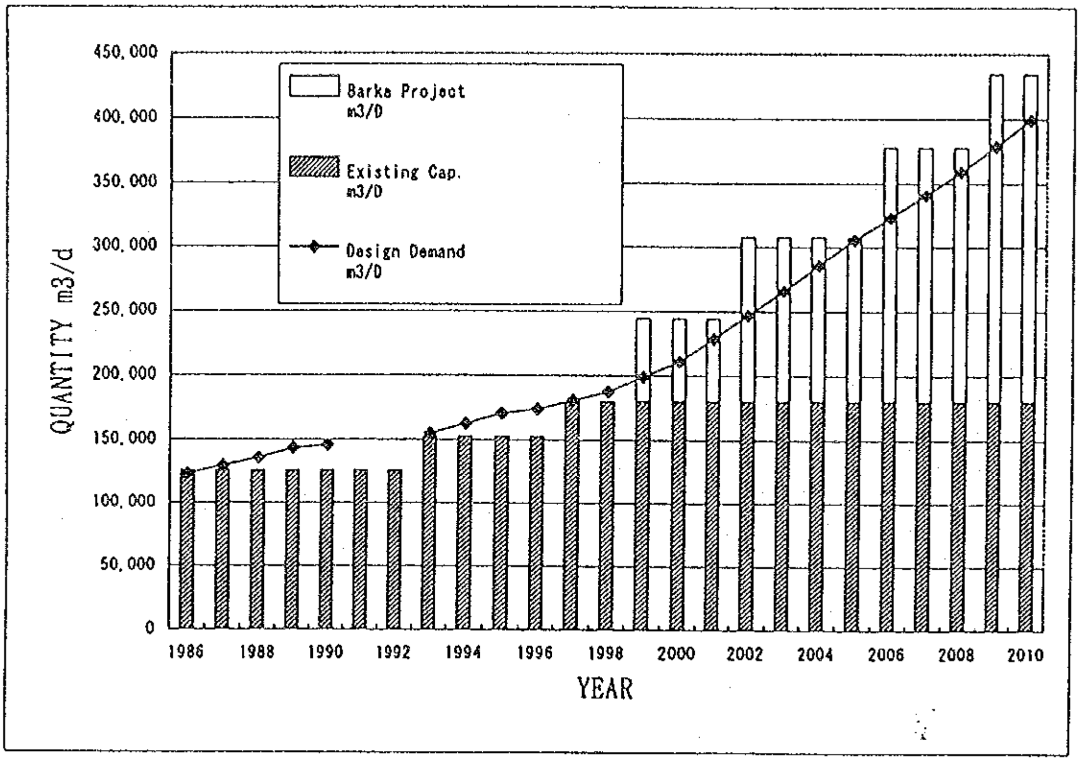


Figure 5.5.1 Development Plan

CHAPTER 6 PROJECT SITE SELECTION

CHAPTER 6 PROJECT SITE SELECTION

6.1 Conditions for Site Selection

The site for the thermal power and desalination plant like this project is, in general, selected taking into consideration technical, environmental and economic aspects as listed below.

(1) Negative impacts to the natural and social environment around the site due to the plant construction and operation are not critical.

(2) It is not difficult to obtain an understanding on the significance of the project from inhabitants around the site and the issue of compensation is not critical.

(3) There is no difficulty in acquisition of land including a space for future expansion and costs are not high.

(4) Subsoil conditions are good enough for reducing the costs of foundations.

(5) Meteorological, marine and geological conditions are not severe and disasters due to storms, cyclones, storm surges, earthquake and so forth are rarely expected.

(6) A large amount of water required for plant operation is easily secured.

(7) Quality of seawater used for desalination is good.

(8) Supply of fuel required for plant operation is readily available.

(9) A site is close to service areas for electric power and water, and construction and maintenance costs for transmission lines and water pipelines are low.

(10) There is no difficulty in transportation of material and equipment required for construction and operation.

6.2 Present Conditions of Project Site

In the 1985 F/S, the proposed sites were selected initially at six locations on the coast between Barka and Seeb Airport according to MEW's request. After the studies on the individual sites from technical and economic points of view, four sites among the six were recommended. However, MEW found difficulties in land acquisition and, finally, MEW itself found an alternative project site which is located about 5.5 km eastward from Barka and belongs to the Royal Family. In receipt of the request from MEW, JICA studied whether the proposed site is suitable for the project, and concluded that there is no significant difference between this one and the other alternatives.

This F/S was started with the understanding that the site selection was completed in the 1985 F/S. However, in the process of site reconnaissance and meetings with MEW, it was found that;

(1) the size of the project site is 610 x 1,000 m, not 1,000 x 1,000 m, and

(2) there is a discrepancy between the site location shown in the land use map prepared by MH and the present site location confirmed by MEW.

Finally, MEW confirmed that the present site, 610 x 1,000 m in size, is the final one.

Figures 6.1.1 and 6.1.2 show the location and surrounding conditions of the project site. The newly proposed site also belongs to the Royal Family, and its topographical and surrounding conditions are almost the same as those of the previously selected site. As shown in the above Figures, the accessibility to the site is good since the existing road runs close to it. The summaries of examination on the proposed site from the technical, environmental and economic points of view are described hereinafter. Judging from these, it is considered that there are no serious problems which will hinder the project.

6.2.1 Surrounding Environment

As shown in Figures 6.1.1 and 6.1.2, the proposed site is located about 5.5 km eastward from Barka Town. There are several towns and villages within a 5 km radius from the site - Romays, Barsit, Haradi, Hayyasim, etc., among which Hayyasim and Haradi are located closer to the site (Hayyasim - about 500 m southward, Haradi - about 2 km westward). The main economic activities of Hayyasim and Haradi are plantation and fishing respectively. Other notable communities, economic activities, facilities and cultural heritages were not seen around the site. Furthermore, the existence of endangered fauna and flora was not observed in the site and there are no reports or information announcing their existence around the site.

From the above, it is considered that the following are major points to be studied;

(1) Impacts to the fishing and aquatic biota due to the hot water discharge

(2) Air pollution due to the exhaust gas emission from the plant

(3) Change of landscape due to the construction of the plant

(4) Noise, turbidity of sea water

It is considered, as described in Chapter 13, that these impacts can be duly mitigated by taking some countermeasures and designing properly.

6.2.2 Topographical Features

The proposed site is located on the coast which is formed of sand dunes. The land is generally flat with gentle undulations (the ground height is approximately HAT +0 ~ +1.8 m). It can be said that there is no restriction from the topographical point of view.

The sea bed has a gentle slope (1/100 ~ 1/200) and it seems uneconomical for the construction of a water intake facility. It is known, however, that there is not much difference in the sea bed profiles of the area between Barka and Seeb Airport. Therefore, this is not a critical point in the site selection.

6.2.3 Geological Features

According to the results of the soil investigation conducted in this F/S, firm strata with SPT value more than 50 are distributed at 5.0 ~ 11.0 m below the ground surface and it is considered that the pile foundation system is technically and economically feasible as described in Chapter 11. It seems that there is not much difference in the soil conditions of the coastal area between Barka and Seeb Airport.

6.2.4 Temperature and Quality of Sea Water

The sea water temperature offshore from the site in December was about 26°C and there was no difference by depth as shown in Figure 6.2.1. On the other hand, the sea water temperature at the surface in summer (from May to August) is estimated to be more than 30°C from the fact that the ambient temperature sometimes reaches about 50°C. Although the efficiency of power or desalination plant is affected by the sea water temperature, it is technically possible to minimize it by taking the water from the deep layer.

The quality of sea water is good judging from the analysis results in this F/S and the 1985 F/S, and the design conditions for Ghubrah Desalination Plant. There is a possibility to suck up the sea water with much sand at the sea bed depending on the type of water intake. This can be solved by adopting an adequate intake system in the detailed design. Oil balls were another concern at the early stage of this F/S, however, it was found that the total amount drifting ashore is very small and it does not create any problem in the existing power and desalination plant at Ghubrah.

6.2.5 Meteorological, Marine and Seismic Conditions

There is no difference in these conditions at any location between Barka and Seeb Airport.

Regarding the meteorological and marine conditions, it is necessary to consider those during cyclones in the design. The frequency and magnitude of earthquakes are so small that the seismic condition is not critical in the design. The details of these points are discussed in Chapter 11.

6.2.6 Transmission Lines and Water Pipelines

(1) Transmission lines

It is required to consider the connection with Muscat System and Wadi Jizzi System in the future. The proposed site is located in the area covered by Muscat System and not far from the service area as well as the existing substations to be connected with the proposed plant. In addition, it is located to the west of the area covered by Muscat System and is convenient to connect with Wadi Jizzi System.

Impact to the landscape is another aspect to be considered since it is often discussed as one of the concerns in recent projects. The proposed site and transmission line route are duly apart from the city area, and accordingly, it is considered that there are no serious impacts.

(2) Water pipelines

The distance (length of pipelines) between the proposed site and the service area is a point to be discussed. Although the capital area and the area west of the capital are major service areas at present, the service area is planned to be expanded to the west of Seeb Airport (Barka, Al-Masuna) and the rural area (Rustaq, Al-Awabi, etc.) in the future. Taking into consideration this plan, the location of the proposed site is reasonable.

6.2.7 Accessibility

There is Batinah Highway (Route 1) connecting Muscat with Sohar along Batinah Coast, to which the distance from the proposed site is about 3.7 km. A rural road branched from Route 1 runs nearby the site and leads to Haradi, Barsit and Barka as shown in Figure 6.1.2. The conditions of these roads are quite good and the costs of access roads are estimated to be very low.

It is considered that the construction material and equipment will be unloaded at Mina Qaboos which is located at the north of Muscat, and transported to the site by road along Route 1 (about 70 km). Since there are grade separations at several places between Mina Qaboos and Seeb Airport, the weight, width and height of cargo will be restricted. It is necessary to consider the above in the design and transportation plan, and the costs relating to reinforcement of road (bridges) need to be scheduled.

6.2.8 Supply of Fuel

For the plant operation, it is planned to use natural gas which is produced at the inland area and will be delivered to the site by pipelines. The details and costs of gas pipelines which are not included in the scope of this F/S are unknown. However, considering the necessity of a large amount of water for producing the drinking water and operating the power plant, it is obviously not feasible to construct the proposed plant inland.

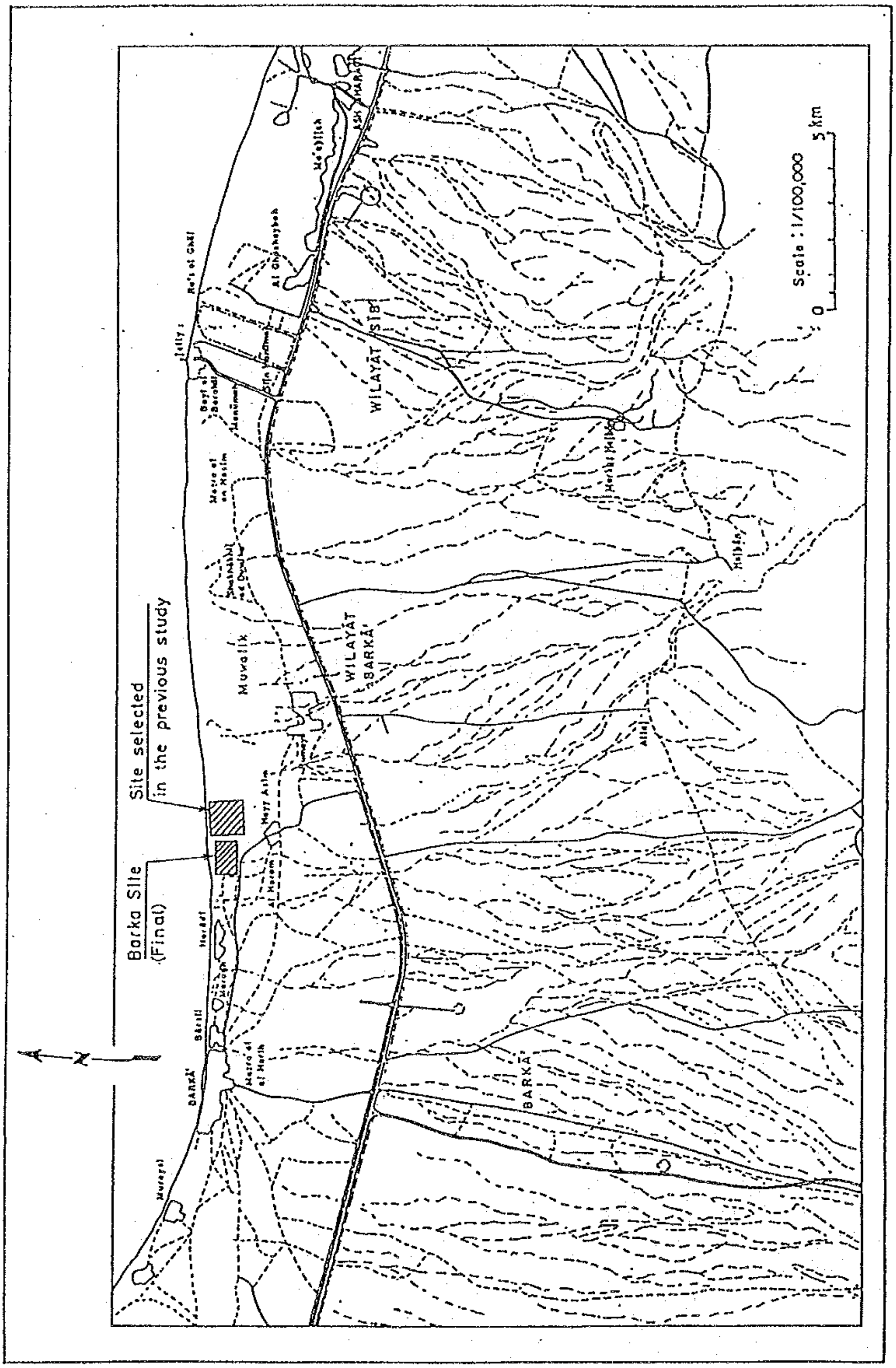


Figure 6.1.1 Location of Barka Site

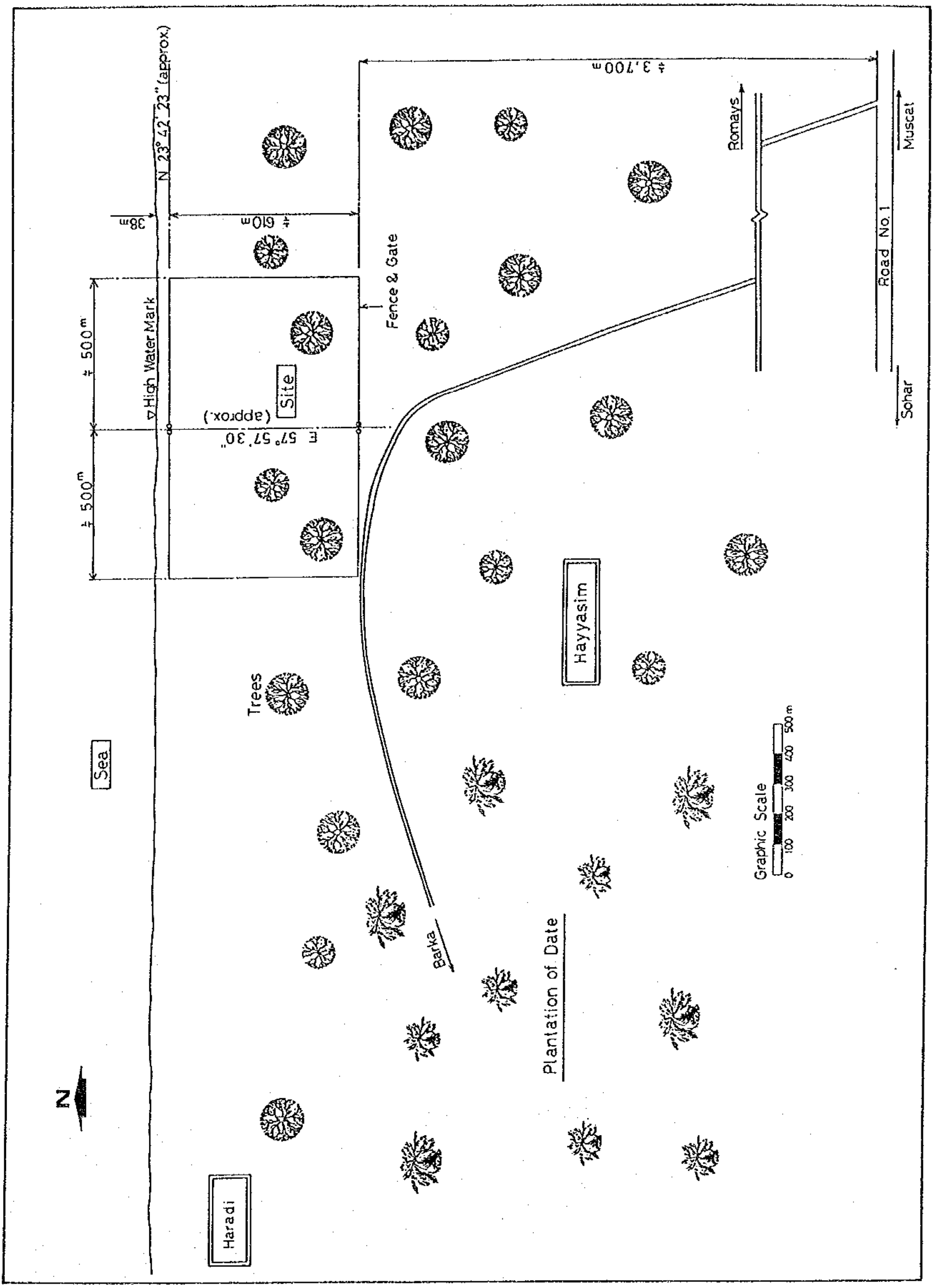


Figure 6.1.2 Site Conditions

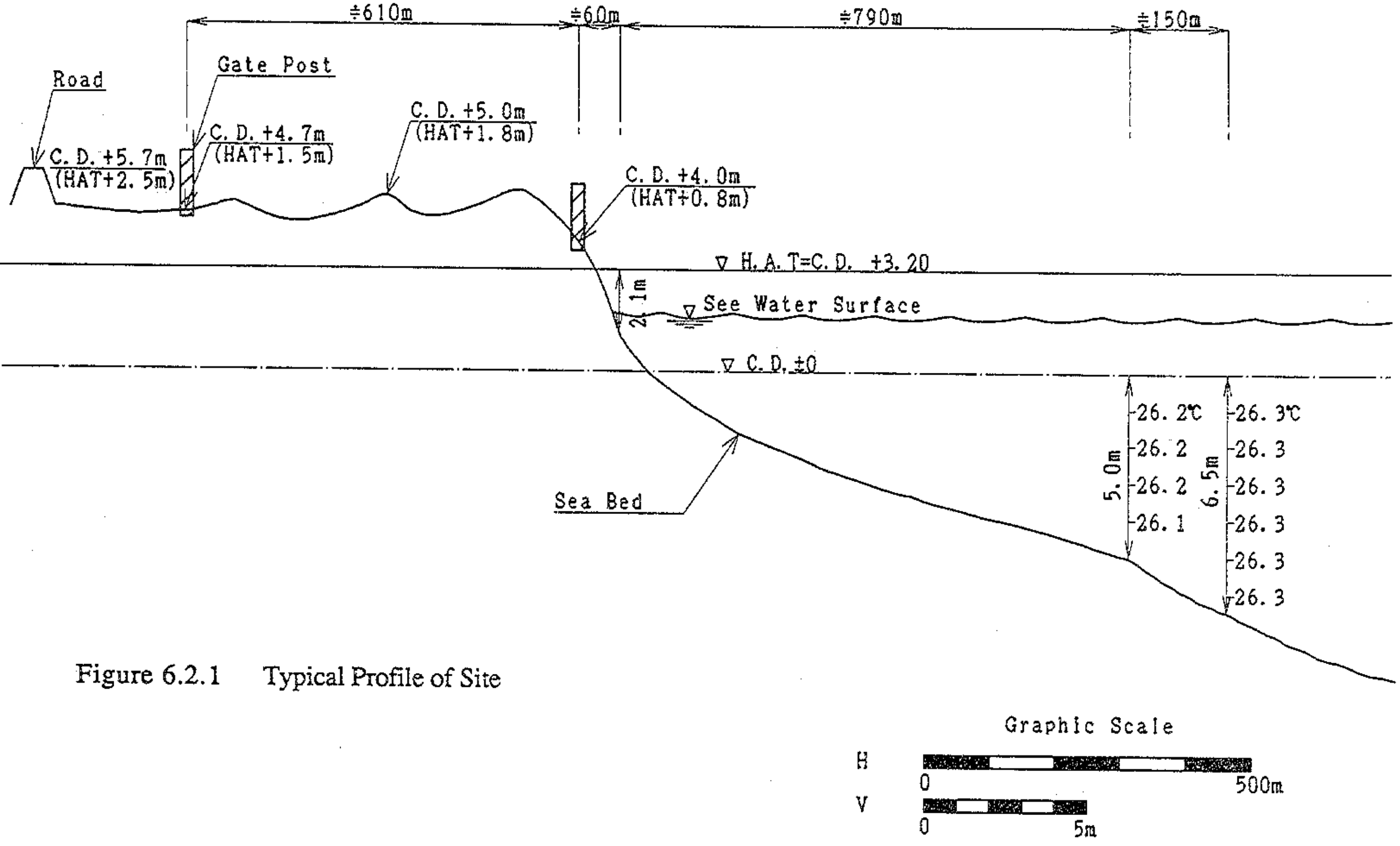


Figure 6.2.1 Typical Profile of Site

CHAPTER 7 CONCEPTUAL DESIGN OF POWER PLANT

CHAPTER 7 CONCEPTUAL DESIGN OF POWER PLANT

This chapter is intended to provide a conceptual design for Barka Power Plant. The plant will have a supply capacity of about 1,800 MW, based on the power development plan described in Section 4.6. The conceptual design covers basic matters, including the power generation system, equipment configuration and equipment specifications. This chapter will also indicate thermal efficiency and operating indices, both closely related to power plant economy and operation.

7.1 Design Conditions and Fuels

7.1.1 Design Conditions

The conceptual design of the mechanical and electrical facilities of the power plant will be based on the following design conditions, standards and criteria.

(1) Design conditions

Atmospheric temperature:	50°C maximum, 5°C minimum, 30°C average, 50°C design
Sea water temperature:	35°C maximum, 30°C design
Relative humidity:	100 % maximum, 40 % annual average, 100 % design
Rainfall:	100 mm annual average, 80 mm maximum in 24 hour period
Maximum wind velocity:	40 m/s
Number of thunderstorm days (IKL):	20 days/year
Elevation:	Maximum of 1,000 m

(2) Voltage classifications and wiring method

Voltage:	220 KV, 132 KV, 33 KV, 11 KV, 6.6 KV, 415 V, 240 V

Frequency: 50 Hz

Wiring system: Three phase three wire system, but three phase four wire system for 415 V and 240 V

Earthing system: Direct earthing system on the primary side of the power transmission transformer and resistance earthing system on the secondary side

(3) Applicable standards and criteria

International Electrotechnical Commission (IEC)
Oman Electrical Standards (OES)
Japanese Electrotechnical Committee (JEC) Standards
Japan Electrical Manufacturers' Association (JEM) Standards
Japan Electrical Association Code (JEAC)
Japanese Cable Makers' Association Standards (JCS)
Japan's Electrical Standards (issued by MITI)

7.1.2 Fuels and Fuel Supply

(1) Fuels

Fuels for the gas turbines in the combined cycle plant and boilers for back pressure steam turbines shall comply with MEW's requirements.

1) Main fuel - natural gas (lower heating value 35,800 KJ/kg)

2) Emergency fuel - distillate oil (lower heating value 42,915 KJ/kg)

Tables 7.1.1 and 7.1.2 show the composition and basic data for natural gas and distillate oil respectively.

(2) Fuel supply

The Ministry of Petroleum and Minerals shall install a natural gas pressure reducing station and connecting pipelines at the project site. All facilities up to the pressure reducing valve (and filter) will come under the jurisdiction of the Ministry of Petroleum and Minerals. The power plant will need to install gas pipes leading from the pressure reducing valve. The natural gas supply must meet the plant's required pressure and volume conditions, namely:

1) Service pressure : 20 kg/cm^2

2) Service quantity : 30,400 kg/h (per GT unit)
37,800 kg/h (per back pressure steam generator)

A distillate oil tank will also be installed to supply emergency fuel to the plant.

Table 7.1.1 Main Fuel (Natural Gas) Data

Component	Mole %
Methane	86.804
Ethane	4.658
Propane	2.011
Iso-Butane	0.411
Butane	0.521
Iso-Pentane	0.168
Pentane	0.147
Hexane	0.126
Heptane	0.032
C8	0.004
Benzene	0.003
Toluene	0.001
Nitrogen	4.652
Carbon Dioxide	0.447
Water	0.015
Hydrogen Sulphate	0.000
TOTAL :	100.000%
Water Dew Point	2°C at 5,400 kPa(g)
Maximum Hydrocarbon Dew Point	6°C at 5,400 kPa(g)
Calculated Molecular Weight	18.59
Density	0.843 kg/m^3
HHV (kJ/Kg)	39,565 (9,452 kcal/kg)
LHV (kJ/Kg)	35,800 (8,553 kcal/kg)

Table 7.1.2 Emergency Fuel (Distillate Oil) Data

Density at 15°C (Kg/l)	0.8377
Kinetic Viscosity at 40°C (cS)	3.9
Cloud Point (°C)	-6
Pour Point (°C)	-15
Sulphur (% weight)	0.44
Ash (% weight)	0.005
Flash Point (°C)	114
Water Content	Nil
Sediment	Nil
HHV (kJ/kg)	45,700 (10,918 kcal/kg)
LHV (kJ/kg)	42,915 (10,252 kcal/kg)

7.2 Thermal Efficiency and Operational Indices

7.2.1 Heat balance and Thermal Efficiency

The power plant generates, absorbs and releases heat in each stage between fuel combustion and power generation. Efficiency control is assisted by a heat balance chart, which quantitatively indicates the heat flow and distribution in each section. The fuel's heat generation is set at 100 % and ach section's heat distribution is shown as a percentage. Figure 7.2.1 is a heat balance chart for the typical combined cycle power plant. The heat generated by the fuel is 100 %. The gas turbine converts 31% of the heat into electricity, releasing 68 % of the remainder as exhaust gas, of which 55 % is recovered by the heat recovery steam generator (HRSG). The steam turbine generator converts 17 % of the recovered heat into electricity. From the original 100 % of heat created by the fuel, 48 % is recovered as electricity, representing 48 % thermal efficiency. The thermal efficiency of an open cycle gas turbine is a relatively low 31 %. The heat balance chart shows that the total thermal efficiency of the open cycle gas turbine can be improved to 48 % by recovering the heat contained in the gas turbine's exhaust gas through the gas and steam combined cycle system.

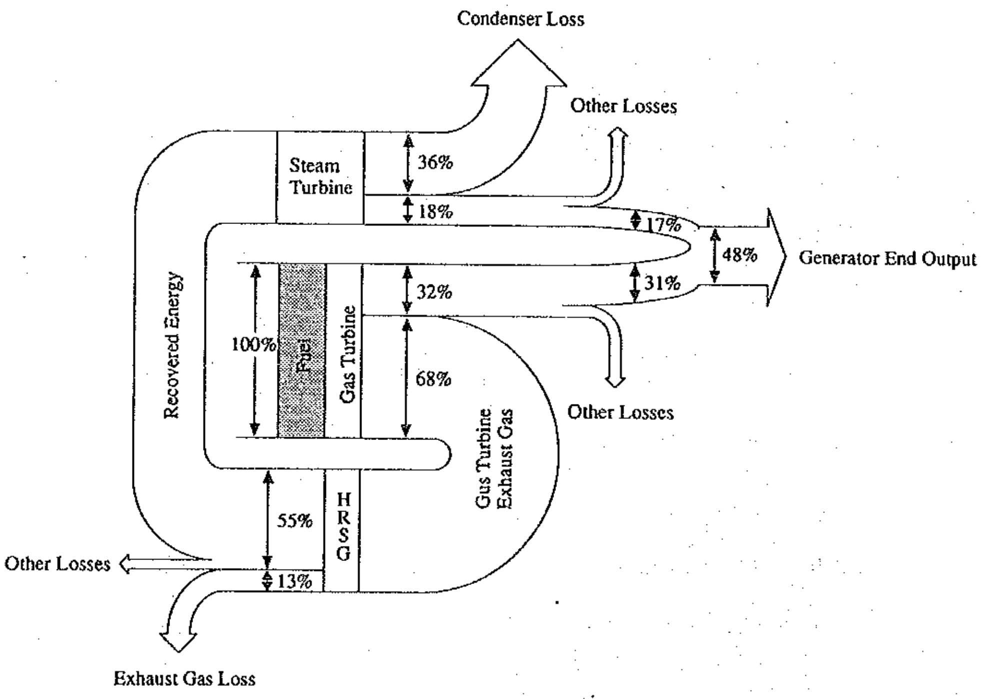


Figure 7.2.1 Heat Balance Chart for Combined Cycle Power Plant (Example) (LHV base 50°C)

7.2.2 Thermal Efficiency

Thermal efficiency indicates the effectiveness of the process by which fuel's heat potential is converted into electricity. This is an important index to promote energy conservation and ensure effective use of fuels. This section defines thermal efficiency and shows a typical calculation.

(1) Total power plant efficiency

The sending end efficiency (η') calculation is based on the following criteria. The efficiency is determined by the quantity of electricity from the sending end of the generator. This figure is obtained by subtracting the electricity consumed inside the power plant (station service energy) from the generator output (corresponding to the generator end efficiency η). The quantity of transmitted electricity is used as a standard. The station service factor (α) is used against station service electric energy. A small α results in a higher rate of power transmitted.

$$\eta = \frac{860P_g}{Gf \cdot H} \times 100\ [\%]$$

$$\eta' = \frac{860P_s}{Gf \cdot H} \times 100\ [\%]$$

$$\alpha = \frac{P_h}{P_g}$$

Where, P_g : Power generated [kWh]
P_h : Station service energy [kWh]
P_s : Power transmitted [kWh] $P_s = P_g - P_h$
Gf : Quantity of fuel used [kg]
H : Heating value of the fuel [kcal/kg]
860 : Conversion coefficient from electric energy to heat quantity
1 [kWh] = 860 [kcal]

Or, η' is shown as follows when α is used:

$$\eta' = \frac{860(P_g - P_h)}{Gf \cdot H} \times 100 = \frac{860P_g}{Gf \cdot H}(1 - \alpha) \times 100 = \eta(1 - \alpha)\ [\%]$$

If we assume that the generator end efficiency is 48 % and the station service factor is 0.02, the sending end efficiency is calculated as 47.04 %, based on the following formula.

$$\eta' = \eta(1-\alpha) = 48 \times (1 - 0.02) = 47.04\ \%$$

(2) Thermal efficiency structure

The following relationship, based on Figure 7.2.2, indicates power plant thermal efficiency by classifying the plant into its principal elements of boiler, turbine, condenser and generator.

$$\frac{\eta}{100} = \frac{\eta_B}{100} \cdot \frac{\eta_c}{100} \cdot \frac{\eta_t}{100} \cdot \frac{\eta_g}{100}$$

Of all these efficiencies, η and η_B are easily measured, while it is difficult to directly measure η_c, η_t and η_g. We therefore combine η_c, η_t and η_g to create turbine island efficiency (η_T) as shown below.

$$\frac{\eta_T}{100} = \frac{\eta_c}{100} \cdot \frac{\eta_t}{100} \cdot \frac{\eta_g}{100}$$

When using ηT, the total thermal efficiency is divided into boiler efficiency ηB and turbine island efficiency ηT, as shown by the following formula:

$$\frac{\eta}{100} = \frac{\eta_B}{100} \cdot \frac{\eta_T}{100}$$

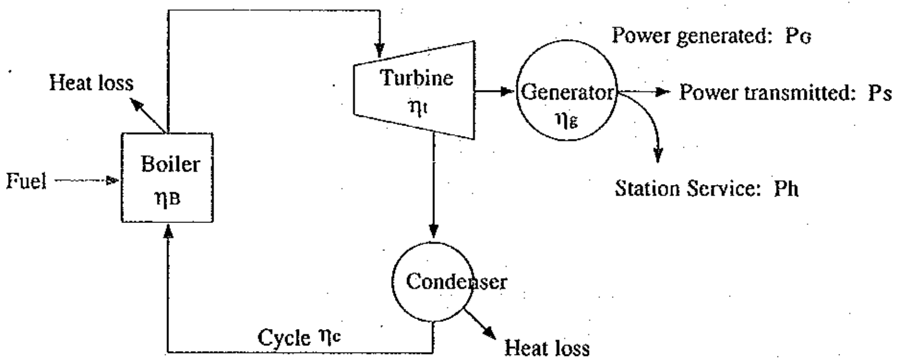


Figure 7.2.2 Thermal efficiency for each section of the power plant

(3) Boiler efficiency (η_B)

Boiler efficiency calculation methods include the input/output heat method and heat loss method. We shall adopt the more widely used input/output heat method. This method calculates efficiency based on the heat absorbed by steam, as a proportion of the heat generated by fuel. The boiler efficiency (η_B) is based on this method and calculated with the following formula:

$$\eta_B = \frac{W_s(i_b - i_a)}{G_f \cdot H} \times 100 \; [\%]$$

Where, W_s : Quantity of steam generated by boiler [kg/h]
i_a : Enthalpy of feed water at boiler inlet [kcal/kg]
i_b : Enthalpy of superheated steam at boiler outlet [kcal/kg]

(4) Turbine island efficiency (η_T)

The efficiency of each section comprising η_T is defined as follows.

1) Cycle efficiency (η_c)

Cycle efficiency is based on heat input added to the water and steam, and the quantity of work (heat output) which can be generated through adiabatic expansion within the turbine. Cycle efficiency is calculated as follows:

$$\eta_c = \frac{i_b - i_c}{i_b - i_a} \times 100 \; [\%]$$

Where, i_a : Feed water enthalpy at boiler inlet [kcal/kg]
i_b : Superheated steam enthalpy at boiler outlet (turbine inlet) [kcal/kg]
i_c : Steam enthalpy at turbine outlet [kcal/kg]

2) Turbine efficiency (η_t)

Turbine efficiency is the turbine shaft's work quantity proportion, calculated by subtracting external loss (such as mechanical loss) and internal loss including steam friction loss and steam leakage loss from theoretical work quantity, which is equivalent to the heat difference of the adiabatic expansion within the turbine.

$$\eta_t = \frac{\text{Work quantity generated by turbine shaft}}{\text{Theoretical work quantity}} \times 100$$
$$= \frac{860\,P_T}{W_s\,(i_b - i_c)} \times 100\ [\%]$$

Where, P_T : Turbine shaft output [kW]
W_s : Steam flow rate [kg/h]

3) Generator efficiency (η_g)

Generator efficiency is shown by the generator electricity output as a proportion of turbine shaft output. The losses are electrical (iron and copper loss) and mechanical (wind and friction loss).

$$\eta_g = \frac{P_G}{P_T} \times 100\ [\%]$$

Where, P_G : Generator output [kW]
P_T : Turbine shaft output [kW]

7.2.3 T-s Chart and Efficiency

(1) T-s chart

Work quantity of the heat engines is determined by the temperature difference in the working media. The difference in temperature is caused by the heat transfer. Entropy is defined as the quantity which shows the degree of thermal dynamic stability. We nominate heat quantity as Q [kcal], absolute temperature as T [K] and entropy as s [kcal/kg • K], to establish the following formula:

$$ds = dQ/T \quad \text{or} \quad dQ = T \cdot ds$$

T-s chart shows thermal dynamic condition changes, with T as the vertical axis and s as the horizontal axis. Figure 7.2.3 shows the example of a combined cycle power plant. Integrating $dQ = T \cdot ds$ on the cycle line establishes the following formula:

$$Q = \int T \cdot ds$$

The difference between heat quantity input and heat quantity lost is the heat quantity converted into work. The T-s chart area encircled by the cycle line indicates work quantity, while the rest of the area represents heat released as ineffective energy.

(2) Thermal efficiency

Cycle thermal efficiency η is shown by the following formula:

$$\eta = \frac{\text{Effective work quantity } Q}{\text{Supplied heat quantity } Q_o}$$

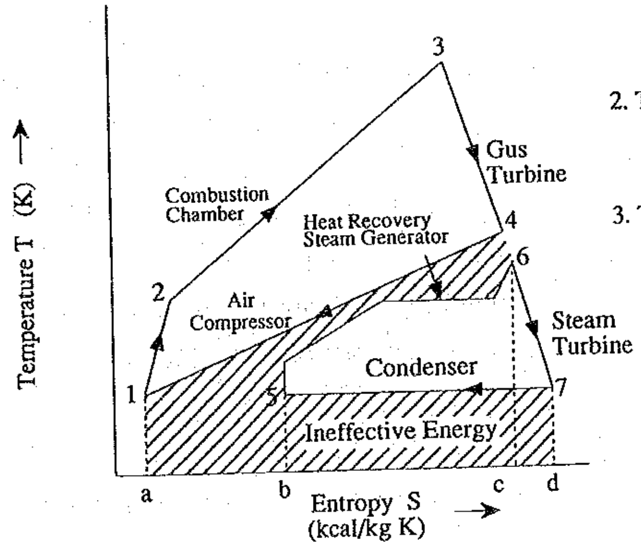
Figure 7.2.3 indicates the calculated thermal efficiency based on the input heat quantity and released heat quantity shown in the T-s chart. Nominating quantity of heat released from the gas turbine as a proportion β of gas turbine input heat quantity Q_{G1} establishes the following formula:

Gas turbine work quantity = $Q_{G1} \cdot \eta_G$

Steam turbine work quantity = $Q_{G1} \cdot \beta \cdot \eta_s$ ($\beta = 1 - \eta_G$)

The thermal efficiency of the combined cycle plant is improved by the portion $(1 - \eta_G)\eta_s$ from the thermal efficiency of the gas turbine as follows:

$$\eta_{cc} = \frac{Q_{G1} \cdot \eta_G + Q_{G1} \cdot \beta \cdot \eta_s}{Q_{G1}} = \eta_G + \beta\eta_s = \eta_G + (1 - \eta_G)\eta_s$$



1. Thermal Efficiency of Gas Turbine

$$\eta_G = \frac{Q_{G1} - Q_{G2}}{Q_{G1}}$$

2. Thermal Efficiency of Steam Turbine

$$\eta_s = \frac{Q_{S1} - Q_{S2}}{Q_{S1}}$$

3. Thermal Efficiency of Combined Cycle

$$\eta_{cc} = \eta_G + (1-\eta_G)\eta_s$$

QG1 : Input Heat to Gas Turbine (Area 1-2-3-4-c-a-1)

QG2 : Output Heat from Gas Turbine (Area 1-4-c-a-1)

QS1 : Input Heat to Steam Turbine (Area 5-6-7-d-b-5)

QS2 : Output Heat from Steam Turbine (Area 5-7-d-b-5)

Figure 7.2.3 T-s Chart for the Combined Cycle Power Plant

7.2.4 Quantity of Fuel Used

(1) Fuel heating value

Fuel heating value includes lower heating value (net heating valuc, HHV) and higher heating value (total heating value, HHV). Lower heating value is calculated by subtracting the water's steam evaporation potential heat caused by combustion and water in the fuel.

As there is moisture in the exhaust gas during the evaporated stage, only LHV is used for the heating. This project will therefore indicate efficiency based on LHV as in the 1985 feasibility study. The generator end efficiency is based on the heating value by the natural gas used in this project, and is calculated with the following formula:

$$\eta_h = \frac{860P_g}{G_f \cdot H_h} \times 100 = \frac{860P_g}{G_f \times 9452} \times 100\ [\%]$$

(HHV = 9,452 [kcal/kg])

$$\eta_l = \frac{860P_g}{G_f \cdot H_l} \times 100 = \frac{860P_g}{G_f \times 8553} \times 100\ [\%]$$

(LHV = 8,553 [kcal/kg])

Assuming the quantity of fuels used (*Gf*) and power generated (*Pg*) are the same, the ratio of η_l and η_h is calculated as follows:

$$\frac{\eta_l}{\eta_h} = \frac{9452}{8553} = 1.105$$

The LHV standard efficiency is 10.5 % higher than that of the HHV standard. A LHV standard efficiency of 48 % is equivalent to 43.4 % on the HHV standard. The 1985 feasibility study was based on the LHV standard, and used a heating value of 9,024 kcal/Nm^3 (10,700 kcal/kg for a specific gravity of 0.843 kcal/Nm^3). As indicated in the Table 7.1.1, we will use an LHV standard of 8,553 kcal/kg for this project, enabling use of fuel which has a heating value 20 % lower than the original 10,700 kcal/kg.

(2) Heat rate

Heat rate (R_h) is the heat quantity required to generate 1 kWh of power:

$R_h = Q/P_G$ [kcal/kWh]

Where, R_h : Heat rate [kcal/kWh]

Q : Fuel's heating value [kcal/h]

Heat rate is disproportionate to efficiency. For an efficiency of 48 %, the heat rate is calculated as follows:

$$R_h = \frac{860}{\eta/100}\ [\text{kcal/kWh}] = \frac{860}{48/100} = 1{,}792\ [\text{kcal/kWh}]$$

(3) Fuel rate

Fuel rate (Rf) is the amount of fuel used per unit of power generated. The fuel rate is calculated with the following formula:

$$R_h = G_f / P_g\ [\text{kg/kWh}]$$

Where, R_f : Fuel rate [kg/kWh]
G_f : Quantity of fuel used [kg/h]
P_G : Generator output [kW]

If we relate this to the generator end efficiency (η), Rf will be disproportionate to the heating value (H), as shown in the following formula. As the heating value falls, the quantity of fuel required to generate the same amount of power rises.

$$R_f = \frac{G_f}{P_G} = \frac{860}{(\eta/100)\cdot H}\ [\text{kg/kWh}]$$

Based on an LHV standard heating value of 8,553 kcal/kg, gas turbine output of 96 MW, and 31 % generator end efficiency, the fuel rate R_f and fuel consumption G_f are calculated as follows:

$$R_f = \frac{860}{(31/100) \times 8553} = 0.324\ [\text{kg/kWh}]$$

$$G_f = 0.324 \times 96 \times 10^3 \times 1 = 31{,}104\ [\text{kg/h}]$$

(4) Fuel used and fuel cost

The quantity of fuel used is determined by the fuel consumption rate. Fuel economy is achieved by improving the thermal efficiency and heating value. As the heating value is fixed, improving plant efficiency is the only available method. The following estimate will determine how much an improvement in plant efficiency will contribute to reducing fuel costs, which represent the greatest proportion of power generation expenses. The estimate will also determine how the improvement in plant efficiency will affect the quantity of fuel used.

1) Increased fuel consumption rate as a result of improved efficiency

Increasing the 96 MW output gas turbine's efficiency of 31 % by one percentage point causes the fuel consumption rate to change as follows:

$$Rf = \frac{860}{(32/100) \times 8553} = 0.314 \text{ [kg/kWh]} = 30{,}144 \text{ [kg/h]}$$

This one percentage point efficiency improvement will reduce fuel consumption by 960 kg/h (= 31,104 - 30,144).

2) Fuel cost reduction as a result of increased fuel consumption rate

The properties of the natural gas used at the Ghubrah Power Plant are as follows:

Heating Value : 7,209 kcal/Nm^3 (= 8,553 kcal/kg)
Price : 0.02834 R.O./Nm^3 (= 0.03362 R.O./kg)
3.93 x 10^{-6} R.O./kcal (= 10.2 x 10^{-6} US$/kcal)
960 kg/h x 0.03362 R.O./kg = 32.3 R.O./h

The annual fuel cost to operate this gas turbine at 70 % load factor is calculated as follows:

32.3 R.O./h x 8,760 h/y x 70 % = 198,100 R.O./y

Improving the 96 MW class gas turbine's efficiency by one percentage point, from 31 % to 32 %, will reduce annual fuel costs by 198,100 R.O. Improving plant efficiency clearly contributes to economic savings through reduced fuel costs. Adopting a highly efficient combined cycle will be vital in selecting an economical power plant.

3) Estimated fuel cost reduction for a combined cycle system

For comparison we have calculated two scenarios; an open cycle plant with three 96 MW gas turbines (total output 288 MW) and a combined cycle plant with two gas turbines, two HRSGs and one steam turbine (total output 292 MW). The results of the comparison are shown in Table 7.2.1.

Table 7.2.1 Comparison of fuel costs

	Open cycle plant	Combined cycle plant
Total output (MW)	288	292
Total efficiency (%)	31	48
Heating value (kcal/kg)	8,553	8,553
Fuel consumption rate (kg/kWh)	0.324	0.209
Operating time (h/y)	6,132	6,132
Fuel used (kg/y)	572×10^6	374×10^6
Fuel unit price (R.O./kg)	0.03362	0.03362
Fuel costs (R.O./y)	19.2×10^6(A)	12.6×10^6(B)
(A) - (B)	6.6×10^6(R.O./y)/block	

Table 7.2.1 indicates that the combined cycle plant annually saves 6.6 million R.O. on fuel costs as a result of the difference between the total efficiencies of 48 % and 31 %. The adoption of a combined cycle plant is a rational solution to a requirement to restrain power generation costs.

7.2.5 Operating Indices

The following operating indices are presented to indicate the operating status of the power plant.

(1) Utilization rate

This is the value calculated by dividing the average electricity generated during a year (or other specified period) by the rated output. The rate is calculated with the following formula:

$$F_a = \frac{P_m}{P_r} \times 100 = \frac{W}{P_r \cdot t_0} \times 100\ [\%]$$

Where, F_a : Utilization rate (%)
P_m : Average electricity generated [kW]
P_r : Rated output [kW]
W : Quantity of electricity generated during a particular period to (h) [kWh] [= $P_m \times t_0$]

(2) Operating rate

Operating rate refers to the proportion of power plant operating time during a year or other specified period:

$$F_t = \frac{t_1}{t_0} \times 100 = \frac{t_0 - t_2}{t_0} \times 100 \ [\%]$$

Where, F_t : Operating rate [%]
t_0 : Specified calendar hours [h]
t_1 : Operating hours [h]
t_2 : Shut down hours [h]

7.3 Selection of Unit Machine Capacity

Construction, operating and maintenance costs per unit output decrease as the power plant's unit machine capacity increases. However, increasing unit machine capacity can exacerbate accidents when they occur. The unit machine capacity for this power plant will be examined from two perspectives.

(1) The proposed Barka Power Plant shall incorporate an optimal unit machine capacity with a focus on economy. The plant will be the main power source for the Muscat and Wadi Jizzi Systems, and supply base and mid-range loads.

(2) The unit machine capacity shall be optimal, with a focus on reliability of power supply and stability during system frequency fluctuations. These will be achieved by carefully utilizing all the power systems, including the proposed Barka Power Plant and the existing plants.

The suitable unit machine capacity for the proposed plant is between 60 and 120 MW. Placing the focus on economy would suggest a 120 MW single machine capacity is most appropriate, while an emphasis on reliability and stability would dictate a 60 MW unit machine capacity.

The Muscat and Wadi Jizzi Systems had a total capacity of 1,037 MW at the end of 1993. The maximum unit machine capacity on the Muscat system is 83 MW, and a single unit tripping resulted in a system frequency decline of ≤ 1 Hz, against a reference frequency of 50 Hz.

The 50 Hz system's turbine generators can be operated under a minimum frequency of 48.5 Hz, and an instantaneous operation shutdown frequency of 47.5 Hz. The 100 MW class unit machine capacity does not present any problems to system reliability and stability, and will offer optimal economy. In assessing unit machine capacity from the perspective of power plant operations and maintenance, the maximum unit machine capacity in existing steam turbine cycle power plants is 50 MW, and 83 MW in gas turbine cycle plants. We are confident that the MEW has sufficient operating and maintenance experience to successfully manage 100 MW class machines. Therefore the maximum unit machine capacity shall be planned to be 100 MW for this project.

7.4 Power Generation Systems and Basic Configuration

Power generation system selection will require a comprehensive assessment of the reliability, stability and economy of the combined power and desalination plants. This section identifies the types and features of power generation systems suitable for combining with either MSF or RO process desalination plant. An optimal power generation system is then identified.

7.4.1 Steam Supply for the MSF Process Desalination Plant and Power Generation System

Up to 1,332 t/h of steam is used at an MSF desalination plant. The quantity of steam used is relatively uniform as there is little fluctuation in water demand, despite seasons or time zones. The power generation system should therefore offer:

(1) Excellent follow up capacity to respond to radical load fluctuations;

(2) Comprehensively high heat utilization rate; and

(3) Operational reliability and stability when combined with the desalination plant.

The first step in selecting a steam supply method for the desalination plant and power generation system will be to choose one of the following:

(1) A heat and electricity co-generation system, in which steam required for the desalination plant is supplied from the steam turbine exhaust or the steam turbine extraction, and power generation is carried out concurrently; or

(2) An independent system in which the desalination plant and power plant each have separate and exclusive steam generation facilities (boilers).

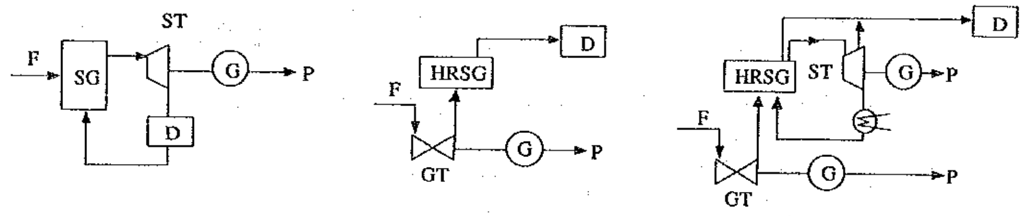
The co-generation system lacks flexibility in managing fluctuating power demand because the quantity of steam used by the desalination plant is uniform. However, the total heat utilization rate is high because the turbine exhaust steam is supplied as the steam load. The independent system has a high boiler heat utilization rate because the boiler is exclusively for the supply of steam, but it has a low heat utilization rate in the power generation facilities. The independent system has excellent follow up capability to manage electrical load fluctuations. We therefore recommend a system which counteracts the disadvantages of these two systems, namely:

(1) A co-generation system for water production and base load power generation; and

(2) An independent system exclusively for power generation to meet fluctuating electricity demand (mid-range and peak loads).

7.4.2 Selection of Co-generation System Power Plant

Appropriate cycles shall be selected for the co-generation system power plant, after conducting comparative examinations of the electricity load magnitude and fluctuation range and restrictive plant operating conditions: whether the desalination plant steam will be supplied by the steam turbine cycle, gas turbine cycle or combined gas and steam cycle; Figure 7.4.1 shows the basic configuration of each cycle.



(a) Steam Turbine Cycle

(b) Gas Turbine Cycle

(c) Gas/Steam Combined Cycle

D : Desalination Plant (MSF Process)
SG : Steam Generator (Boiler)
HRSG : Heat Recovery Steam Generator
ST : Steam Turbine
GT : Gas Turbine

C : Condenser
G : Generator
F : Fuel
P : Power

Figure 7.4.1 Comparison of Power Generation Cycle when Combined with Desalination Plant

(1) Annual base load

The minimum winter season base load will be about 486 MW in the year 2010. This forms the base load throughout the year. We shall assume that the 135.5 MW capacity steam turbine generators to be enhanced at Ghubrah Power Plant by 1996 will be maintained and continue to operate in the future. The base load supplied by Barka Power Plant will be about 350 MW.

(2) Plant Maintenance

Power plant maintenance will be implemented during winter because of the low electricity demand during that season. The Barka Power Plant generators must maintain the 350 MW power output, even when one generator is shut down for maintenance purposes.

(3) Unit machine capacity for the combined needs of the desalination plant

The desalination plant will comprise eight 7 MGPD (31,820 m^3/d) units. These units have ample flexibility to cope with water demand fluctuations and operational and plant maintenance considerations. The power plant should adopt appropriate operating systems to ensure reliability (decentralized power source within the system) and stability of the power supply. Possible unit structures are:

1) 1 power generation unit : 1 desalination unit; or
2) 1 power generation unit : 2 desalination units.

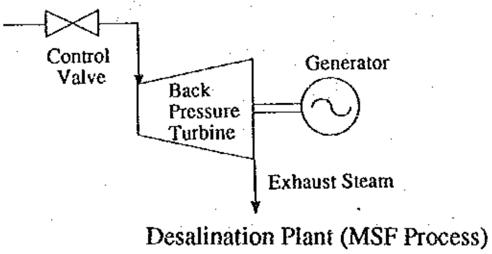
The power plant unit machine capacity to meet steam requirements will be about 30 MW for a 1 : 1 unit ratio, and 60 MW for a 1 : 2 ratio. The 1 : 2 ratio offers better economy, and ensures that the frequency will not drop below 47.5 Hz if one generator is dropped from the system for some reason. The 1 : 2 unit structure will be adopted, with four 60 MW generators in a unit machine capacity, supplying a base load of about 350 MW. The shortage in supply capacity (approximately 110 MW = 350 - 240) will be supplemented by the independent system.

(4) Power generation system to meet the base load

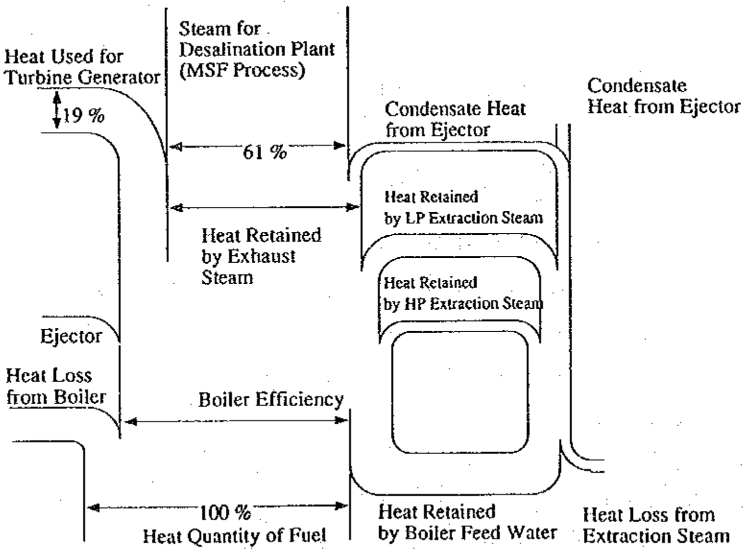
The power generation system to meet the base load must ensure that the total heat utilization rate is high, that is, fuel consumption is low. The load follow up (quick response) capability is not very important, as the load is stable. Base load supply does not require the gas turbine cycle's excellent quick response capability.

The steam turbine cycle is therefore the appropriate cycle for the co-generation system power plant. The steam turbine cycle concurrently meets the base load electricity demand and steam demand, and offers high total heat utilization rate.

A heat and electricity co-generation system enables efficient power generation using the high pressure steam generated by the boiler. It also enables the desalination plant to use all or part of the heat used by the condenser. The co-generation system can ensure effective use of energy throughout the plant. This type of power generation system includes a back pressure turbine, extraction/condensing turbine and extraction/back pressure turbine. The back pressure turbine is operated with uniform exhaust pressure (back pressure), and uses all of the turbine exhaust's heat to achieve a total thermal efficiency of ≥ 80 %. The back pressure turbine is more economical than other turbines, and is therefore selected for the co-generation system. This system's generator output will fluctuate with the quantity of boiler steam, meeting the steam quantity required by the desalination plant. The system is suited to base load operations, where electricity and steam load are uniform. Figure 7.4.2 shows the power plant configuration and heat balance chart for a back pressure turbine. A fuel heat quantity of 100 % results in a 61 % steam load and 19% electricity load, producing a total heat utilization rate of 80 %.



(a) Configuration



(b) Heat Balance

Figure 7.4.2 Back Pressure Turbine Configuration and Heat Balance Chart (example)

7.4.3 Selection of independent system power plant

(1) Criteria and System Selection Results

An independent system power plant will supply mid-range and peak loads, thereby accommodating seasonal and daily load demand fluctuations. The system must support significant load follow up and frequent start up and shut down functions. It must also maintain high thermal efficiency during partial load, to reduce the consumption of natural gas fuel, while generating electricity in response to load fluctuations.

A combined gas and steam cycle system would sufficiently meet these requirements. When combined with an RO process desalination plant there is no steam load, and the electricity load is 100 %. A combined cycle power generation system which maintains high thermal efficiency is important because the electricity load becomes the base load for the plant. We therefore recommend the combined cycle for the independent system power plant.

(2) Combined cycle power plant outline and characteristics

A combined cycle power generation system uses a gas turbine based on Brayton cycle, in which the fuel's combustion heat is used as the heat source of the high temperature cycle. The combined cycle system also uses a Rankine cycle, which uses the exhaust gas of the gas turbine as the heat source of the low temperature cycle. The combined cycle system uses these combined cycles as a heat engine to control the operating temperature, thus improving the total thermal efficiency. Figure 7.4.3. shows the power plant configuration, while Figure 7.4.4 provides a T-s (temperature-entropy) chart.

The characteristics of combined cycle power generation system are as follows.

1) High thermal efficiency

The heat balance chart in Figure 7.4.5 indicates that while the gas turbine's thermal efficiency is 31 % and thermal power generation is 40 %, combined cycle power generation achieves a total thermal efficiency of ≥ 48 % at the generator end (at the LHV base: 50°C). The short start up and shut down time minimizes heat loss, saving more than 10 % in fuel costs, when compared with conventional thermal power plant.

2) Ability to maintain rated efficiency at partial load

The combined cycle power plant forms a large capacity plant by combining several relatively small capacity units. It is possible to maintain high thermal efficiency across an expansive range by adjusting the output of each unit.

3) Short start up and shut down time

The combined cycle power plant comprises small capacity units. This ensures a large tolerance to load changes, and enables short start up time of about one hour, compared to two or three hour start up time for conventional thermal power plants. The combined cycle power plant also enables independent gas turbine operation, further reducing start up time to 15 - 30 minutes.

4) Maximum output changes with atmospheric temperature

A combined cycle power plant primarily comprises gas turbines. The maximum output changes with the atmospheric temperature; the lower the atmospheric temperature, the greater the generator output (a single gas turbine unit with a rated output at 50°C of 100, operating at a temperature of 15°C will produce almost 130 - an output increase of 30 %). In contrast, a steam turbine following a drop in atmospheric temperature will increase the quantity of steam generated by the heat recovery steam generator (HRSG), increasing the maximum output from that component (a rated output of 100 at a temperature of 50°C will produce a maximum output of about 110 at a temperature of 15°C). A multishaft, combined cycle plant comprising two gas turbines and one steam turbine, with a 100 % shaft output at an atmospheric temperature of 50°C, will increase output to about 120 % when the temperature drops to 15°C.

5) Small quantity of hot water discharge

The steam turbine of a combined cycle power plant generates about 1/3 of the entire plant's output; a relatively small proportion. The quantity of hot water discharge is 60 - 80 % that of a steam power plant of the same capacity.

6) Responding to environmental control requirements regarding NOx (nitrous oxide)

Natural gas, the main fuel, contains only a small portion of sulfur and nitrogen. Thermal NOx, generated when nitrogen in the air is oxidized during combustion, is thought to be the only air contamination source.

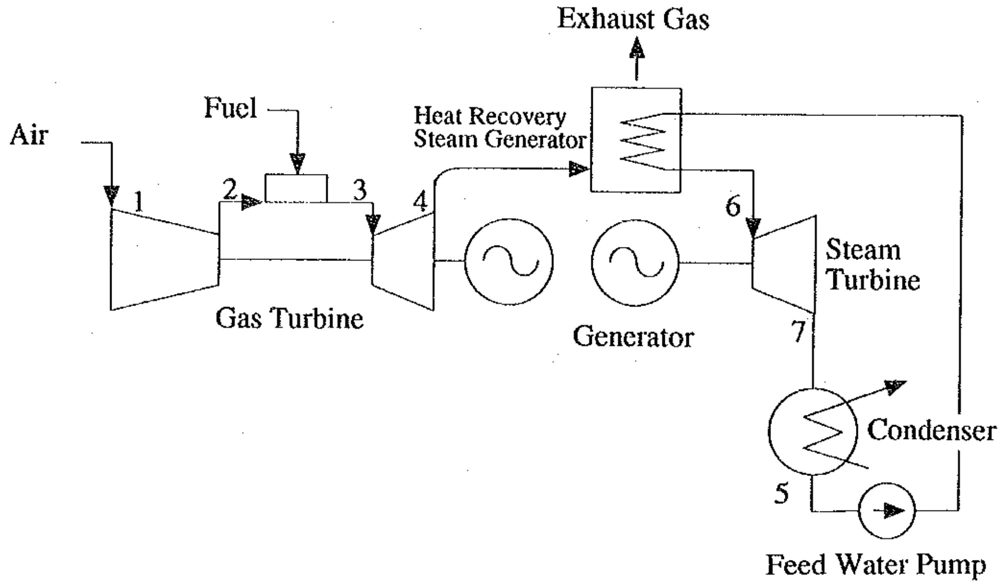
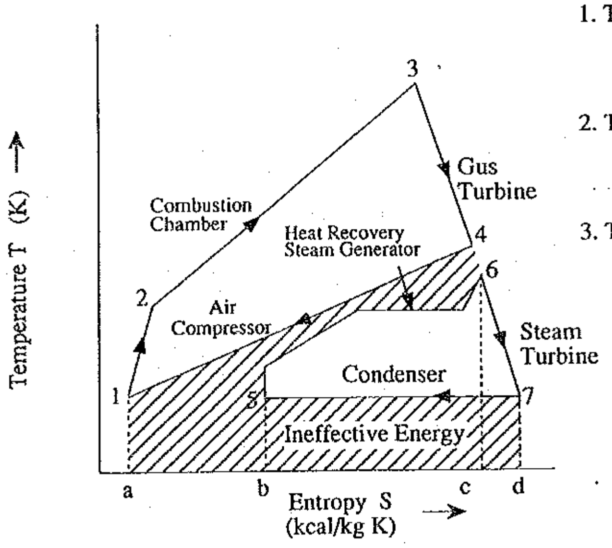


Figure 7.4.3 Basic Configuration of Combined Cycle Power Plant



1. Thermal Efficiency of Gas Turbine

$$\eta_G = \frac{Q_{G1} - Q_{G2}}{Q_{G1}}$$

2. Thermal Efficiency of Steam Turbine

$$\eta_S = \frac{Q_{S1} - Q_{S2}}{Q_{S1}}$$

3. Thermal Efficiency of Combined Cycle

$$\eta_{CC} = \eta_G + (1-\eta_G)\,\eta_S$$

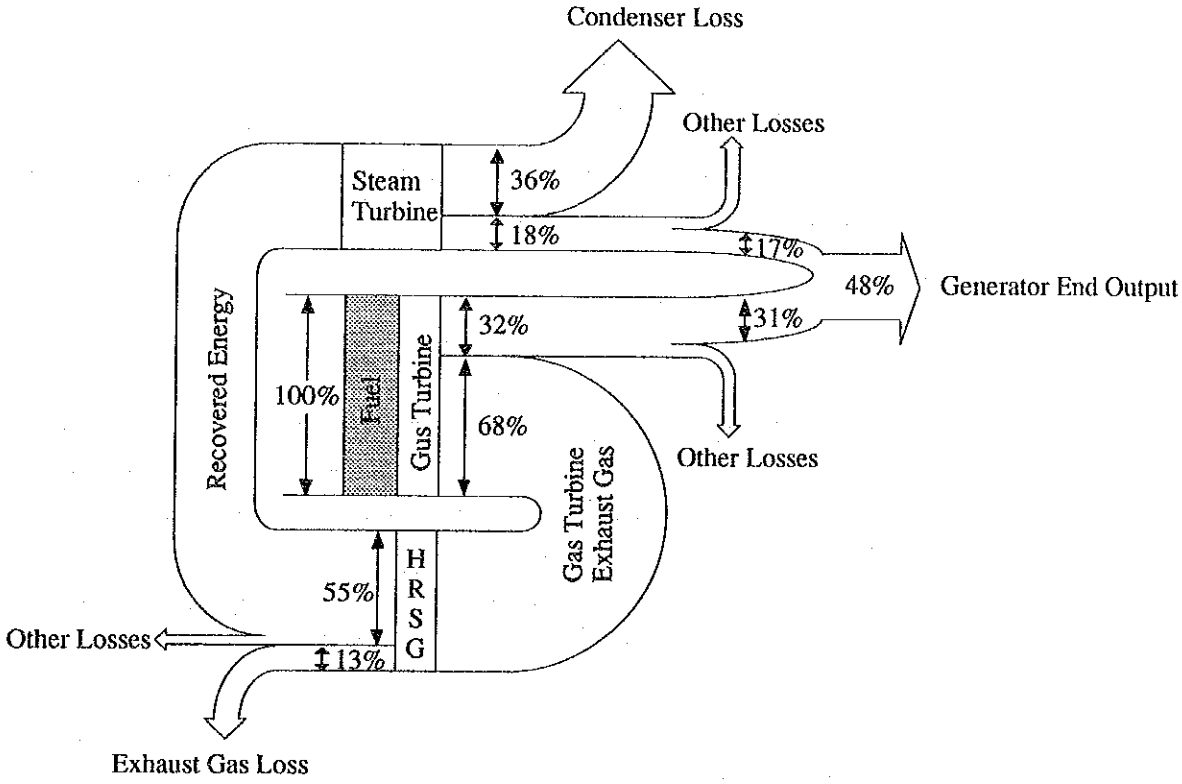
Q_{G1} : Input Heat to Gas Turbine (Area 1-2-3-4-c-a-1)

Q_{G2} : Output Heat from Gas Turbine (Area 1-4-c-a-1)

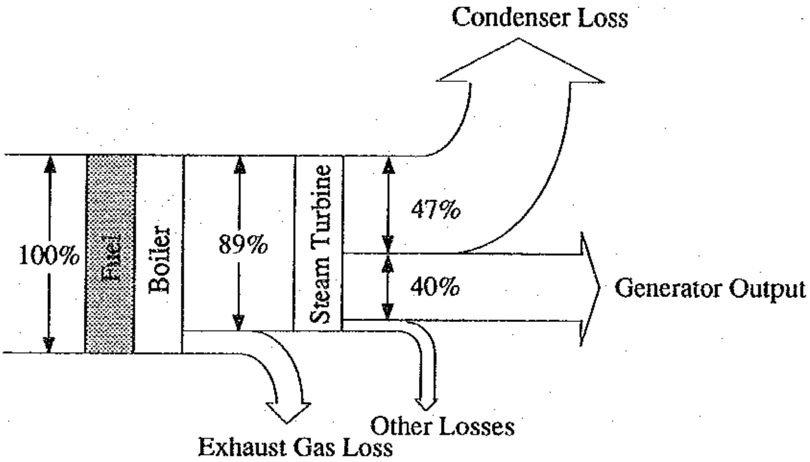
Q_{S1} : Input Heat to Steam Turbine (Area 5-6-7-d-b-5)

Q_{S2} : Output Heat from Steam Turbine (Area 5-7-d-b-5)

Figure 7.4.4 *T-s* Chart for the Combined Cycle Power Plant



(a) Combined Cycle Power Plant (Example)



(b) Large Capacity Thermal Power Plant (Example)

Figure 7.4.5. Heat Balance Chart Comparing Combined Cycle Power Plant with Conventional Thermal Power Plant (LHV base, 50C°)

7.4.4. Power plant development plan

(1) Selection of development plan

Technical and economical rationalism for the plant's joint use with the desalination plant has resulted in selecting and incorporating the following options.

1) Alternative A:

The desalination plant shall be based on the MSF process. The power plant shall generate electricity by supplying boiler-generated steam to the back pressure turbine. A heat and electricity co-generation system shall be adopted, whereby the latent heat of the turbine's exhaust steam will be supplied to the desalination plant. A high thermal efficiency, combined cycle power plant shall be established as an independent system exclusively for the electricity load.

2) Alternative B:

The desalination plant shall be based on the RO process. A high thermal efficiency combined cycle system shall be used as the independent system because the power plant needs only to meet the electricity load.

(2) Structure and scale of development plan

Figure 7.4.6 indicates the system structure and power plant's installed capacity for alternatives A and B, based on the following basic plant conditions:

Power plant installed capacity:	About 1,800 MW
Power plant single unit capacity:	60 - 100 MW
Desalination plant installed capacity:	254,560 m^3/d (7 MGPD x 8)
Desalination plant steam requirement:	1,332 t/h

The alternatives A and B power plant structure and installed capacities are as follows:

1) Alternative A: Power generation:

Combined cycle plant
Five blocks x 292 MW/block = 1,460 MW

Open cycle gas turbine 1 unit x 90 MW/unit = 96 MW

Desalination plant: Back pressure turbine plant
Four systems x 60 MW/system = 240 MW

Total capacity: 1,796 MW

2) Alternative B: Power generation:
Combined cycle plant
Six blocks x 292 MW/block = 1,752 MW

Open cycle gas turbine 1 unit x 96 MW/unit = 96 MW

Total capacity: 1,848 MW

(3) Development plan thermal efficiency

The calculated thermal efficiency of both options is based on an atmospheric temperature of 50°C and LHV (low heating value). Thermal efficiency corresponds to the electricity load for the combined cycle system. The back pressure turbine plant's thermal efficiency corresponds to the heat quantity required by the electricity load and the steam load.

1) Calculation conditions:

(a) Combined cycle (per block)
Generator output: 292 MW
Thermal efficiency: 48 %
Heat input: $292 \times 10^3 \times 860/0.48 = 523 \times 10^6$ kcal/h

(b) Open cycle gas turbine (per unit)
Generator output: 96 MW
Thermal efficiency: 31 %
Heat input: $96 \times 10^3 \times 860/0.31 = 266 \times 10^6$ kcal/h

(c) Back pressure turbine plant (per unit)
Generator output: 60 MW
Thermal efficiency: 80 %
Heat input: $\{60 \times 10^3 \times 860 + 333 \times 10^3 \times (668 - 115)\}/0.80 = 295 \times 10^6$ kcal/h

2) Alternative A

Total heat output: $(292 \times 5 + 96 \times 1 + 60 \times 4) \times 10^3 \times 860 + 4 \times 333 \times 10^3 \times (668 - 115) = 2{,}282 \times 10^6$ kcal/h

Total heat input: $(523 \times 5 + 266 \times 1 + 295 \times 4) \times 10^3 = 4{,}061 \times 10^6$ kcal/h

Total thermal efficiency: 56.2 %

3) Alternative B

Total heat output: $(292 \times 6 + 96 \times 1) \times 10^3 \times 860 = 1{,}589 \times 10^6$ kcal/h

Total heat input: $(523 \times 6 + 266 \times 1) \times 10^6 = 3{,}404 \times 10^6$ kcal/h

Total thermal efficiency: 46.7 %

(4) Selecting the optimal development plan

Determining which alternative (A or B) will be better suited to the Barka power development objectives will require an analysis of comparative targets to select the optimal development plan.

<u>Targets for comparison</u>

1) Back pressure steam turbine based power plant (alternative A's co-generation system)

This plant supplies 1,332 t/h of steam to the MSF process desalination plant, and generates a 182 MW sending end output (240 MW generator output minus 58 MW station service load comprising 16 MW for power plant and 42 MW for desalination plant).

2) Combined cycle power plant (alternative B's independent system)

This system meets the RO process desalination plant's 69 MW electricity demand, and generates a 182 MW sending end output (same as that described in 1) above). One 292 MW combined cycle plant has a station service load of 6 MW, and the sending end output is 286 MW. After supplying 69 MW to the desalination plant, 217 MW will remain for transmission.

The alternatives A and B independent power plants are identical facilities, equivalent to five combined cycle plant systems. Alternative A uses a 240 MW back pressure turbine plant, while alternative B uses a 292 MW combined cycle plant.

Points of comparison and results

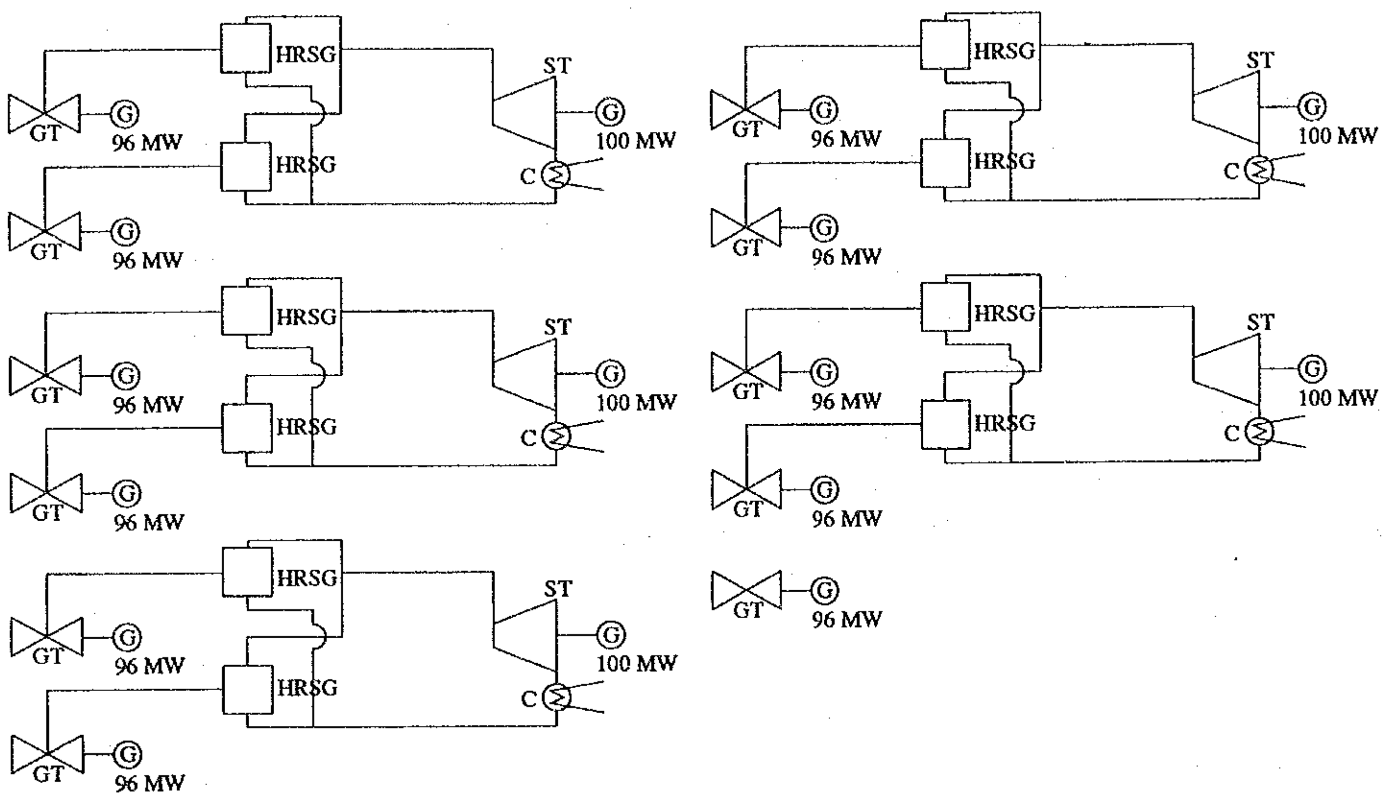
Our comprehensive comparative examinations are based on the outline above. Comparison factors include thermal efficiency, operational reliability and stability, operations and maintenance, construction period, fuel consumption rate and construction expenses. Table 7.4.1 compares these factors for Alternatives A and B.

Table 7.4.1 indicates that alternative A has a high total heat utilization rate and excellent operational reliability and stability. Although the heat balance chart in Figure 7.4.2 shows that, in terms of thermal efficiency, alternative A has a small 19 % electricity load and a large 61 % steam load, the turbine's exhaust steam is used effectively because option A provides this steam load. Alternative A attains a high total heat utilization rate of 80 %, but the thermal efficiency of power plant itself is 19 %, and fuel consumption is high.

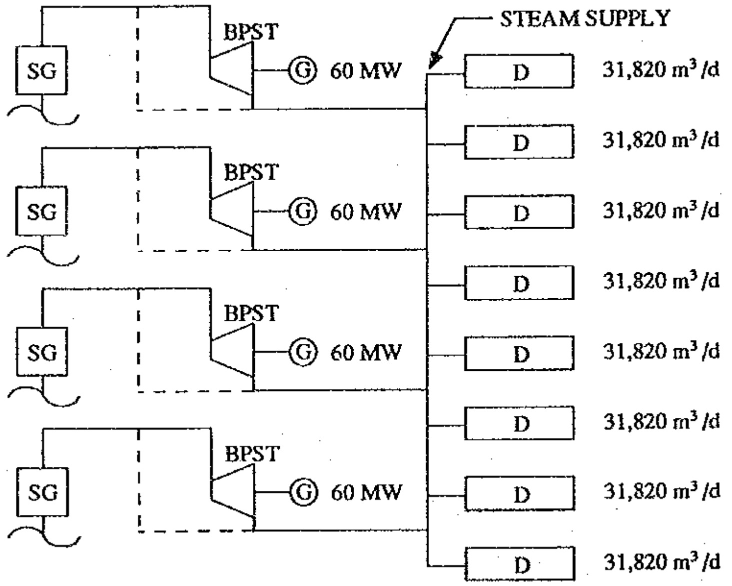
At half alternative A's fuel consumption rate, alternative B offers excellent economy. From a comprehensive perspective, alternative B is considered a far superior power plant because it takes advantage of the excellent characteristics of a combined cycle plant (economy, quick load follow up capability, and fast start up and shut down). Technological and economic considerations would dictate a co-generation system using a back pressure turbine plant to supply the steam load, and a combined cycle plant to supply the electricity load.

ALTERNATIVE A

(1) GAS-STEAM COMBINED CYCLE POWER PLANT



(2) BACK PRESSURE STEAM TURBINE CYCLE POWER PLANT AND DESALINATION PLANT (MSF TYPE)

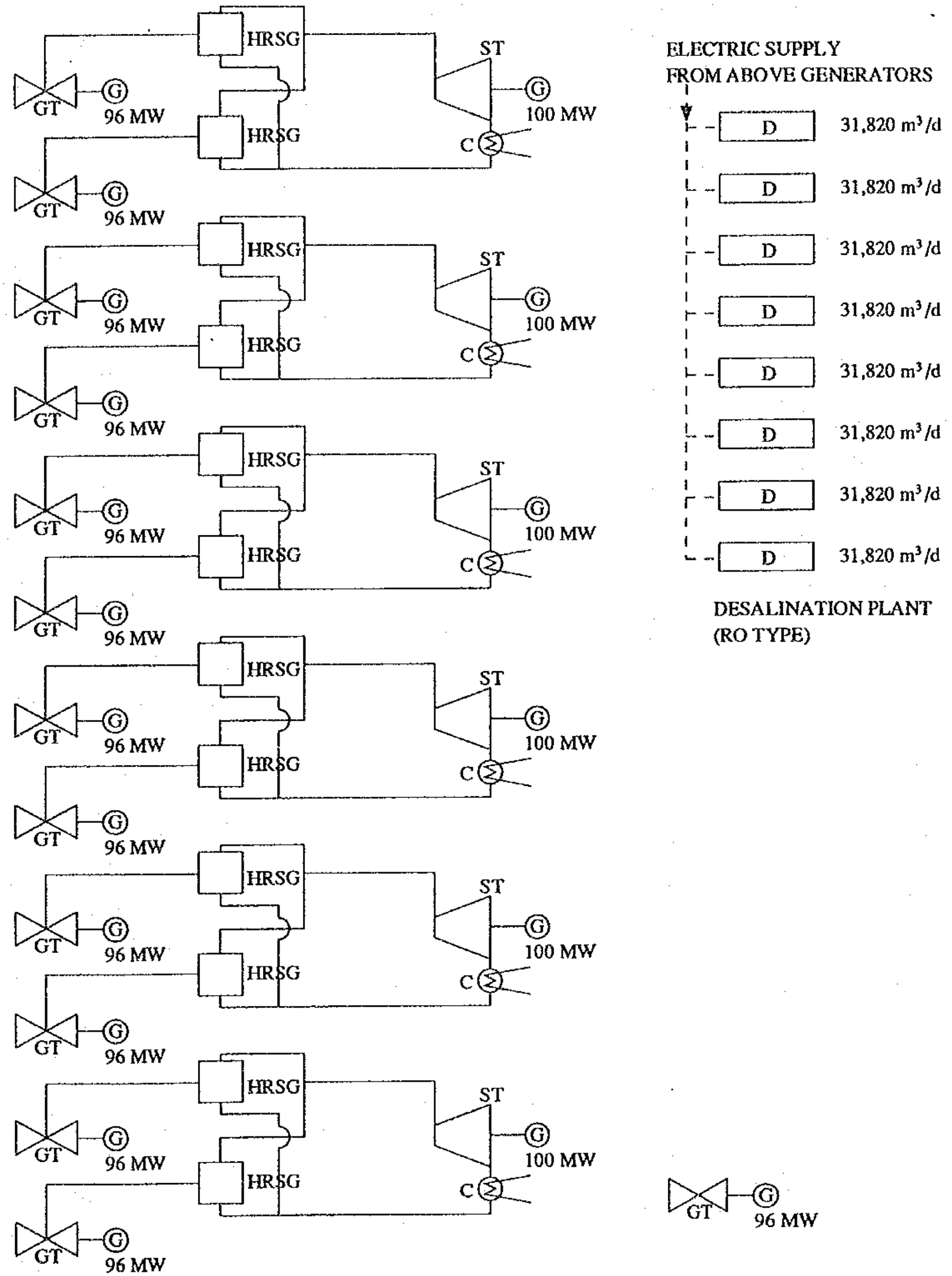


TOTAL OUTPUT

• Power Plant	Combined Cycle	292 MW x 5 =	1,460 MW	1,796 MW
	Gas Turbine (open cycle)	96 MW x 1 =	96 MW	
	Back Pressure Turbine	60 MW x 4 =	240 MW	
• Desalination Plant		31,820 m /d x 8 =	254,560 m /d	

ALTERNATIVE B

(1) GAS-STEAM COMBINED CYCLE POWER PLANT



TOTAL OUTPUT

• Power Plant	Combined Cycle	292 MW x 6 =	1,752 MW	1,848 MW
	Gas Turbine (open cycle)	96 MW x 1 =	96 MW	
• Desalination Plant		31,820 m3/d x 8 =	254,560 m3/d	

ABBREVIATIONS

GT :	Gas Turbine	G :	Electric Generator
ST :	Condensing Steam Turbine	SG :	Steam Generator (Boiler)
BPST :	Back Pressure Steam Turbine	D :	Desalination Plant (MSF or RO type)
HRSG :	Heat Recovery Steam Generator (Boiler)	C :	Condenser

NOTES

1. This system diagram indicates major part of the power and desalination plant for a comparison of Options A and B. Details are omitted for clarity.

Fig. 7.4.6 System Diagram of Power and Desalination Plant

Table 7.4.1 Comparison of Power Plant Development Plan

Options Compared		Alternative A	Alternative B
Configuration of Power Plant	Type of Plant	Back Pressure Steam Turbine Plant	Combined Cycle Power Plant
	Generator Output	4 Blocks x 60 MW/Block = 240 MW	1 Block x 292 MW/Block = 292 MW
	Station Service Load	58 MW (Incl. 42 MW for Desalination Plant)	75 MW (Incl. 69 MW for Desalination Plant)
	Sending-End Output	182 MW	217 MW
1	Durability in Continuous Operation	17,000 h	8,000 h
2	Reliability of Operation	96 %	86 %
3	Stability in Operation (When Operated Jointly with Desalination Plant)	Good	Good
4	Ease of Operation and Maintenance	Good	Good
5	Adaptability to Local Conditions	Good	Good
6	Expansibleness of Installed Capacity	Good	Good
7	Operation Records	Good	Good
8	Months for Construction	32 Months	32 Months
9	Required Space	100 %	90 %
10	Stability in Power Supply	Good	Good
11	Load Follow Up Characteristics	Good	Good
12	Interchangeability with Existing Plant	Good	Good
13	Fuel Consumption	100 %	50 %
14	Construction Cost (Total Output Base)	100 %	70 %
15	Construction Cost (Unit Output Base)	100 %	60 %

7.5 Power Plant Applications

7.5.1 Electricity Load Fluctuations and Load Allocation of the Power Plant

Section 4.5 projects maximum electricity trends to the year 2010. It will be necessary to produce a daily load curve based on these figures and use the curve to determine the load allocation for the Barka Power Plant. If we assume that trends for monthly load fluctuations and daily load fluctuations, both given in Section 4.3, are similar up to 2010, then load fluctuations on maximum load day and minimum load day based on the maximum electricity of 2,929 MW projected in the year 2010 will be as shown in Table 7.5.1. Figure 7.5.1 shows this in terms of daily load curves. Based on the table and the figure, maximum electricity on the maximum load day for the year will be 2,929 MW, while the minimum electricity on the maximum load day for the year will be 1,904 MW. The maximum electricity on the minimum load day will be 990 MW and the minimum electricity on the minimum load day will be 486 MW. The minimum electricity of 486 MW during the winter season becomes the base load for the year and the minimum electricity of 1,904 MW during summer becomes the base load for summer. Which part of the daily load is allocated to the power plant is an important consideration in choosing the type of plant to build and single unit capacity. We will therefore plan the load allocation for Barka Power Plant as follows:

(1) As water demand remains steady throughout the year, the electricity load and steam load of the desalination plant will become the power plant's base load for the year. As the steam turbine cycle excels in economy and has high total heat utilization rate, it will be used to supply the base load. Another effective method will be for the power plant, which uses a gas steam combined cycle, to meet the base load. We will design the Barka Power Plant in a way that ensures that thermal efficiency is high. Part of the power generated will be used to meet the base load for the desalination plant. (Under the MSF process, if we assume uniform electricity load and steam load at rated output, then gross generator output will be approximately 240 MW.) The steam turbine generators at Ghubrah Power Plant, which have relatively low thermal efficiency, will be used with secondary priority to meet the base load.

(2) To meet the summer base load, in addition to the electricity for the desalination plant mentioned in (1), Barka Power Plant, with its high thermal efficiency, will be operated with greater priority. The supply shortfall from the Barka Power

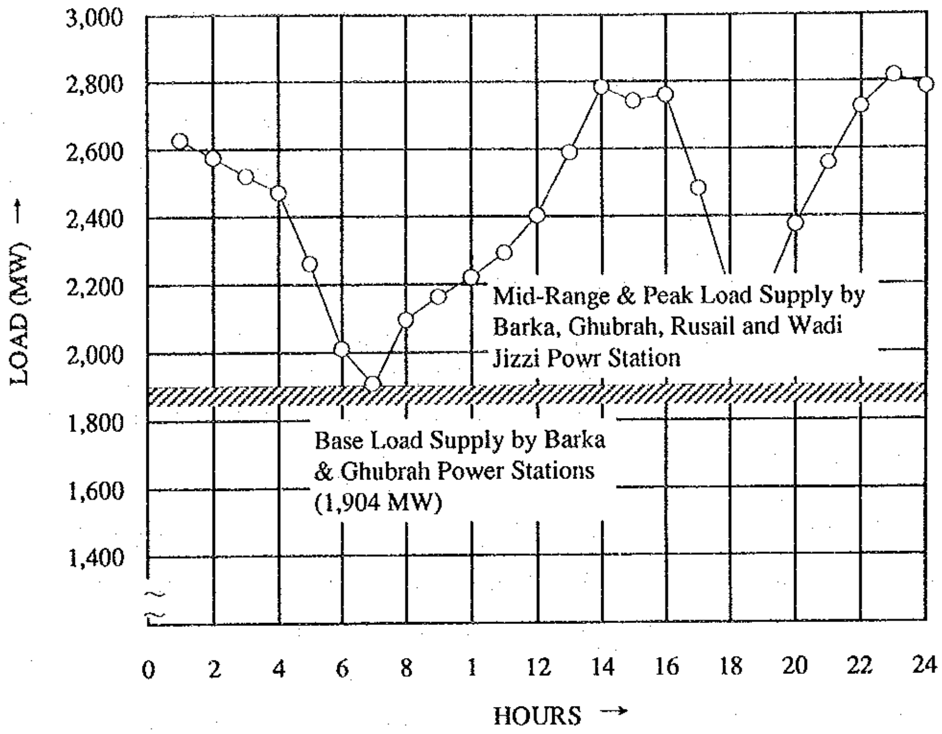
Plant will be supplemented by switching on additional gas turbines at Rusail Power Plant.

(3) To meet the peak load, gas turbines with excellent load follow-up capability, albeit rather low thermal efficiency, are most suited. In response to demand fluctuations, the small-capacity gas turbines at Ghubrah Power Plant will therefore be started up and shut down as required.

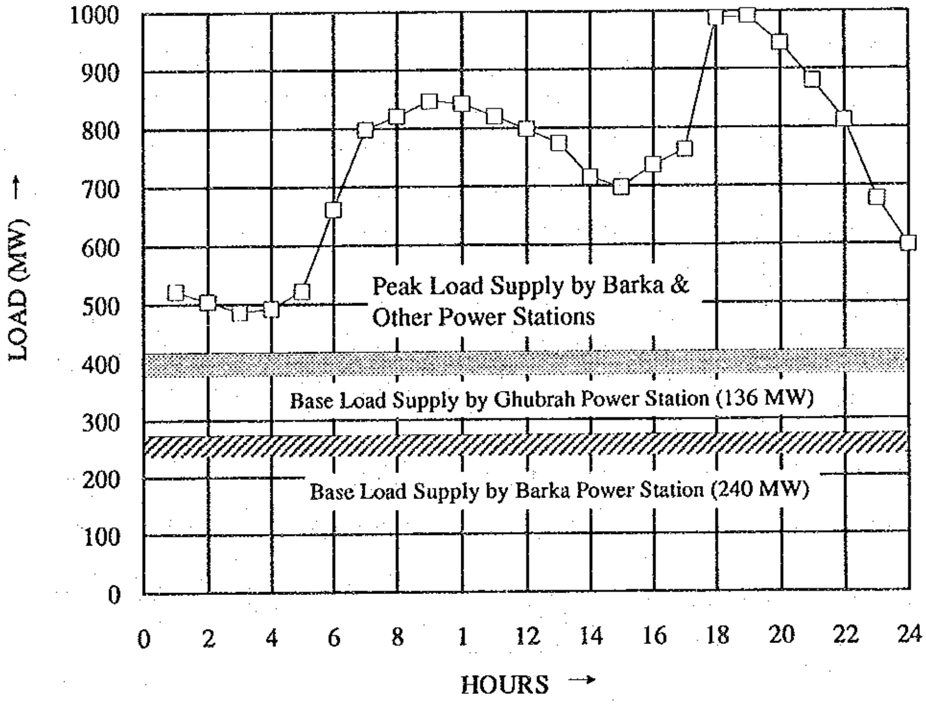
As shown above, Barka Power Plant will supply the base load and the mid-range load. Figure 7.5.1 shows the Barka Power Plant's position in the daily load curve.

Table 7.5.1 Projecte Daily Load Fructuations in 2010

	Maximum Load Day (2,929 MW)		Minimum Load Day (486 MW)	
Time (Hrs)	System Load		System Load	
	(MW)	(%)	(MW)	(%)
0100	2,627	89.7	521	17.8
0200	2,575	87.9	504	17.2
0300	2,519	86.0	486	16.6
0400	2,469	84.3	492	16.8
0500	2,261	77.2	521	17.8
0600	2,009	68.6	662	22.6
0700	1,904	65.0	797	27.2
0800	2,094	71.5	820	28.0
0900	2,162	73.8	846	28.9
1000	2,220	75.8	841	28.7
1100	2,293	78.3	820	28.0
1200	2,402	82.0	797	27.2
1300	2,589	88.4	773	26.4
1400	2,783	95.0	715	24.4
1500	2,742	93.6	697	23.8
1600	2,759	94.2	735	25.1
1700	2,481	84.7	762	26.0
1800	2,176	74.3	987	33.7
1900	2,144	73.2	990	33.8
2000	2,375	81.1	943	32.2
2100	2,557	87.3	879	30.0
2200	2,724	93.0	811	27.7
2300	2,815	96.1	677	23.1
2400	2,783	95.0	598	20.5



(a) MAXIMUM LOAD DAY



(b) MINIMUM LOAD DAY

Figure 7.5.1 Projected Daily Load Variation Curve in 2010

7.5.2 Power Plant Operations

As mentioned in Section 7.6, Barka Power Plant will adopt multi-shaft combined cycle systems, each comprising two gas turbines. Achieving high thermal efficiency and economy for the entire load range therefore requires operating the appropriate number of gas turbines to meet the load. This means that:

(1) It will be better to operate all the gas turbine units in order to achieve operationability and meet load fluctuation requirements.

(2) It is more efficient to operate a minimum number of gas turbine units to meet load requirements.

It will be necessary to maintain a balance between these conflicting factors. More specifically, when the load temporarily drops during the lunch break, a comprehensive economic evaluation should be made to determine the difference in fuel costs, station service power costs, and utility costs, in terms of: 1) Losses resulting from the lower efficiency at partial load when all gas turbine units are operated; and 2) Losses incurred by starting up and shutting down gas turbines when changing the number of operational units. The number of units to be operated shall be changed accordingly.

In general, when partial load only continues for about two hours after the load drop, it is more economical to continue operating all units. Thus, if the load drops for a short time, for the duration of the lunch break for example, it is better to keep all units operating. In contrast, we recommend operating the minimum number of units to meet low electricity demand at night or in the early morning.

The daily load fluctuations at the Muscat system are particularly evident during summer. Therefore, the above guidelines should be used in changing the number of gas turbine units to be operated.

The number of gas turbine units in operation should be changed when the power plant receives the following demand from the central load dispatch center:

(1) Demand in a load range where efficiency can be comparatively high, depending on the number of units to be operated.

(2) Scheduled load demand for a day if possible, but at least for two to three hours.

7.5.3. Plant Dynamic Characteristics during Load Fluctuations

Another strong characteristic of the combined cycle power plant is its excellent load follow-up capability. Making full use of this feature requires an understanding of the dynamic characteristics of the plant in connection with changes in the fuel ratio of the gas turbine. These dynamic characteristics are as follows:

(1) The gas turbine load will immediately follow-up in accordance with changes in the fuel ratio.

(2) The HRSG steam generation quantity will include a delay in transmission caused by ducts and pipes as well as a delay caused by the heat capacity possessed by HRSG. The delay will be for a few minutes.

(3) The steam control valve is kept open. Therefore, the generator output will be proportionate to steam quantity.

To compensate for the delay in the response of the steam turbine, the gas turbine must have a quick response characteristic within the range of the allowable change rate. The gas turbine's maximum output changes with atmospheric temperature: the greater the temperature, the smaller the maximum output. These points must also be reflected in plant operations.

7.6 Specifications of the Combined Cycle Power Plant

7.6.1 Combined Cycle System and Basic Plant Structure

(1) Combined cycle system

Combined cycle power generating systems are classified depending on the combination of gas and steam turbines. The exhaust heat recovery cycle and exhaust supplementary firing cycle mainly utilize gas turbines, while steam turbines are employed in the exhaust recombustion cycle, super charged boiler cycle and feed water heating cycle. These cycles have particular characteristics. The system will be selected with consideration to plant output, types of fuel, and operating and site environmental conditions. As exhaust gas temperature increases with rising gas turbine temperatures, an exhaust heat recovery cycle is the most efficient system. Figure 7.4.3 shows the operation of the exhaust heat recovery cycle, in which gas turbine exhaust gas is led to the heat recovery steam generator (heat exchanger HRSG), where HRSG generates steam to operate the steam turbine. This is the simplest of all combined cycle systems and is used at many plants around the world. The system's features include:

1) A high proportion of gas turbine output than steam turbine output.

2) Increasing thermal efficiency as the gas turbine inlet temperature rises.

3) Short start-up time.

4) Small level of hot water discharge per plant.

5) Small level of CO_2 discharge per plant.

The combined cycle system enables installation of gas turbines in the first phase, with HRSG and steam turbines added in the second phase as electricity demand increases. As exhaust heat recovery systems promise increased power output and improved thermal efficiency, this plant structure will be used for the Barka Power Plant.

(2) Single shaft and multi-shaft systems

As Figure 7.6.1 shows, the combination of equipment under the combined cycle plant can be classified into either single shaft or multi-shaft. The single shaft system directly links one gas turbine with one steam turbine by a common shaft to create one unit, and combining several of these units to create a large-capacity plant. The multi-shaft system combines one steam turbine with more than one gas turbine. The characteristics of the multi-shaft arrangement are:

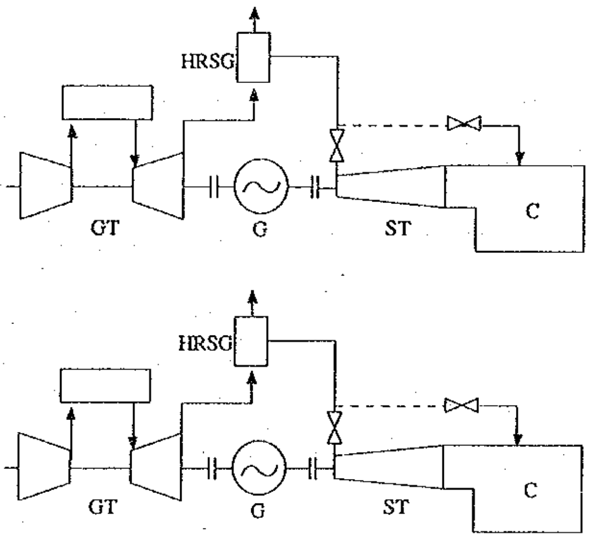
1) Power generation can continue when HRSG or steam turbine generator stops by independently operating the gas turbine (GT) (closing the HRSG inlet damper and opening the GT outlet bypass damper). Independent gas turbine operation is not possible in single shaft arrangements.

2) As one gas turbine unit and one steam turbine meet minimum load operations, other gas turbines can be stopped.

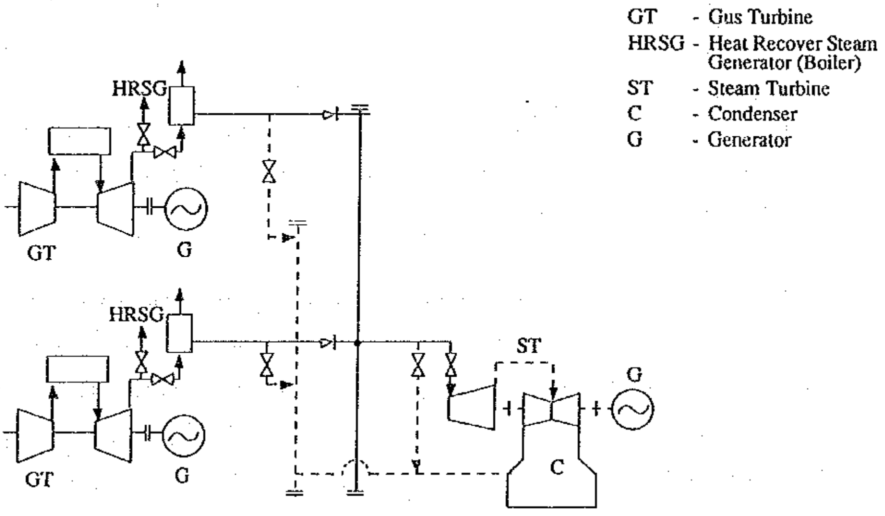
3) Each gas turbine unit can be started and loaded sequentially. Steam is allowed into the steam header when the HRSG-generated steam conditions match those during operations.

This project's power plant must be operated with the desalination plant while smoothly responding to wide load fluctuations, from base load to peak load.

With a unit machine capacity of 100 MW, the plant configuration shown in Section 7.6.1 dictates a single shaft plant capacity of 200 MW, while a multi-shaft plant would need a capacity of 300 MW. The output of the single shaft arrangement falls from 200 MW to 100 MW when one gas turbine is stopped in response to load fluctuations. In contrast, a multi-shaft arrangement can adjust the output, for example to 300 MW, 200 MW, 150 MW and 100 MW. As the Barka Power Plant will require this performance characteristic, a multi-shaft arrangement will be deployed.



(a) Single Shaft Type



(b) Multi Shaft Type

Figure 7.6.1 Comparison of Combined Cycle Power Plant Configurations

(3) Single and complex (dual) pressure types

The single pressure system has one pressure level (high pressure) for HRSG and steam turbine. The complex pressure type adds a low pressure steam system to the HRSG to effectively recover exhaust heat energy and lead low pressure steam to the steam turbine's low pressure section. The complex pressure type has a higher energy utilization rate and offers better efficiency and energy use economy. A complex pressure type will be used on this project.

(4) Basic structure of the power plant

Figure 7.4.6 shows the overall structure of the power plant. As examined in Section 7.3, the combined cycle plant's unit machine capacity for gas turbines, the principal component of the plant, should be about 100 MW. Consequently, a large-capacity plant will be built by combining 100 MW capacity machines.

The operation of each unit in an organically combined plant can be controlled, enabling swift response to load changes through rapid start up and shut down, and ensuring high partial load efficiency. The plant utilization rate will increase because there are few areas for equipment failures.

The following section outlines the main conditions and specifications for the combined cycle plant's principal equipment. The quantity of equipment is that for the power plant combined with the RO process desalination plant.

7.6.2 Gas Turbine

Gas turbines are the most important element in the exhaust heat recovery system of the combined cycle plant, accounting for about two thirds of plant output and having a significant impact on thermal efficiency.

Gas turbines employ high-temperature and high-pressure gas to make the blades revolve through an expansion process. As gas is not subject to phase changes, heating alone cannot provide heat energy. The gas must first be compressed, so the turbines incorporate a compressor and a combustion unit. The special features of the gas turbine are:

(1) There are few rows of blades as the expansion pressure drop is small.

(2) High temperature gas is used because of the major impact of working media temperature on thermal efficiency.

(3) As the working media temperature is extremely high, about 1,100°C, an ultra heat-resistant alloy is used, in association with measures such as air cooling of the blade.

The special features of the gas turbine power generation system are:

(1) Short start up time of 15-30 minutes for quick response to load changes.

(2) Low construction costs.

(3) Compact, standardized and lightweight plant requires short construction period, and small building, foundation and installation areas.

(4) Simple operation requires only a small number of operators.

(5) Simple structure and few components ensure high reliability and short open inspection period.

(6) Only requires a small amount of cooling water (no treated water is required).

This project's gas turbine design specifications are as follows. As the gas turbine output will be significantly affected by atmospheric temperature, the design temperature is set at 50°C and the rated output at 96 MW, equivalent to a 100 MW single machine capacity.

Type:	Axial-flow
Quantity:	13 units
Rated output:	96 MW (50°C atmospheric temperature), 123 MW (15°C atmospheric temperature)
Compressor:	Axial-flow
Fuel shift:	Automatic shift between main fuel (natural gas) and emergency fuel (distillate oil).

7.6.3 Heat Recovery Steam Generator (HRSG)

The HRSG basic design guidelines are: (1) Excellent thermal efficiency; (2) Ability to perform continuous and long-term operations; and (3) Safety. Strength and anti-corrosion characteristics will also be considered. Thermal stress must be examined to ensure the HRSG can withstand the frequent, rapid start-up and shut-down characteristic of gas turbines. Design considerations and factors which affect the HRSG's functions are:

(1) Exhaust gas components

(2) Exhaust gas temperature and flow rate.

(3) Steam temperature

(4) Steam pressure

(5) Pinch point temperature difference and approach point temperature difference.

(6) Exhaust gas pressure loss

HRSG performance is assessed through boiler efficiency by examining the ratio of heat output to heat input. Heat output is the amount of heat absorbed through HRSG working media, while heat input is the amount of heat supplied by the gas turbine exhaust gas. HRSG efficiency increases as the HRSG exhaust gas temperature drops. This requires a large thermal conductive area. However, larger-scale facilities and problems of low temperature corrosion mean that exhaust gas temperature will be restricted.

Figure 7.6.2 shows the complex pressure natural circulation-type HRSG's main system to be used for the Barka Power Plant. The design specifications are as follows:

Type:	Fin tube system natural circulation model (module structure)
Quantity:	12 units
Pressure level:	Complex pressure
Rated steam flow rate:	160/15 t/h
Outlet steam pressure:	80/9 ata
Outlet steam temperature:	510/230°C
Economizer inlet feed water temperature:	164°C
Exhaust gas temperature:	170°C
Exhaust gas pressure loss:	250 mm H_2O (atmospheric temperature 50°C)
Efficiency:	82 %

Remarks: The complex pressure system's high-pressure and low-pressure values are on the left and right of the slash respectively.

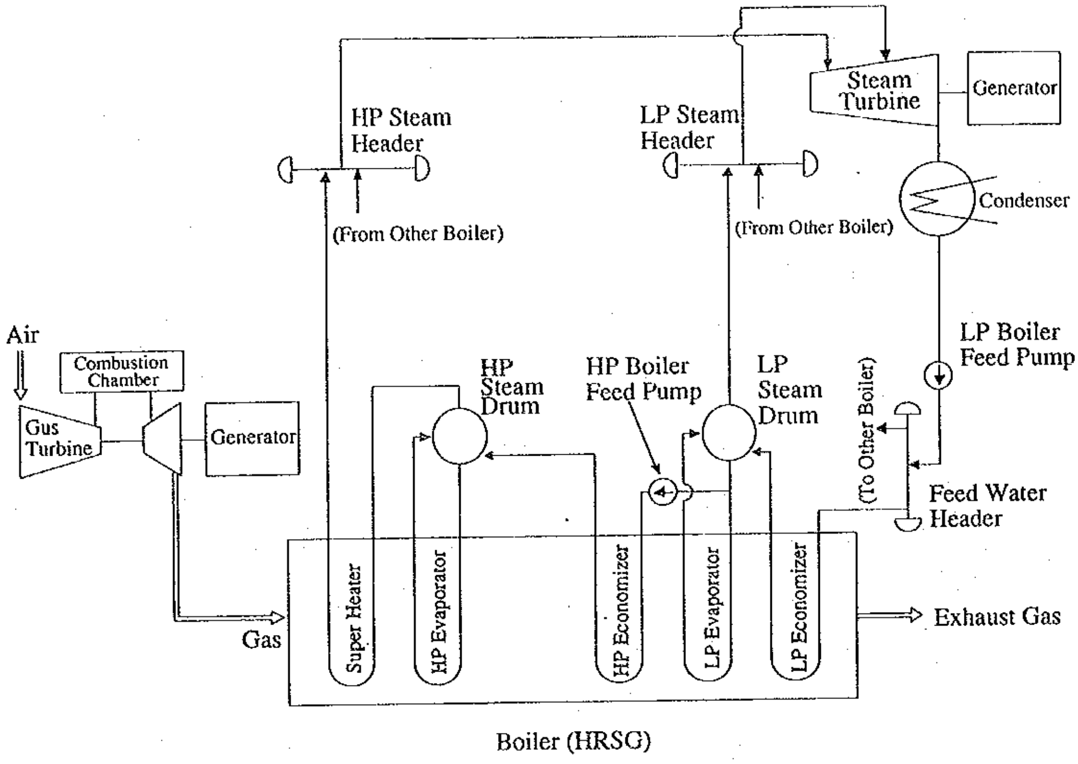


Figure 7.6.2 System Diagram of Power Plant with Dual Pressure Natural Circulation Boiler

7.6.4 Steam Turbine and Condenser

The high-pressure and low-pressure steam generated by the complex pressure system HRSG is sent to the steam turbine to generate power. Exhaust steam from the steam turbine flows into the condenser and is converted to water by a vacuum deaerating. The feed water pump increases the water pressure before supplying water to the HRSG's economizer. The steam turbine is designed to mitigate heat stress, and is adapted to frequent, rapid start up to improve the plant's thermal efficiency under a complex pressure system. The design specifications of the steam turbine and condenser are as follows.

(1) Steam turbine

Type:	Water condensing, single flow exhaust system, axial-flow model
Quantity:	Six units
Rated output:	100 MW (50°C atmospheric temperature), 109 MW (15°C atmospheric temperature)
Number of revolutions:	3,000 rpm
Steam pressure	

in the first stage: 80 ata

Steam temperature in the first stage: 510°C

Exhaust steam pressure: 90 mm Hg

Efficiency: 31 %

(2) Condenser

Type: Surface type

Quantity: Six units

Cooling water flow rate: 8.4 m^3/s (maximum increase of 7°C) per unit

Condenser load: 210 kcal/h

Inlet temperature: 30°C

Condenser outlet temperature: 49°C

Degree of vacuum: 670 mm Hg

(3) Sea water cooling system

Figure 7.6.3 outlines a typical sea water cooling system for the condenser. This project will employ six condensers and each will be fitted with cooling water pipes. Two 50 % capacity water intake pumps or three 50 % capacity water intake pumps (with one as reserve) will be installed on the cooling water pipes. Figure 7.6.3 shows two condensers, each fitted with three 50% capacity water intake pumps.

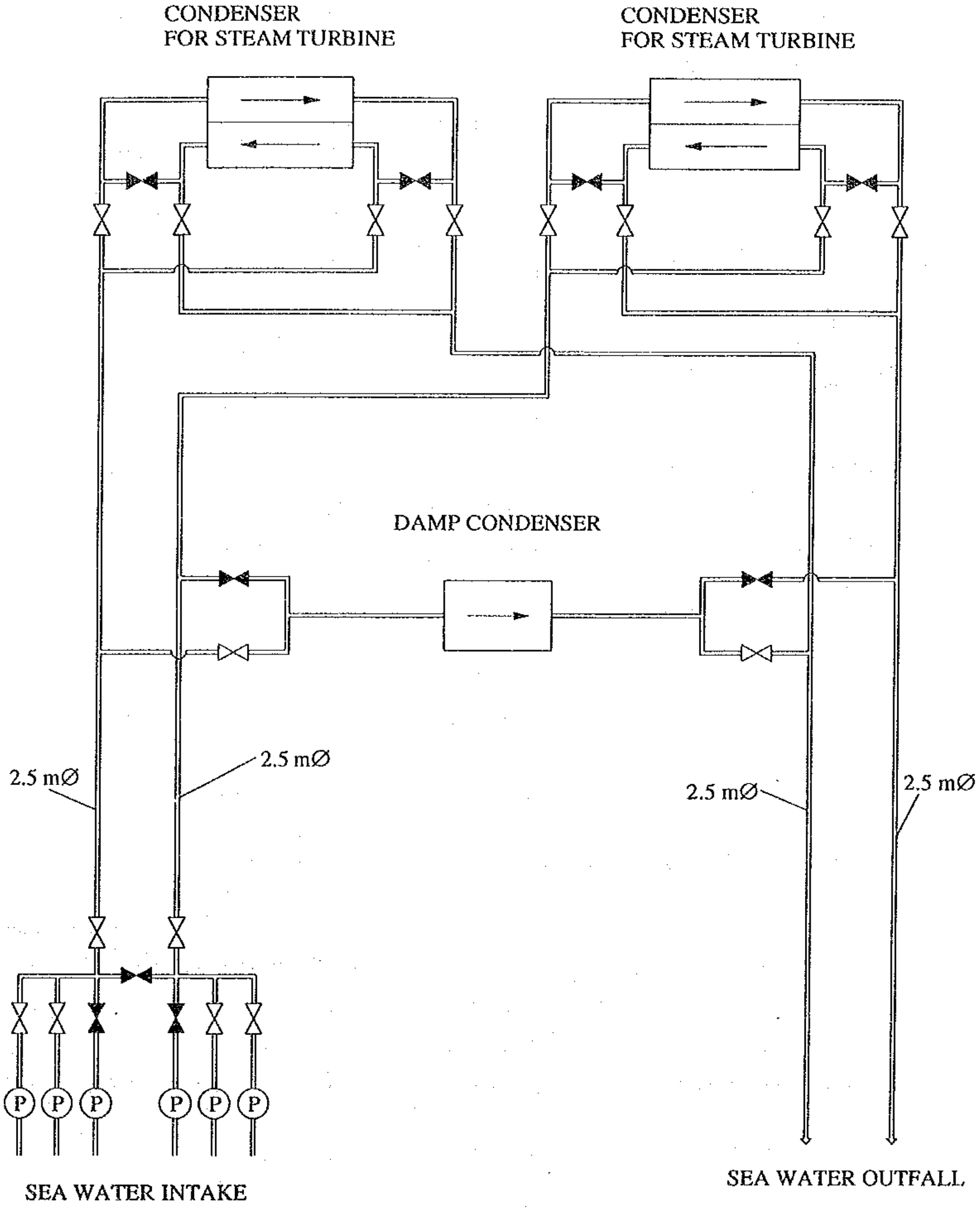


Figure 7.6.3 Sea Water Cooling System Diagram (Example)

7.6.5 Generator

The generator will employ air cooling, and is structured to convert the steam turbine's revolution energy into high-efficiency electrical energy. A quick-response static excitation system will be used to ensure system stability. The generator's design specifications are:

Type:	Indoor type, horizontal, axial, cylindrical, rotary, field winding type, totally closed air cooling type.
Quantity:	19 units
Rated capacity:	126 MVA (for ST), 120 MVA (for GT)
Power factor:	0.8
Voltage:	11,000 - 15,000 V
Frequency:	50 Hz
Number of phases:	3
Number of poles:	2
Number of revolutions:	3,000 rpm
Insulation:	Type F (type B used)
Cooling system:	Air cooling (stator) Air cooling (rotor)
Short circuit ratio:	0.5
Reactance:	Xd - 200 % Xd' - 20 % Xd" - 15 %
Excitation system:	Static type
Peak voltage:	1.5 pu
Response time:	≤ 100 ms (at 95% of peak voltage)

7.7 Specifications of the Back Pressure Steam Turbine Power Plant

The back pressure steam turbine power plant employs a co-generation system that generates 240 MW electricity and supplies steam (1,332 t/h) to the desalination plant running on the MSF process. Figure 7.4.6 shows the equipment configuration of the back pressure steam turbine power plant. The design specifications of principal equipment comprising this power plant are given below.

7.7.1 Steam Generator

Type:	Fin tube system, natural circulation type (module structure)
Quantity:	Four units
Rated steam flow:	385 t/h

Outlet steam pressure:	84 ata
Outlet steam temperature:	503°C
Economizer inlet feed water temperature:	180°C
Exhaust gas temperature:	140°C
Efficiency:	94 %

7.7.2 Back Pressure Steam Turbine

Type:	Back pressure type
Quantity:	Four units
Rated output:	60 MW (atmospheric temperature 50°C)
Number of revolutions:	3,000 rpm
Inlet steam pressure:	80 ata
Inlet steam temperature:	500°C
Exhaust steam pressure:	4 ata

7.7.3 Generator

Type:	Indoor type, horizontal, axial, cylindrical, rotary, field winding type, totally closed air cooling type.
Quantity:	4 units
Rated capacity:	75 MVA
Power factor:	0.8
Voltage:	11,000 - 15,000 V
Frequency:	50 Hz
Number of phases:	3
Number of poles:	2
Number of revolutions:	3,000 rpm
Insulation:	Type F (type B used)
Cooling system:	Air cooling (stator) Air cooling (rotor)
Short circuit ratio:	0.5
Reactance:	Xd - 200 % Xd' - 20 % Xd" - 15 %
Excitation system:	Static type
Peak voltage:	1.5 pu
Response time:	Within 100 ms (at 95 % of peak voltage)

7.8 Electrical and Control System

7.8.1 Electrical System

Electricity generated at Barka Power Plant is stepped up to 245 KV transmission voltage from the terminals of the gas turbine generator and the steam turbine generator to the unit transformer. The electricity is then transmitted to the Muscat system. Figure 7.8.1 shows the single line diagram.

7.8.2 Control System

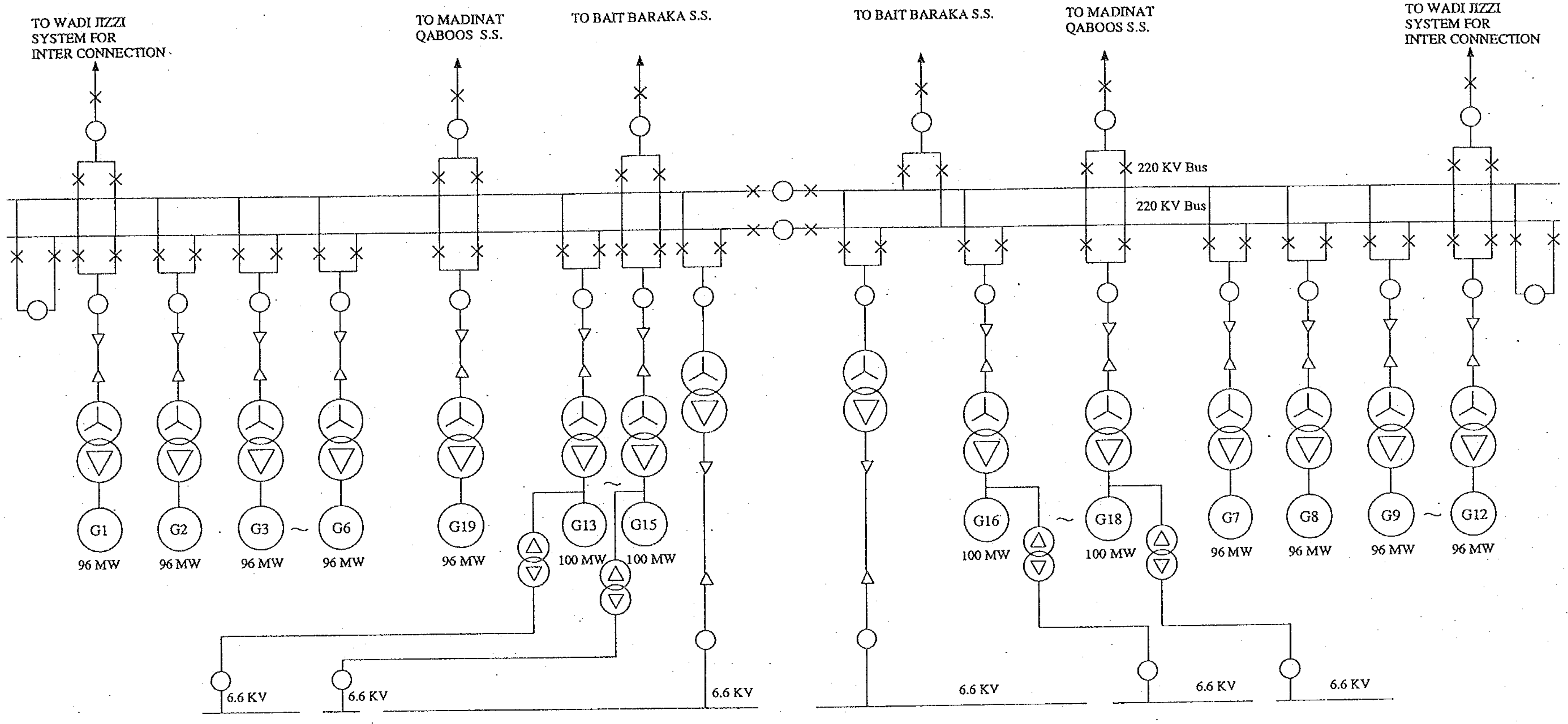
Rapid automation of operations has been promoted in the combined cycle power plant control system in response to such requirements as man-machine communications to reduce the burden on operators and the need to diversify and advance operations based on the power supply and demand situation. Consequently, the control system shall be built according to the following concept. Figure 7.8.2 shows an example structure. The figure shows a control system for one system comprising two gas turbines, two HRSGs and one steam turbine.

(1) Standardized and distributed control system structure.

(2) Central operation panel with a compact structure for single operator control

(3) Load control and unit operation systems to suit the large number of plant units.

(4) Rational application of digital technologies.



LIST OF GENERATOR .

GEN. No.	G1	G2	— —	G11	G12	G13	— —	G18	G19
USE	FOR GAS TURBINES					FOR STEAM TURBINES			FOR OPEN CYCLE GAS TURBINE
	COMBINED CYCLE PLANT								

SYMBOLS

○ : CIRCUIT BREAKER

✳ : DISCONNECTING SWITCH

⚭ : TRANSFORMER

⧖ : CABLE

Ⓖ : GENERATOR

NOTE : 1. THIS SINGLE LINE DIAGRAM CORRESPONDS TO A POWER PLANT WHEN COMBINED WITH RO PROCESS DESALINATION PLANT.

2. ALL TRANSFORMERS SHALL BE RATED AT 15 KV / 220 KV, 120 MVA EACH.

Figure 7.8.1 Single Line Diagram

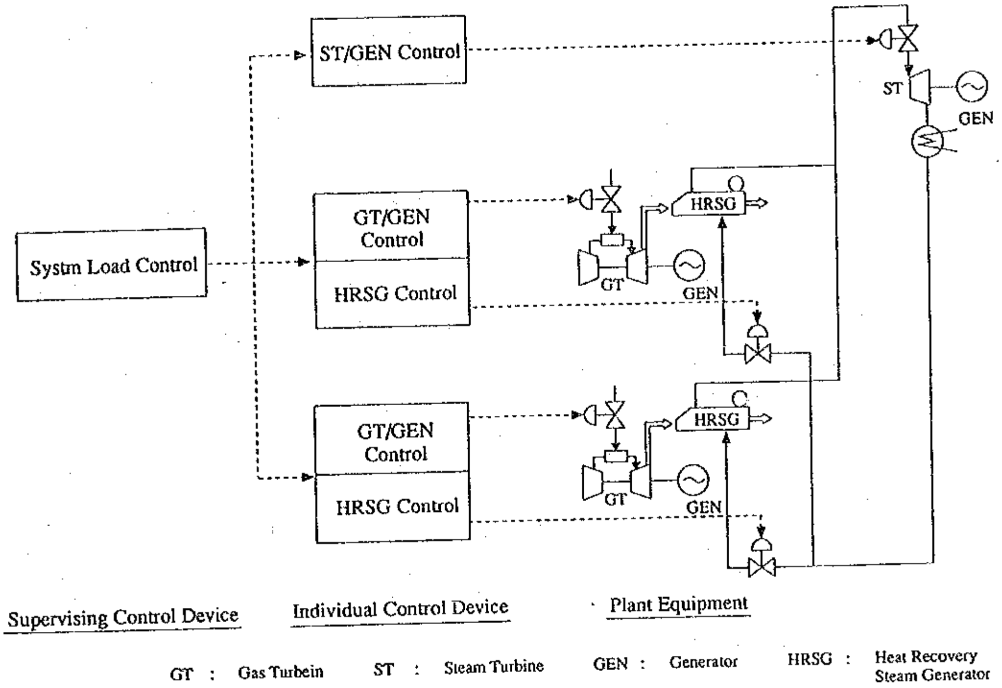


Figure 7.8.2 Example Control System Structure

To ensure that the frequent start up and shut down operations of the combined cycle power plant are safe and reliable, and to reduce the burden on operators, the central operation panel functions mentioned in (2) above are crucial. The central operation panel enables system load control and unit operation. It also has a man-machine interface function and enables a one man automated system operation. Therefore, the combined cycle power plant shall be built so that cold start up will be automated under normal operations and that at the principal break-points operations can be carried out only with the operator's permission.

7.8.3 Control Devices

The functions of principal control devices comprising the control system are given below.

(1) System load control device

The system load control device receives a load dispatching order for specific systems (or blocks) from the load dispatch center, allocates the output order to each system and carries out output control of each system. With the combined cycle power plant, it will be necessary to enable economic load control, automatic frequency control (AFC) and governor-free operation based on orders from the load dispatch center, as is the case with conventional thermal power plant.

(2) Automatic voltage and reactive power control device (AVQR)

AVQR as the entire system shall enable the automatic voltage regulator (AVR) to control the bus voltage at the set up value. AVQR should also control the balance to ensure that the reactive power of each generator is equal.

(3) Gas turbine control device

The gas turbine control device will control the quantity of fuel supplied to gas turbines, based on orders given from the system load control device.

(4) Steam cycle control device

The steam cycle control device will control the exhaust heat recovery boiler and the steam turbine. Principal components to be controlled by the device include:

1) Steam control valve control
2) Drum level control
3) Economizer re-circulation control
4) Turbine bypass control

(5) Auxiliaries control device

The auxiliaries control device will carry out the sequential control in relation to each shaft in the system.

Principal sequential control functions include:

1) Seawater system start up/shut down master
2) Vacuum increase/break master
3) Deaired steam master
4) HRSG start up/shut down master

(6) Computer system for control and management

The computer system shall have the following functions.

1) Plant automatic function (including multi-shaft simultaneous start up and multi-shaft uniform operation)
2) Sharing peripheral equipment among shafts
3) Plant monitoring function
4) Operator request processing
5) Plant failure analysis function
6) Data collection through serial data transmission

CHAPTER 8 CONCEPTUAL DESIGN OF POWER TRANSMISSION AND TRANSFORMATION FACILITIES

CHAPTER 8 CONCEPTUAL DESIGN OF POWER TRANSMISSION AND TRANSFORMATION FACILITIES

Barka Power Plant's total installed capacity will be about 1,850 MW. Construction of the power plant will be phased to the match the growth in electricity demand. Most of the generated electricity will be transmitted to the Muscat area. Substations for system interconnection will be located close to demand centers, in sites which facilitate interconnection to primary substations in the Muscat system. There shall be no system imbalance in the electrical load through interconnection. These factors will be considered in selecting substation sites. The MEW intends to connect these substations to the existing Bait Barka Substation and Madinat Qaboos Substation. We will analyze the power system to review the position of substations to be interconnected, the capacity of transformers to be interconnected, and a new voltage for connecting with the existing 132 KV transmission system.

The Wadi Jizzi System's capacity shortfall will be met by the Muscat System. The capacity shortfall of the Wadi Jizzi System shall be considered as the bulk load of the Muscat System. The same approach shall be taken to the interconnection with the Manah System.

The transmission line and substation plan will focus on the system interface for transmitting electricity generated at Barka Power Plant. The plan includes basic transmission line and substation plans based on the power system analysis and production of basic design specifications.

8.1 Design Policies and Criteria

8.1.1. Transmission and Transformation Facility Design Policies

The following policies will guide the design of transmission and transformation facilities:

(1) Facility capacity and extension space will facilitate future expansion in response to increased demand

(2) The system will ensure improved reliability and economic rationality, while minimizing voltage fluctuations and voltage drops

(3) Design will consider compatibility with existing power transmission and transformation facilities

Power failures resulting from accidents or operations have a significant impact on consumers. Power transmission and transformation facilities will be designed to minimize the impacts of power failures. The design will improve supply reliability, based on a comprehensive assessment of facility locations, layout, specifications, insulation coordination, bus system, high speed re-closing system and climatic conditions (high temperature, humidity, salt spray, sandstorms and sand dust).

8.1.2 Power System Operating Conditions

Power system operations will be similar to those of existing systems, and shall be based on the following conditions:

Voltage maintained on the system: 100 ±5 %
Generator operational voltage: 100 ±5 %
Generator operational power factor: 0.80
Transformer tap ratio: 100 + 5/-15 % (in accordance with OES27)
Load power factor: 0.80
Load time: Peak time

8.1.3 Applicable Standards

The applicable standards are the standards and criteria listed in Section 7.1.

8.2 Power Transmission Plan

8.2.1 Scope and Target

The power transmission and transformation facilities will reliably and effectively distribute electricity generated at the Barka Power Plant to consumers. Power transmission facilities are designed to transfer electricity by connecting the power plants and substations via power transmission lines. The substation facilities step down the voltage of the transmitted electricity to an appropriate distribution voltage. There is a network of facilities to distribute electricity to industrial and domestic consumers. These combined facilities constitute a power system.

The functions of this power system can be classified into power transmission, interconnection, power supply and distribution. The structure is shown in Figure 8.2.1.

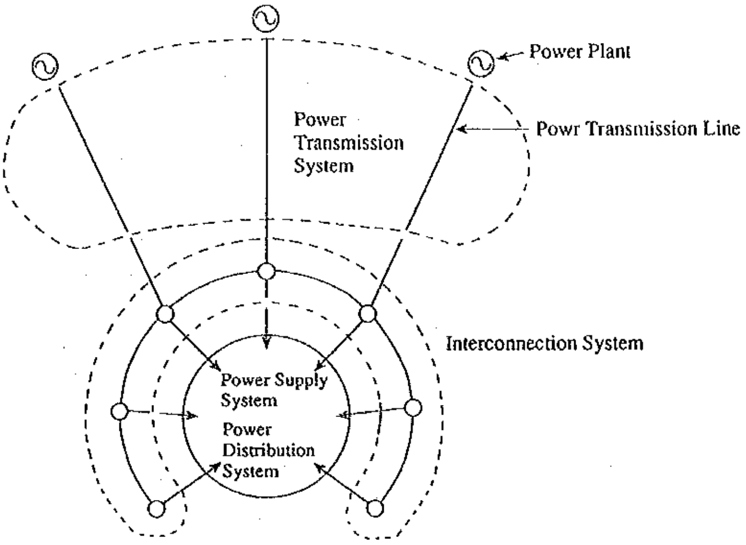


Figure 8.2.1 Power System Structure

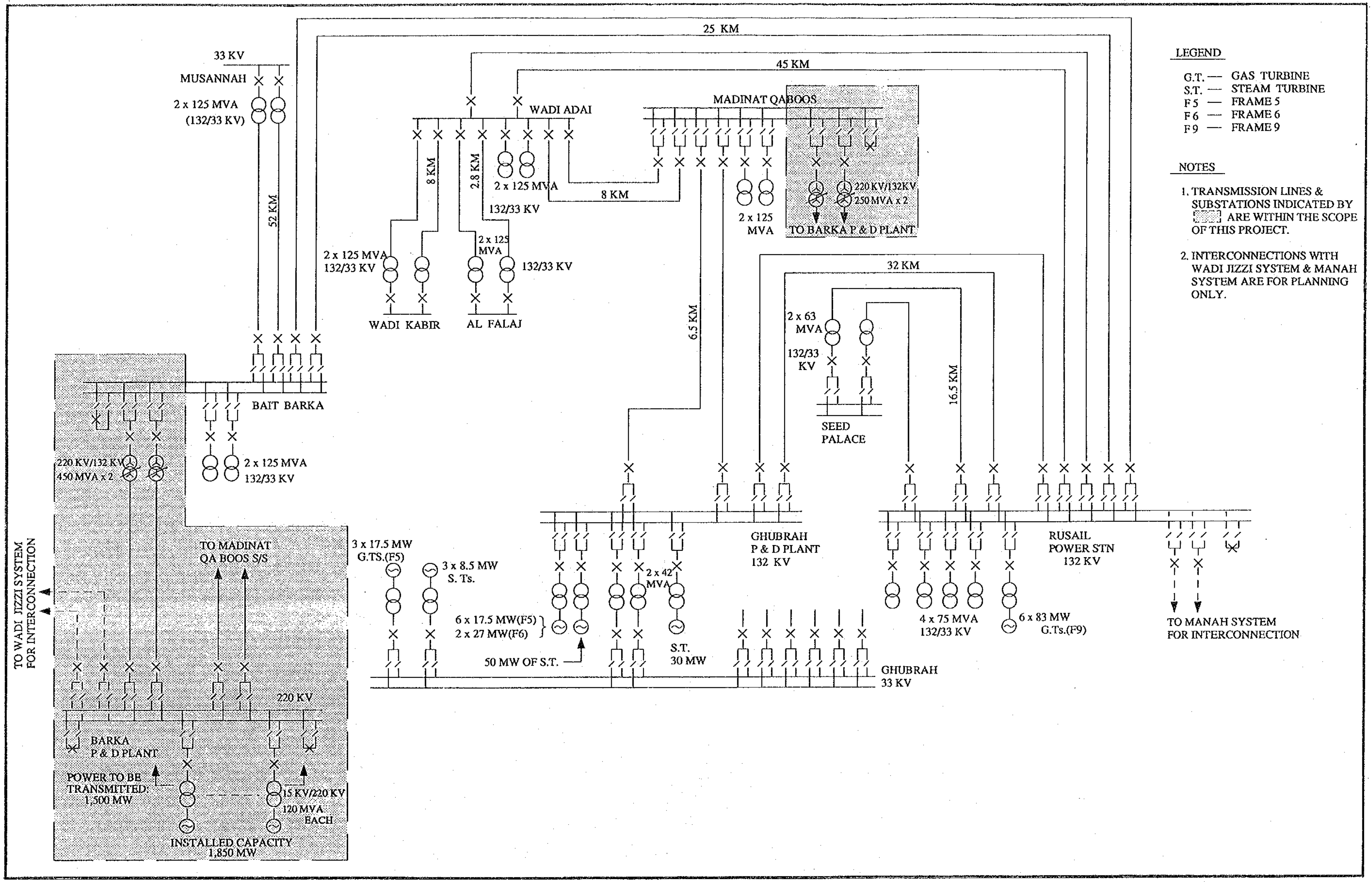
The power transmission system transmits the power plant's generated electricity to sites near electricity demand. The interconnected system is provided to connect power transmission lines and primary substations to supply electricity to consumers.

The transmission plan for this Project includes the power transmission and interconnected systems, which are composed of transmission and transformation facilities. As stated at the beginning of this Chapter, the interconnection substations will be located within the Bait Barka Substation and Madinat Qaboos Substation. Therefore, the power transmission plan will include the transmission and transformation facilities needed to send the Barka Power Plant's electricity to these substations. Figure 8.2.2 indicates an outline of the power transmission plan.

The principal matters to be examined in preparing the power transmission plan include supply reliability, frequency, voltage, stability, short circuits, and line to ground faults. Many formulae must be calculated to analyze, examine and evaluate the steady-state and transient power flow, voltage and phase angle. We will conduct a power system analysis for power flow and system stability by using a computer program.

8.2.2 Supply Reliability

Indicators of power supply quality include frequency fluctuations, voltage fluctuations and duration and frequency of power failure. Understanding these issues from the perspective of reliability, stability and economy will be MEW's most important power supply business.



LEGEND

G.T. — GAS TURBINE
S.T. — STEAM TURBINE
F 5 — FRAME 5
F 6 — FRAME 6
F 9 — FRAME 9

NOTES

1. TRANSMISSION LINES & SUBSTATIONS INDICATED BY ▨ ARE WITHIN THE SCOPE OF THIS PROJECT.
2. INTERCONNECTIONS WITH WADI JIZZI SYSTEM & MANAH SYSTEM ARE FOR PLANNING ONLY.

Figure 8.2.2 Power Transmission Plan for Barka Project

(1) Frequency fluctuations

The standard frequency of 50 Hz must not drop below 48.5 Hz if generator operations are to continue. Induction motors, widely used in industrial and domestic applications, will tolerate a frequency fluctuation of ±5 %, or 2.5 Hz. A significant frequency fluctuation range will result in massive power flow fluctuations on interconnected power transmission lines. This may restrict the capacity of interconnected power transmission lines or may make interconnection difficult. The adopted frequency fluctuation range shall therefore be smaller than ±5 %, for example ±2 % or ±1 Hz (the allowable fluctuation rate may be set at ±0.2 Hz or 0.4 % if the interconnection is to a large scale system).

(2) Voltage fluctuations

Voltage fluctuations at the receiving and shall be regulated within the allowable limit during normal operations. This serves as a scale of electricity quality. The receiving end reference voltage is normally 240 V ±10 %. The secondary bus voltage at the primary substation shall maintain a system voltage within ±5 % of the reference voltage.

(3) Duration and frequency of power failures

The duration and frequency of power failures is an important indicator of supply reliability. This is expressed as an annual frequency and duration of power failures experienced by each electricity consumer. The actual level of power failures in Oman is unknown. Japanese data would suggest an annual frequency of about 0.3 times per year, with a power failure duration of about 10 minutes per year.

Power supply failure has a greater impact than frequency or voltage fluctuations, and must be strictly controlled. This project's power transmission and transformation facilities will form Oman's core system. These facilities shall be based on the following concepts:

1) Single facility failure shall not limit power generation capability nor result in supply failure.
2) Major power source drops or system isolation shall be prevented in the event of dual facility failure. Supply failure shall be minimized in each system if the system is isolated.

3) The supply reliability stated in 1) and 2) above shall not decline when facilities are partially shut down for maintenance or repair works.

8.2.3 Promoting Higher Voltage

(1) Need to introduce a higher voltage

The current Muscat and Wadi Jizzi systems have a maximum operating voltage of 132 KV. This will not be sufficient to meet future demand, and will result in a shortage of power transmission capacity. This may cause problems such as declining system stability and increasing loss during power transmission. Barka Power Plant will transmit about 1,500 MW at the year 2010. Out of this capacity, about 80 %, namely 1,200 MW, will be transmitted to the Muscat System. The Madinat Qaboos Substation is about 60 km away. The 132 KV system will need to be upgraded to a more appropriate voltage, based on the following guidelines:

1) The power transmission capacity will increase in proportion to the square of the voltage.
2) High voltage power transmission lines will be more expensive, but power transmission line construction cost per unit of transmission capacity will decrease.
3) As there is a limit on the size of power transmission lines, the number of circuits and routes will need to be reduced by boosting voltage.

(2) Voltage selection criteria

While economy shall be given the highest priority in selecting higher voltage, the following requirements shall also be considered:

1) The voltage shall be standard and widely applicable

2) The voltage shall enable rational interconnection with existing systems

3) The voltage shall enable nationwide and international interconnection

4) There shall be few voltage and transformation stages

The new higher voltage shall be selected from the most economical options, based on load density, transmission capacity and transmission line distance.

(3) Voltages examined

The Oman Standards (OES 11) use the International Electrotechnical Commission (IEC) Standards as an application base and set the highest voltage at 132 KV (highest operating voltage 145 KV). IEC's upper standard voltages are 170 KV, 245 KV, 300 KV, 362 KV, 420 KV and 525 KV. The simplified Still formula to calculate the transmission line voltage is as follows:

$$V = 5.5 \times \sqrt{0.6 \times L + P/100}$$

Where, V: Transmission voltage (KV)
L: Transmission distance (km)
P: Transmission power (KW)

If $L = 60$ km and $P = 600 \times 10^3$ KW (dividing 1,200 MW into two transmission line circuits) are applied to Still's formula, $V = 427$ KV is obtained and the applied voltage will be 420 KV.

The Gulf Cooperation Council (GCC) countries use 245 KV and 420 KV transmission voltages. MEW will interconnect the Muscat and Wadi Jizzi Systems, and intends to interconnect Oman's power system to those of the United Arab Emirates. While this interconnection will not be determined by technology only, it will be important to prepare flexible plans which consider this intention. From this perspective, the suitable voltage might be 420 KV. As this is not the IEC's standard voltage, we also examine 275 KV, which has proven operating results in Japan. The new higher voltages assessed for this project are 245 KV (nominal: 220 KV), 275 KV and 420 KV (nominal: 400 KV).

(4) Selection of higher transmission voltage

We have undertaken power flow calculations for the three voltage grades. Section 8.4 states the results of a multi-faceted assessment, including supply reliability, transmission power loss, economy, compatibility with existing facilities, environmental sensitivity, future interconnection with GCC countries, and post-2010 system scale.

8.2.4 System Interconnection

The Muscat and Wadi Jizzi Systems are not interconnected, and operate independently, while the proposed Manah System will be interconnected with the

Wadi Jizzi Systems in the early stages of power system development, because of the substantial current and future demand on electricity supplies. We have produced a plan on the assumption that these two systems are interconnected under this project. System interconnection has many advantages and will:

(1) Reduce reserve margin

(2) Ensure scale merit following a shift to greater power supply facility capacity

(3) Reduce operating expenses and power loss following the comprehensive application of power systems

(4) Avoid overlap through mutual facility use

(5) Improve supply reliability

(6) Reduce frequency and voltage fluctuation ranges during normal operations

The most important benefit of the system interconnection is to ensure stability of demand and supply. Electricity can be supplied from other systems to supplement a supply capacity shortage resulting from an accident in one system.

Precautions must be taken to ensure that a severe accident in one system has no impact on other interconnected systems. In this event, the system interconnection must immediately be cut to contain the impact of the accident within one system. An under frequency relay and out-of-step separation relay will ensure system separation.

8.3 System Characteristics

8.3.1 System Voltage and Frequency Characteristics

(1) Load characteristics

Most voltage fluctuations result from reactive power fluctuations. The power consumption of the load is affected by frequency fluctuations. System planning requires an understanding of the load characteristics with a focus on the relationship between load flow and voltage/frequency.

1) Voltage characteristics

Voltage-power characteristics of the load at the rated voltage are expressed as:

$P_L = P_{LO} (V/V_O)^{\alpha}$

$Q_L = Q_{LO} (V/V_O)^{\beta}$

Where, P_L, P_{LO}: Real power when voltage is V and V_O
Q_L, Q_{LO}: Reactive power when voltage is V and V_O
α: Voltage characteristic constant of real power

$$\alpha = \frac{\Delta P}{P} / \frac{\Delta V}{V}$$

β: Voltage characteristic constant of reactive power

$$\beta = \frac{\Delta Q}{Q} / \frac{\Delta V}{V}$$

Ascertaining characteristic constants a and ß is difficult because they change with load type and operating condition. From a macro perspective, substations in Japan suggest measured load characteristic constants of a = 0.5 - 2 and ß = 1 - 3. Table 8.3.1 shows typical, micro-perspective voltage characteristic constants of the single load.

Table 8.3.1 Voltage Characteristics of Load

Load types		α	β
Fluorescent light	2 x 20 W	1.9	0.8
Refrigerator	100 W	1.0	0.7
Air conditioning induction motor	1 KW	0.5	1.6
Industrial induction motor	7.5 KW	0.6	1.6

The following classifications are usually applied to the values α and β. Figure 8.3.1 shows these characteristics.

α, β = 0: Constant KVA characteristics
= 1: Constant current characteristics
= 2: Constant impedance characteristics

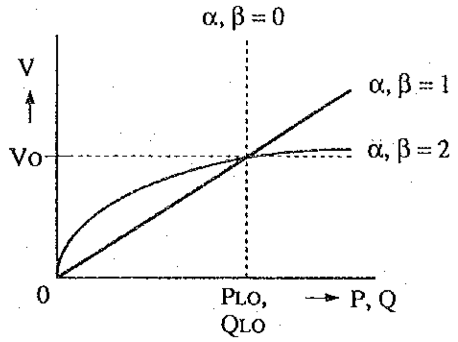


Figure 8.3.1 Voltage Characteristic Constants

2) Frequency characteristics

The load's frequency-power characteristics close to the rated frequency are expressed as follows:

$$P_L = P_{LO} \left(\frac{f}{f_O}\right)^{K_L}$$

Where, P_L, P_{LO}: Real power when frequency is f and fo

K_L: Frequency characteristic constant of the load

$$K_L = \frac{\Delta P_L}{P_{LO}} / \frac{\Delta f}{f_O}$$

The system load can be classified into resistance load and rotating load. While frequency fluctuations do not cause any power changes in resistance load, they cause a proportionate power change in rotating load (air conditioning induction motor, for example). A frequency fluctuation of 0.1 Hz will result in a 0.4 - 0.6 % power change in a typical system.

(2) Generator characteristics

The generator's operating output is adjusted in accordance with load fluctuations, and in response to accidental or maintenance shut down. An increase in power demand will also require a modification in the power transmission line and transformer configuration. By understanding the system characteristics we will know how load fluctuations and generator tripping will affect voltage and frequencies in generators, transmission lines and transformers.

1) Voltage characteristics

When the generator is operated with constant excitation current, the terminal voltage changes with fluctuations in the load's reactive power. It is necessary to adjust the excitation current (eventually internal inductive voltage) in response to terminal voltage fluctuations in order to maintain the terminal voltage at a particular level, regardless of reactive power fluctuations. Increasing the generator's excitation current in response to the rising reactive power of the load will supply the increased portion of the load's reactive power during constant voltage operations. Figure 8.3.2 shows the voltage characteristics which express the relationship between reactive power and voltage.

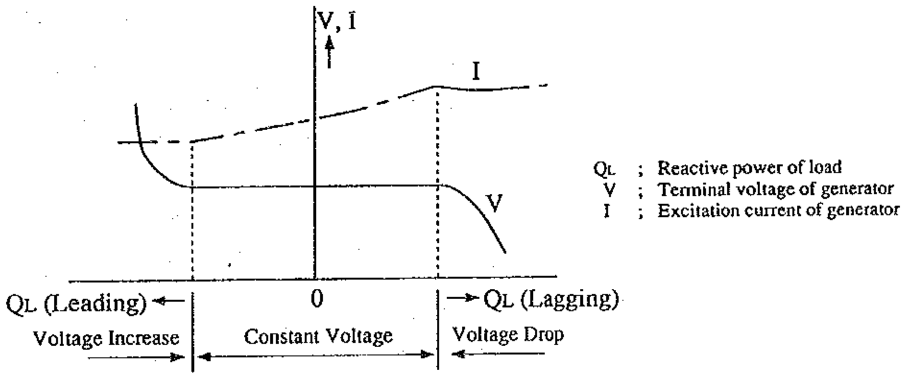


Figure 8.3.2 Generator Voltage Characteristics

2) Frequency characteristics

It is important to maintain a constant revolution and prevent significant acceleration or deceleration when the generator output changes rapidly as a result of system failure or generator tripping. It is also vital to appropriately distribute the load to each generator. The generator's prime mover is equipped with a governor for this purpose. The governor has the drooping characteristic of reducing the revolutions as the generator output increases. The system frequency has a constant relationship with the revolutions. If generator output fluctuations are ΔP_G when the frequency changes by Δf, the generator frequency characteristic constant K_G is expressed as follows:

$K_G = -\Delta P_G/\Delta f$ (MW/Hz)

Figure 8.3.3 shows the frequency characteristics which represent the relationship between the generator output and frequency.

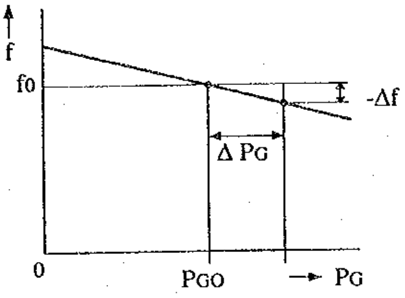


Figure 8.3.3 Generator Frequency Characteristics

(3) System characteristics

In addition to transmission lines and transformers, the load and generator constitute principal elements of the system. We need a comprehensive understanding of the load and generator characteristics, as they impact upon the system.

1) Voltage characteristics

The reactive power increases as the load's power consumption increases, causing the voltage to drop. A fall in voltage results in a reduction in load, power and reactive power. The generator voltage drops when reactive power is supplied, as shown in Figure 8.3.4. Stable operations are possible when a balance has been achieved, indicated on Figure 8.3.4 by crossing of the characteristic lines for the load and system (generator).

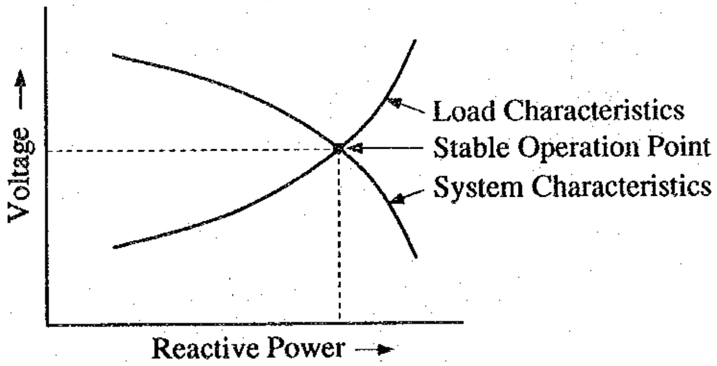


Figure 8.3.4 System Voltage Characteristics

2) Frequency characteristics

Figure 8.3.5 illustrates the load and generator frequency characteristics. When system operation is well-balanced at point A, with power P_1 and frequency f_1, the load frequency characteristics will move from L_1 to L_2 (direction 1), if power increases by ΔL from P_1 to P_2. The generator increases output by ΔP_G, changing the frequency from f_1 to f_2 (direction 2). When the frequency drops by Δf, power also decreases proportionately, indicated by ΔP_L (direction 3).

These relationships are expressed in the following formulae:

$$\Delta P_G = K_G (f_1 - f_2) = K_G \Delta f$$
$$\Delta P_L = K_L (f_1 - f_2) = K_L \Delta f$$
$$\Delta L = \Delta P_G + \Delta P_L = (K_G + K_L)\Delta f$$
$$\Delta L/\Delta f = K_G + K_L = K$$

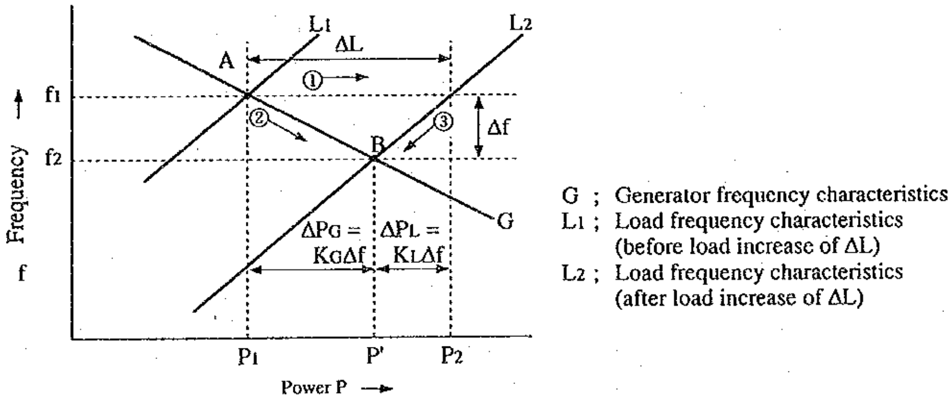


Figure 8.3.5 System Frequency Characteristics

As the generator and load frequency characteristics are different, even when the load increases by ΔL, the generator output increase is sufficient with $\Delta P_G < \Delta L$. The load naturally decreases the rate of increase, resulting in a $\Delta L - \Delta P_G$ power generation effect. The point of well balanced system power then shifts from A to B, and balanced power $P' = P_1 + \Delta P_G$.

$K_G + K_L = K$ is the system's inherent frequency characteristic constant, and is determined by the generator capacity and load capacity. The frequency fluctuations against load fluctuations fall as K rises. A large K is therefore preferred.

K_G and K_L are not constant, fluctuating as the system capacity and load characteristics change. K_G and K_L generally have the following values: