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Performance of a Typical Simple Gas Turbine Unit Under Saudi Weather Conditions

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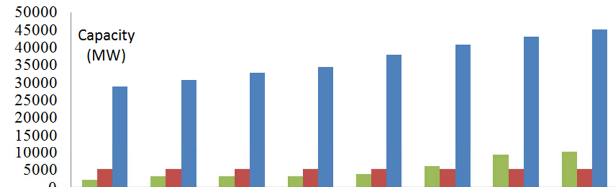
Abstract: Gas turbine units are widely used in KSA and other countries particularly during the peak demands and in inland regions. They produce about 50% of the total capacity of power generation in the kingdom. Despite their numerous advantages, their thermal efficiency remains very low and their resulting environmental impacts are significant. In this study, the effect of ambient conditions on the performance of a typical gas turbine used in KSA has been studied theoretically using the average hourly temperature and relative humidity for three regions of the country (Eastern, Central, and Western) which have almost the same power demand. Mass and energy balance equations with typical and realistic specifications of power plant units have been used to develop the model. The results present time variations of power generation, fuel consumption and efficiency for several typical cities. The maximum monthly power loss due to weather variation in Riyadh, Ad Dammam, and Jeddah are estimated at 8.9, 9.41 and 9.32 GWh respectively. While the annual power production loss in Riyadh, Ad Dammam, and Jeddah are 7.1, 8.2, and 11.2%, respectively. Power generation increases to about 4220 and 3028 kW when inlet air is cooled to 8.9 and 10.15°C, respectively. In conclusion, the effect of weather conditions of several Saudi areas on the performance of gas turbine units is significant. Therefore, the incorporation of inlet cooling technologies should be considered seriously.

Keywords: Gas Turbine Performance, Ambient Effect, Fuel Consumption, Power Production

1. Introduction

The Kingdom of Saudi Arabia is located in the south west of the continent of Asia. It has large daily and seasonal ambient temperature variations. As a consequence, electricity demand varies considerably from summer to winter and from day to night. The peak demand period for electric power occurs during the middle of the day in the summer, mainly due to the cooling loads required by air conditioning equipment.

The electrical energy is produced mainly by the Saudi Electricity Company (SEC) with more than 70% of total capacity of the Kingdom[1]. In 2012, the electric utility company in Saudi Arabia (SEC) produced 207131GWh of energy, of which 97664GWh (47%) was produced by simple cycle combustion turbines, 93475GWh (45 %) by steam turbines,15615GWh (7.5%) by combined cycle turbines, and 377GWh (0.5%) by diesel engines[2]. Other companies such as Saline Water Conversion Corporation (SWCC), Jubail Water and Power Company, Shuaibah Water and Electricity Company produce the remaining part of the needed electric power [1]. Figure 1 shows the installed capacity of producing companies in KSA. The total electrical power in Saudi Arabia is produced using four types of power plants; gas turbine, steam turbine, combined cycle, and diesel engine power plants[1].



	2005	2006	2007	2008	2009	2010	2011	2012
Others	2166	3249	3249	3249	3705	5971	9366	10175
SWCC	5120	5120	5120	5120	5120	5120	5120	5120
SEC	28927	30623	32696	34417	37846	40812	42938	45185

Figure 1. *Installed capacity and main producing companies[1].*

Modern gas turbine (GT) plants are being installed and are used to produce electrical power in inland regions and in particular to cover peak load demand. These power plant units are used single or integrated with steam power plants to form combined cycle plants.

Gas turbines, considered constant volumetric flow rate machines, are widely used to produce electricity particularly in inland regions. As ambient air is used as working fluid in these types of power plants, the ambient conditions (temperature, humidity and pressure) are considered as important factors affecting their performance. The production capacity of gas turbines is rated by the International Standards Organization (ISO) which specified the following air inlet conditions as reference conditions: air temperature 15°C (59°F), relative humidity 60%, and absolute pressure (sea-level) 101.325kPa (14.7psia). Figure 2 shows that, as the temperature of air entering the compressor section of the gas turbine increases, the power output, thermal efficiency, and air mass flow rate decrease, while the heat rate increases in comparison with ISO rated values.

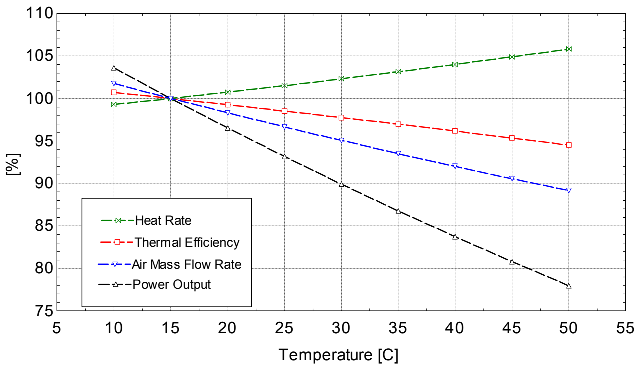


Figure 2. *Effect of inlet ambient temperature on the gas turbine performance* (ω = 0.006284 $\frac{kg_w}{kg_a}$).

The effect of ambient conditions on the performance of gas turbines has been discussed in various studies. De Sa and Al Zubaidy[3]considered specific gas turbines (SGT 94.2 and SGT 94.3) installed at the Dewa Power Station located at Al Aweer, Dubai. They investigated units performance at various ambient temperatures and concluded that for every 1°C rise in ambient temperature above ISO conditions the units lose 0.1% in terms of thermal efficiency and 1.47 MW of gross (useful) power output. Ameri and Hejazi[4] reported that there are more than 170 gas turbine units in Iran with a combined capacity of 9500 MW. 20% of this capacity is lost during summer time. From the performance curves of the gas turbines, they concluded that for every 1°C increase in ambient air temperature, the power output and the air mass flow rate will decrease by 0.74%and 0.36% respectively. Erdem and Sevilgen[5] studied the effect of ambient temperature on the electricity production and fuel consumption of two simple gas turbine models and seven climate regions in Turkey by using average monthly temperature data corresponding to those regions. They reported that electricity production loss occurs in all regions during the periods when the temperature is above 15°C and loss rates vary between 1.67% and 7.22% depending on the regions. Electricity generation increases by 0.27 to 10.28% when inlet air is cooled to 10°C. Al Ibrahim et al.[6] tested a simple gas cycle in the central Qaseem region of Saudi Arabia. They reported that a high mid-day ambient temperatures during summer can cause a 24% decrease in system capacity[7].

The performance of gas turbines can be enhanced by reducing air temperature at the compressor inlet. This is mainly because a cooled air has higher density giving the turbine a higher mass flow rate and a lower power required by the compressor. Several studies have investigated various air cooling techniques effects on the performance of gas turbines and combined cycles [4, 7-26]. Alhazmy and Najjar[27] conducted a comparative study between water spraying system and cooling coils. Spray coolers were found to be the less expensive option but deeply influenced by ambient temperature and relative humidity. The spray coolers reduced the temperature of incoming air by 3 to 15°C, enhanced the power by 1 to 7% and improved efficiency by 3%. Cooling coils give full control over inlet conditions but have large parasitic power requirements and improve the turbine output power by 10% during cold humid conditions and 18% during hot humid conditions; the lack of energy storage, however, causes net power to fall by 6.1% and 37.6%, respectively. Dawoud et al.[10] compared the performance of gas turbines using some inlet air cooling technologies in two locations in Oman. They reported that fogging cooling offered 11.4% more electrical energy than evaporative cooling in both locations. The LiBr–H_2O cooling offered 40% and 55% more energy than fogging cooling at Fahud and Marmul, respectively. Aqua-ammonia water and vapor-compression cooling techniques were better, offering 39% and 46% of annual energy production more than LiBr–H_2O cooling at Fahud and Marmul, respectively.

Recently, Al-Ansary et al.[28] have investigated the prospects of using a hybrid turbine inlet air cooling (TIAC) system consisting of mechanical chilling followed by evaporative cooling. The following four technologies were considered: Mechanical chilling only with dry cooling of the condenser (Base Case), Mechanical chilling only with wet cooling of the condenser, hybrid TIAC system with dry cooling of the condenser, and hybrid TIAC system with wet cooling of the condenser. The analysis used weather conditions for a typical hot and dry region in KSA, near Riyadh city as well as the technical specifications of the main components of each TIAC system in order to estimate the energy produced and consumed and the water consumption. The results of these analyses were used to estimate the cost of operation and benefits related to using TIAC systems. The results show clearly that configuration - hybrid TIAC using cooling towers- gives the most attractive option. Therefore, the authors proposed that it would be profitable to install it in the new gas turbine power plants.

The present study deals with electric power generation in KSA. It has two main sections. In the first section, a general picture on the status of this utility sector is drawn. Details on the used technologies and capacities in the main regions of the Kingdom are given. The second part of the study concerns the analysis of the effect of ambient conditions on the performance of a typical gas turbine used in KSA. The analysis is based on average hourly temperature and relative humidity for three typical regions.

2. Gas Turbine Cycle

Simple gas turbines operate in the open Brayton thermodynamic cycle. As the ambient fresh air enters the gas turbine, it passes through a compressor which causes its pressure to increase rapidly. Fuel is then injected into the high-pressure air and ignited in the combustion chamber. The combustion products flow into the turbine and produce the work that is used to drive the generator shaft and so generates electricity. Part of the generated work is also used to drive the initial stage compressor. A schematic diagram of the open Brayton thermodynamic cycle is depicted in figure 3.

2.1. Thermodynamic Model

The gas turbine is modeled by considering the following:

- Each component of the gas turbine is analyzed as a control volume assumed to be at steady state, with neglected pressure drop.
- The heat losses to the environment, the kinetic and the potential energy effects are neglected.
- Combustion chamber is considered as insulated chamber and the heat is added at constant pressure process.
- All fluid thermo-physical properties are modeled as temperature- and pressure-dependent.

Ambient air enters the compressor at T_1, P_1 and ϕ_1, where T, P and ϕ refer to the moist air temperature, its total pressure, and to its relative humidity respectively. Table 1 shows the technical parameters used for modeling of the gas turbine unit.

The total temperature and pressure of the fluid leaving a compressor can be calculated as:

$$T_2 = T_1 + \frac{T_1}{\eta_c}\left[r_c^{\frac{\gamma_a - 1}{\gamma_a}} - 1\right] \quad (1)$$

$$P_2 = r_c \times P_1 \quad (2)$$

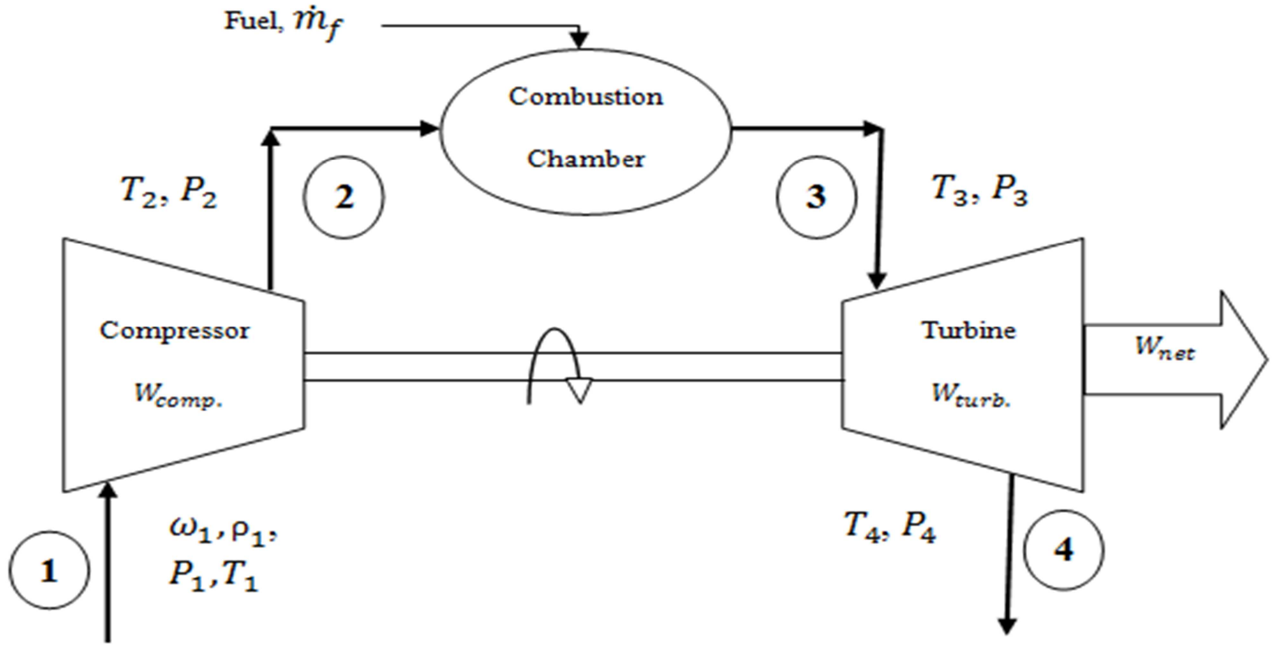


Figure 3. *An open Brayton thermodynamic cycle –turbine engine.*

Where r_c is the pressure ratio, γ_a is the ratio of the air specific heats, and η_c is the compressor isentropic efficiency that can be evaluated as[29]:

$$\eta_c = 1 - \left[0.04 + \frac{r_c - 1}{150}\right] \quad (3)$$

By using the first law of thermodynamics, the compression work can be estimated as:

$$w_c = \dot{m}_a\left[C_{pa}(T_2 - T_1) + \omega(h_{w2} - h_{w1})\right] \quad (4)$$

C_{pa} is the air specific heat at constant pressure, $\dot{m}_a$ is the air mass flow rate and equals to:

$$\dot{m}_a = \frac{\dot{V} \times \rho}{1 + \omega} \quad (5)$$

Where $\dot{V}$ is the volume flow rate of moist air and ρ is the density of moist air and it is a function of inlet conditions.

h_{w2} and h_{w1} in Eq. (4) are the enthalpies of saturated vapor at the inlet and outlet of the compressor, respectively. The saturation pressures (P_w) of water vapor depends on the absolute humidity as:

$$\omega_k = \frac{0.622 \times P_{wk}}{P_k - P_{wk}} \text{ k refers to states 1,2, or 3} \quad (6)$$

In the combustion chamber, inlet fluids are the humid air coming from the compressor and the fuel added for the combustion process. The exit fluids are the flue gas and water vapor (combustion products). The energy balance on the combustor gives:

$$\dot{m}_a h_{a2} + \dot{m}_w h_{w2} + \dot{m}_f \text{ FLV} = \dot{m}_g h_g + \dot{m}_w h_{w3} \quad (7)$$

$\dot{m}_g$ is the mass flow rate of the flue gases, defined as $\dot{m}_g = \dot{m}_a + \dot{m}_f$. Dividing Eq.(7) by the air mass flow rate gives:

$$C_{pa} \times T_2 + f \times FLV = (1+f) \times C_{pcom} \times T_3 + \omega(h_{w3} - h_{w2}) \quad (8)$$

f is the fuel to air ratio defined as $f = \dot{m}_f/\dot{m}_a$, then from Eq.(8):

$$f = \frac{C_{pcom} \times T_3 + \omega(h_{w3} - h_{w2}) - C_{pa} \times T_2}{FLV - C_{pcom} \times T_3} \quad (9)$$

Where FLV is the lower Calorific Value of the fuel, C_{pcom} is the combustion gases specific heat at constant pressure, and h_{w3} is the enthalpy of saturated vapor at the outlet of the combustion chamber.

The temperature of the fluid leaving the turbine can be determined using the polytropic relations for ideal gases as follows:

$$T_4 = T_3 + T_3 \eta_{tu} \left[\left(\frac{1}{r_c} \right)^{\frac{\gamma_g - 1}{\gamma_g}} - 1 \right] \quad (10)$$

Where γ_g is the gas specific ratio, and η_{tu} is the turbine isentropic efficiency that can be evaluated as[29]:

$$\eta_{tu} = 1 - \left[0.03 + \frac{r_c - 1}{180} \right] \quad (11)$$

The total mass of working fluid flowing through the turbine equals to:

$$\dot{m}_{total} = \dot{m}_a + \dot{m}_w + \dot{m}_f$$

$$\dot{m}_{total} = \dot{m}_a (1 + \omega + f) \quad (12)$$

The total work produced by the turbine can be estimated as:

$$w_{tu} = \dot{m}_a (1 + f + \omega) C_{pg} (T_3 - T_4) \quad (13)$$

Where C_{pg} is the gas specific heat at constant pressure. The net work and the thermal efficiency of the gas turbine can be calculated as:

$$w_{net} = w_{tu} - w_c \quad (14)$$

$$\eta_{th} = \frac{w_{net}}{Q_{in}} \quad (15)$$

Q_{in} is the heat added to the combustion chamber and equals to $Q_{in} = \dot{m}_f \times FLV$. The heat rate (HR) and specific fuel consumption (SFC) can be calculated as:

$$HR = \frac{3600}{\eta_{th}} \quad (16)$$

$$SFC = HR \times FLV \quad (17)$$

Finally, the electric power output from the gas turbine power plant is,

$$Pr = \eta_{gen.} \times w_{net} \quad (18)$$

Where $\eta_{gen.}$ is the generator efficiency.

As given in the above equations, the performance of simple gas turbines expressed in terms of total produced net power, efficiency and heat rate depends on the weather conditions particularly on the ambient temperature. In the following, the difference between these quantities at ISO and actual ones will be quantified and discussed.

Table 1. *Assumptions and inputs used in the model.*

Description	Unit	Value
Pressure ratio, r_c	[---]	12.7
Turbine inlet temperature, T_3	K	1408
Volume flow rate of moist air, $\dot{V}$	m^3/sec	239.792
Air specific heat at constant pressure, C_{pa}	kJ/kg.°C	1.005
Gas specific heat at constant pressure, C_{pg}	kJ/kg.°C	1.147
Combustion chamber specific heat at constant pressure, C_{pcom}	kJ/kg.°C	1.236
Air specific ratio, γ_a	[---]	1.4
Gas specific ratio, γ_g	[---]	1.333
Lower Calorific Value of the fuel (FLV) “Methane”	kJ/kg	50000
Generator efficiency ,$\eta_{gen.}$	[---]	0.83

The ISO gas turbine performance refers to the gas turbine performance key parameters measured at ISO conditions (air temperature 15°C, relative humidity 60%, and absolute pressure 101.325kPa). They are equal to 84400.22kW, 32.59%, 11046.249kJ/kWh, and 0.2209kg/kWh for the power output, thermal efficiency, heat rate, and specific fuel consumption, respectively.

The difference between the ISO gas turbine power output and efficiency and actual ones evaluated at the average hourly temperature and relative humidity are:

$$\Delta Pr_i = Pr_i - Pr_{ISO} \quad (19)$$

$$\Delta \eta_{th_i} = \eta_{th_i} - \eta_{th_{ISO}} \quad (20)$$

i represents the time of the day. In the above equations (19-20), the negative and positive signs stand for the loss and excess in the power output and thermal efficiency of the gas turbine, respectively. The corresponding differences in the heat rates and specific fuel consumptions are:

$$\Delta HR_i = HR_i - HR_{ISO} \quad (21)$$

$$\Delta SFC_i = SFC_i - SFC_{ISO} \quad (22)$$

The monthly power production of the gas turbine is:

$$Pr_m = \sum_{i=0}^{23} N \times Pr_i \quad (23)$$

Pr_m is the monthly power production, *N* is the number of days in that month, and *i* represents the time of the day. While the annual power production is:

$$Pr_{an} = \sum_{j=1}^{12} Pr_{m_j} \quad (24)$$

Where Pr_{an} the annual power production and *j* represents the month.

2.2. Model Validation

The above equations of the gas turbine were solved using

Engineering Equation Solver (EES). EES software has been widely used for these kinds of systems due to its capability to solve non-linear equations and its unique features in having accurate thermodynamic properties of various fluids. The gas turbine model was validated with a typical gas turbine[30] at the ISO conditions. Table 2 presents a comparison between the performance of a typical gas turbine and the computed performance parameters obtained from the gas turbine modeling at the ISO conditions. The maximum error is 0.07012% for the hate rate, thereby demonstrating good agreement.

Table 2. *Comparison of typical and measured performance parameters for gas turbine at ISO conditions.*

Performance parameter	Unit	Ref*.	Calculated using this model	Error** [%]
Gas turbine power output, Pr	kW	84360	84400.22	0.04768
Gas turbine efficiency, η_{th}	[---]	0.3257	0.3259	0.06217
Turbine outlet temperature, T_4	K	809	809.1	0.0095
Exhaust flow rate, $\dot{m}_{total}$	kg/sec	297.222	297. 221	-0.0004
Hate Rate, HR	kJ/kWh	11054	11046.249	-0.07012

*Ref. refers to the performance of a typical gas turbine[30].
**Error [%] = (Calculated - Ref.)×100/ Ref.

3. Results and Discussion

The country is divided into several different geographical locations with different climatic conditions (average temperature and humidity). Ad Dammam and Jeddah are coastal regions and their climate is hot and humid, while Riyadh is a desert region and its weather is hot and dry. The weather data for 2012 for those regions are obtained through the Department of Energy's EnergyPlusProgram[31]. These data include the dry bulb temperature, dew point temperature, and barometric pressure. For missing weather data in 2012, the average weather data in the previous three years (2011, 2010, and 2009) are taken at the same day and time.

3.1. The Eastern Operating Area, Ad Dammam

The weather data for the Eastern Operating Area (Ad Dammam) were taken from the weather station at King Fahd International Airport (OEDF) in Ad Dammam for 2012[31]. Figure 4 shows the average hourly temperature and relative humidity data in Ad Dammam for 2012. As observed, during the middle of the day "peak demand period" the temperature is higher than the ISO temperature and the relative humidity is less than the ISO humidity for all months. The maximum temperature reaches 45.19°C in July, while the minimum temperature and maximum relative humidity are 10.15°C and 76.56%, respectively and occur in January.

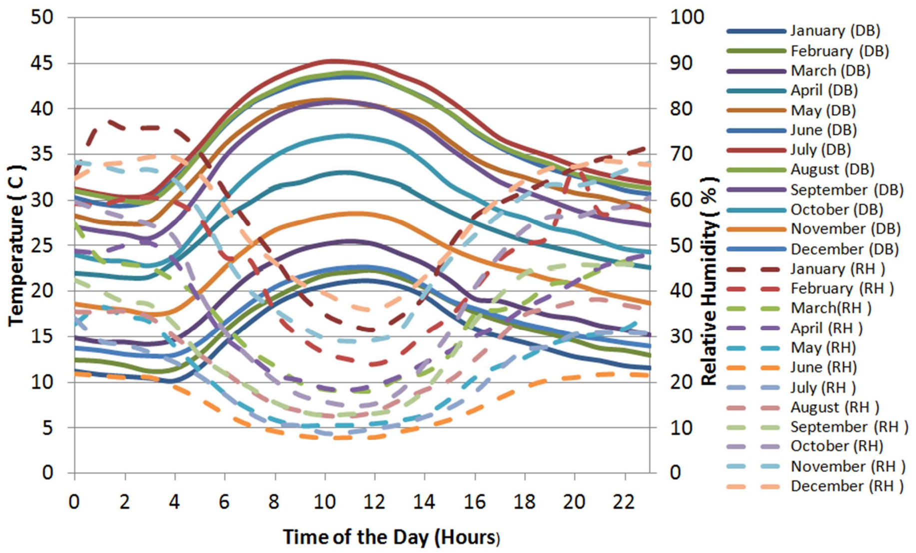


Figure 4. *Average hourly temperature and relative humidity in Ad Dammam, 2012[31].*

The maximum, minimum, and average monthly temperature and relative humidity curves in Ad Dammam during 2012 are shown in figure 5. The period from the beginning of April to the end of November has a higher temperature than ISO temperature, while the temperature of the period from the beginning of December to the end of March is fluctuating. For the relative humidity, the period from the beginning of March to the end of September has lower relative humidity than ISO case. In general, Ad Dammam is facing high temperature and high relative humidity conditions.

Therefore, the fact that the temperature during the middle of the day "peak demand period" is higher than the ISO temperature while the relative humidity is less than the ISO humidity causes significant decrease in the performance of the gas turbine. Figure 6 depicts the difference between the power production rates of the gas turbine at the ambient conditions in Ad Dammam for all months of 2012 and those at the ISO conditions. The negative and positive values refer to the losses and excesses in the power output, respectively. As figure 6 shows, during the summer months, the power production of the gas turbine is less than the production at the ISO conditions and the maximum losses can reach 16139 kW occurring in July. This can represent about 20% of the ISO production rate. In some of the winter months (December, January, February, and March), the electric production during the middle of the day is less than the ISO production, and for the remaining winter months, the production is almost equal to the production in the summer months. When the temperature becomes below the ISO temperature the production increases, and the maximum power gain is 3028 kW at temperature 10.15°C in January. One can conclude that, the effect of weather conditions of Ad Dammam region on the performance of gas turbines is significant; therefore, adding inlet cooling technologies may be needed when further justified with economic analysis.

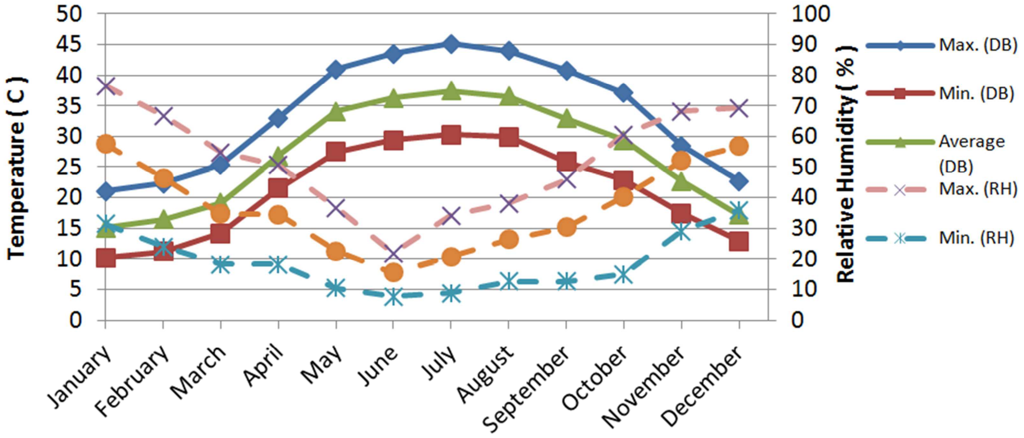


Figure 5. *Max., min., and average monthly temperature and relative humidity in Ad Dammam, 2012[31].*

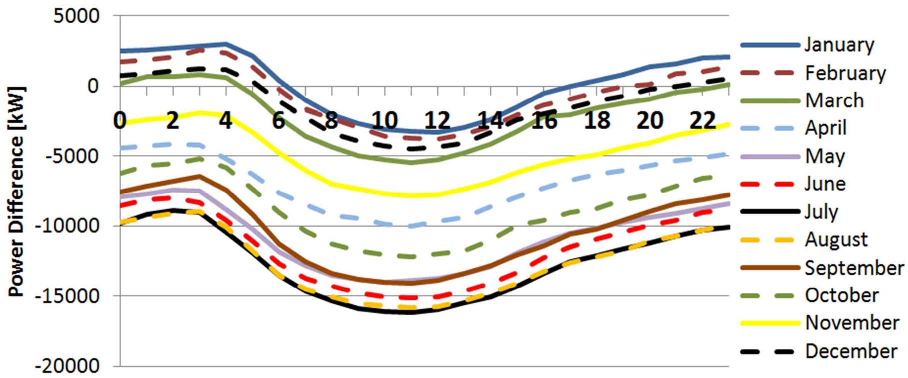


Figure 6. *Effect of ambient conditions on the hourly power production, in Ad Dammam.*

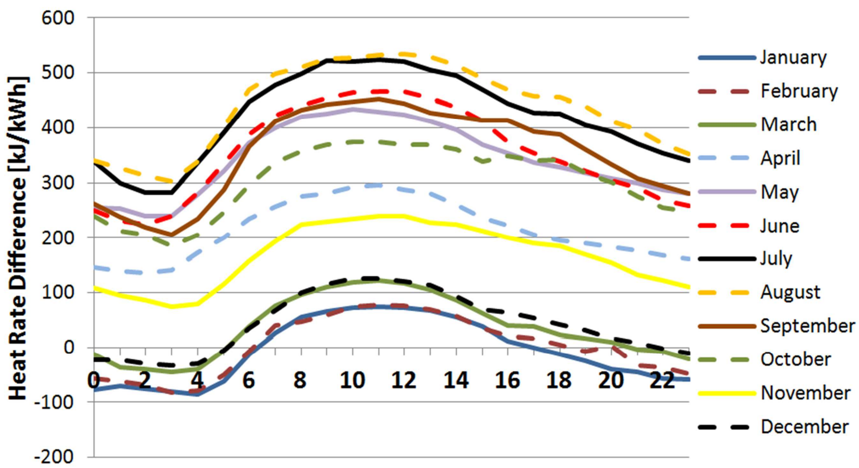


Figure 7. *Effect of ambient conditions on the hourly heat rate, in Ad Dammam.*

Figure 7 presents the difference between the heat rates of the gas turbine at the ambient conditions in Ad Dammam for all months of 2012 with the heat rate at the ISO conditions. The maximum additional part in the heat rate is 535kJ/ kWh in August which represents about 5% of the ISO heat rate and the benefit in the heat rate is 85kJ/kWh in January at a temperature of 10.15°C.

As a summary of these results shown in figures 4 - 7, and for August for example, the maximum value of the power losses reaches about 15,800kW occurring when the ambient temperature reaches a maximum of 43.94°C and the relative humidity has a minimum of 12.51% at eleven o'clock. The gas turbine performance is affected not only by the ambient temperature but also by the ambient humidity.

3.2. The Central Operating Area, Riyadh

Riyadh, located in the central region of the Kingdom, is characterized by large daily and seasonal ambient temperature variations. The weather data for the Central Operating Area (Riyadh) was taken from the weather station at King Khaled International Airport (OERK) in Riyadh for 2012[31].

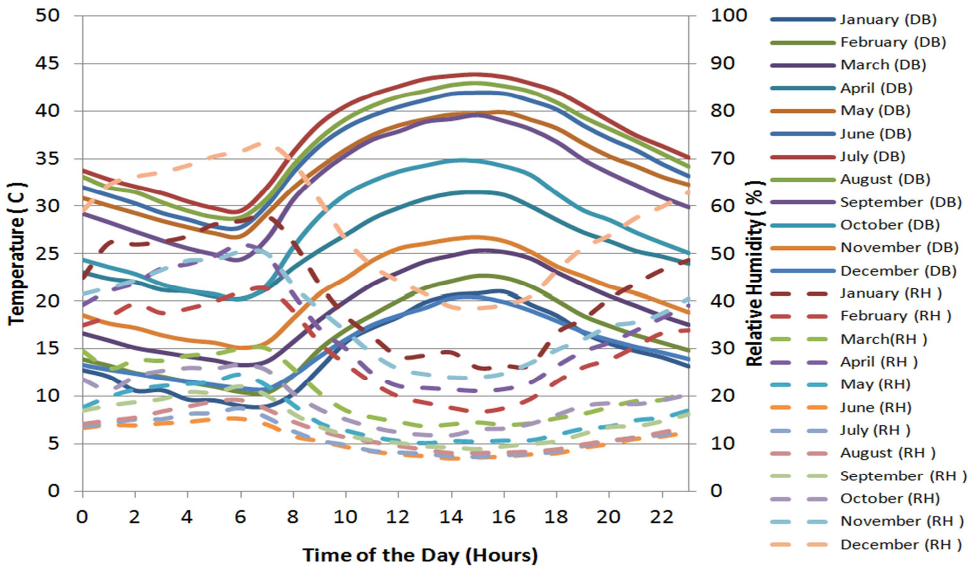


Figure 8. *Average hourly temperature and relative humidity in Riyadh, 2012[31].*

As figure 8 shows, the temperature is higher than the ISO temperature during the middle of the day "peak demand period". The maximum temperature reaches 43.87°C in July and the minimum temperature is about 8.9°C in January. The relative humidity is less than the ISO humidity for all months except the period from the beginning of the mid night until dawn in December. The minimum relative humidity is 6.91% in June.

Figure 9 presents the maximum, minimum, and average monthly temperature and relative humidity curves in Riyadh for 2012. The temperature of the period from the beginning of April to the end of November is higher than ISO temperature. The relative humidity is lower than ISO relative humidity for all months except some times in December. In general, Riyadh is a desert area characterized by a higher temperature and lower relative humidity.

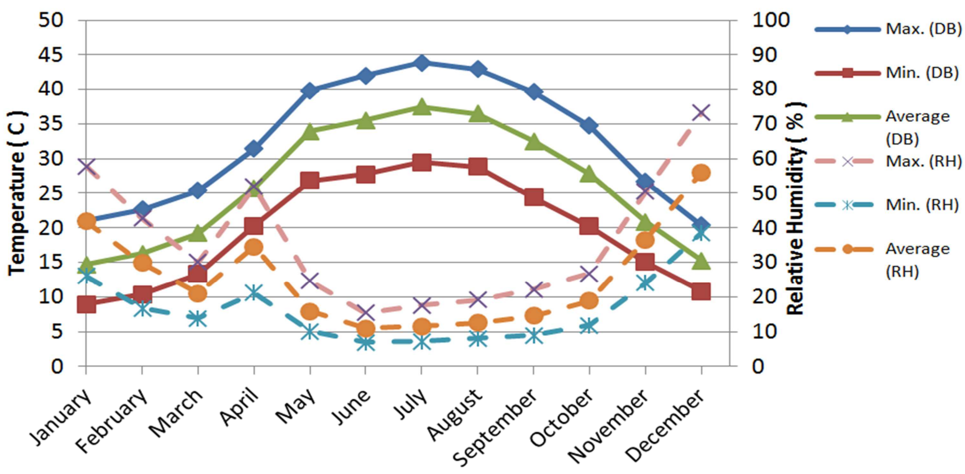


Figure 9. *Max., min., and average monthly temperature and relative humidity in Riyadh, 2012[31].*

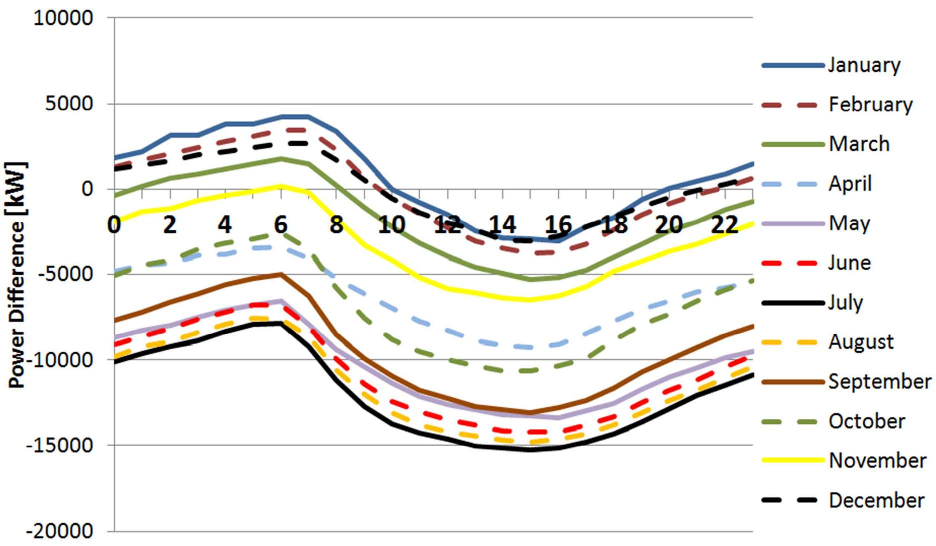


Figure 10. *Effect of ambient conditions on the hourly power production, in Riyadh during 2012.*

Figure 10 presents the difference between the power production rates of the gas turbine at the ambient conditions in Riyadh for all months of 2012 and those at the ISO conditions. The power production of the gas turbine is less than the ISO production during the year, except for the period from the beginning of the mid night until dawn for some months of the winter season (December, January, February, and March). The maximum power loss is 15,246kW which occurs in July and represents about 18% of the ISO production while the maximum power gain is 4,220kW in January when the temperature is 8.9°C. Therefore, for every 1°C drop in the temperature the power gain can be about 703.33kW.

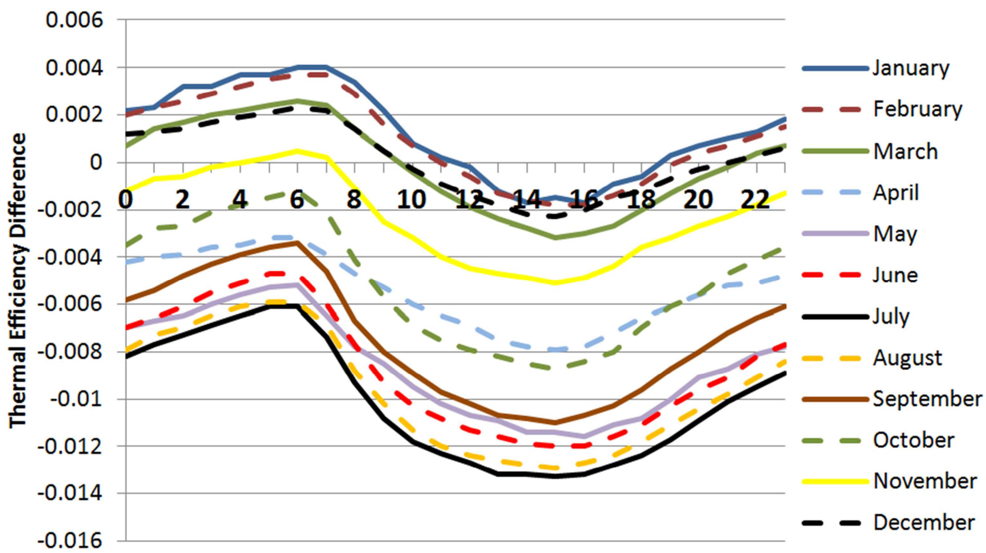


Figure 11. *Effect of ambient conditions on the hourly thermal efficiency, in Riyadh.*

The difference between the thermal efficiencies of the gas turbine at the ambient conditions of Riyadh for all months of 2012 and the thermal efficiency at the ISO conditions is depicted in figure 11. Such a difference becomes important during the summer months (June, July and August) particularly between 10:00 AM and 6:00 PM.

3.3. The Western Operating Area, Jeddah

Jeddah, located on the Red Sea, is characterized by high temperature and relative humidity levels. The weather data for the Western Operating Area (Jeddah) was taken from the weather station at King Abdulaziz International Airport (OEJN). in Jeddah for 2012[31].

Figure 12 depicts the average hourly temperature and relative humidity data in Jeddah for 2012. The temperature is higher than the ISO temperature while the relative humidity is fluctuating, for all months. The temperature is ranging between 18.9 and 39.47°C in January and July, respectively.

Figure 13 gives the maximum, minimum, and average monthly temperature and relative humidity curves in Jeddah for 2012. The temperature has approximately the same value for all months with small increase during summer season. The fluctuations of the relative humidity are small during the year.

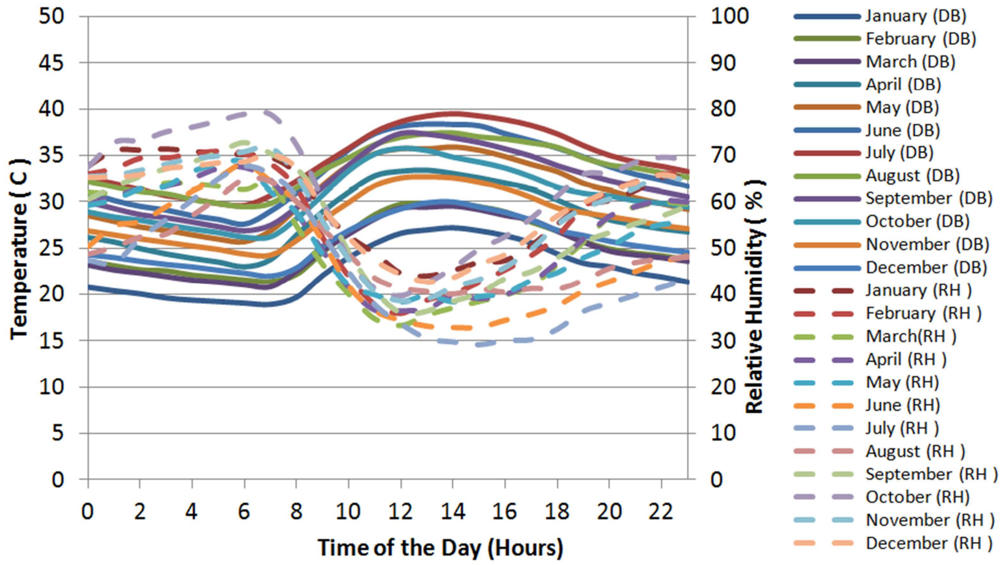


Figure 12. *Average hourly temperature and relative humidity in Jeddah, 2012[31].*

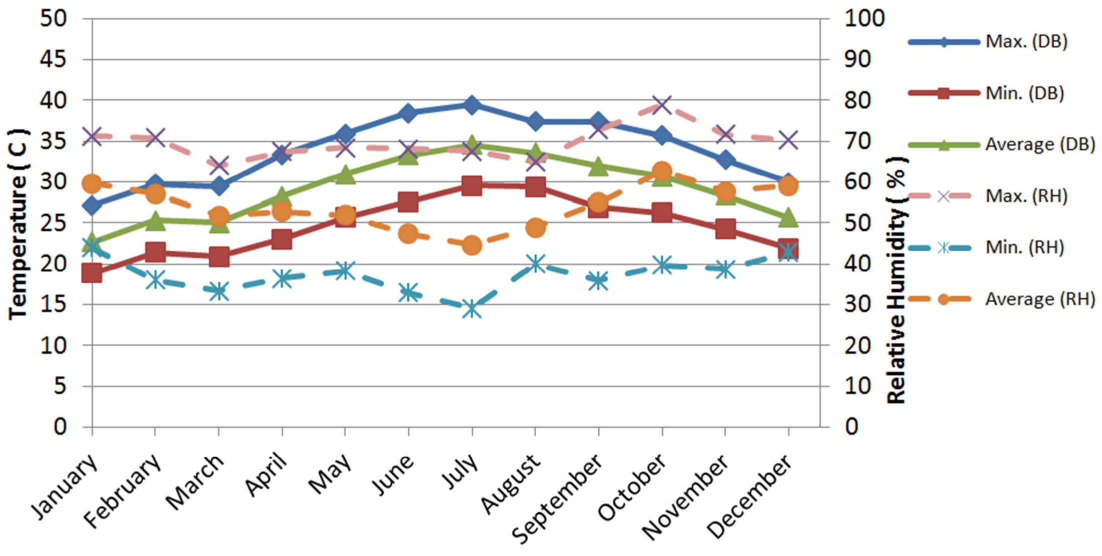


Figure 13. *Max., min., and average monthly temperature and relative humidity in Jeddah, 2012[31].*

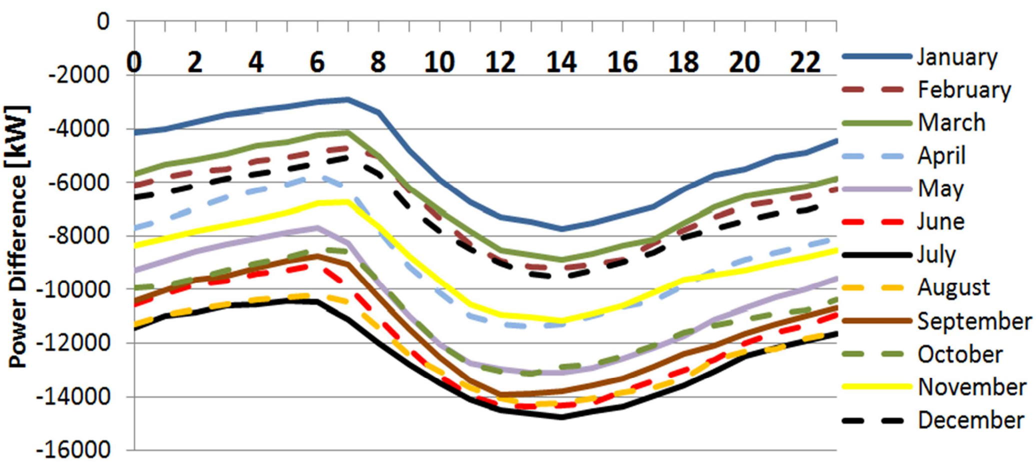


Figure 14. *Effect of ambient conditions on the hourly power production, in Jeddah.*

Figure 14 shows the difference between the power production rates of the gas turbine at the ambient conditions in Jeddah for all months of 2012 and those at the ISO conditions. Besides, the differences between the specific fuel consumption rates of the gas turbine at the ambient conditions in Jeddah for all months of 2012 and those at the ISO conditions are depicted in figure 15. The production of the gas turbine is lesser than the ISO production for all months. The maximum power loss is 1,4781kW which occurs in July and represents about 17.5% of the ISO production and the maximum additional specific fuel consumption is 0.0118kg/ kWh in August.

Figure 16 compares the power production rates in Ad Dammam, Riyadh, and Jeddah for two months; January and July. The maximum power losses and gain occur in Ad Dammam while there is no power gain in Jeddah. Therefore, one can say that Jeddah has the worst effect of the weather conditions compared to the other regions.

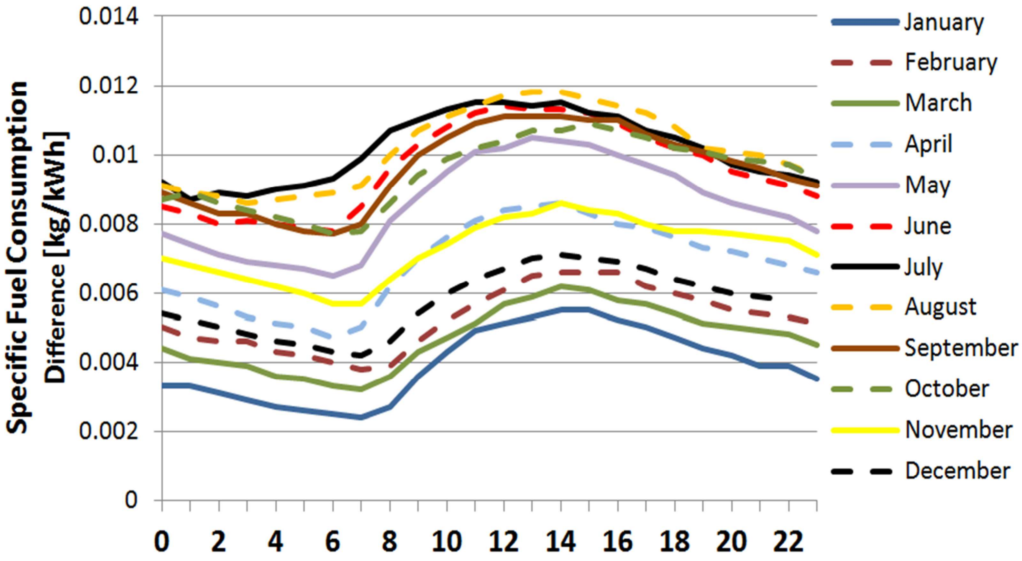


Figure 15. *Effect of ambient conditions on the hourly specific fuel consumption, in Jeddah.*

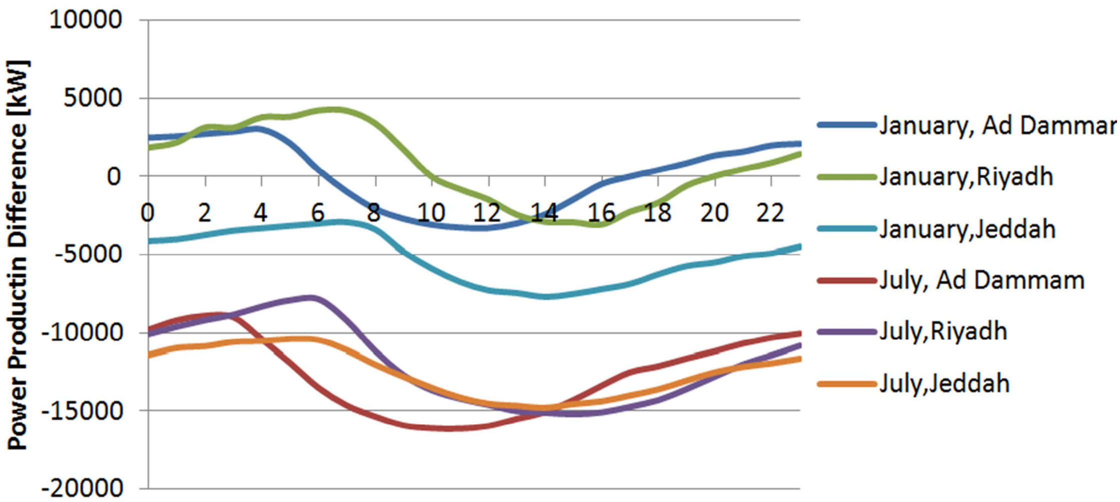


Figure 16. *Comparison of power production rates for Riyadh, Jeddah and Al Dammam for July and January.*

3.4. Comparisons

Figure 17 gives a general picture of the monthly and annual production rates for the three regions compared to the production rates at ISO conditions. In Riyadh, the maximum monthly power losses reaches 8.9 GWh which occurs in July and represents about 14.23% of the ISO production, while the maximum monthly production gain is 0.51GWh in January and represents about 0.81%. In Ad Dammam, the maximum monthly power loss and gain are 9.41 and 0.07 GWh occurring also in July and January, respectively. The maximum monthly power losses in Jeddah is 9.32 GWh which represents about 14.84% of the ISO production in July, and there is no power gain during the year in Jeddah. The annual power production loss in Riyadh, Ad Dammam, and Jeddah is 7.1, 8.2, and 11.2%, respectively. Table 3 compares the weather data in Ad Dammam, Riyadh, and Jeddah while table 4 summarized the main results of this work.

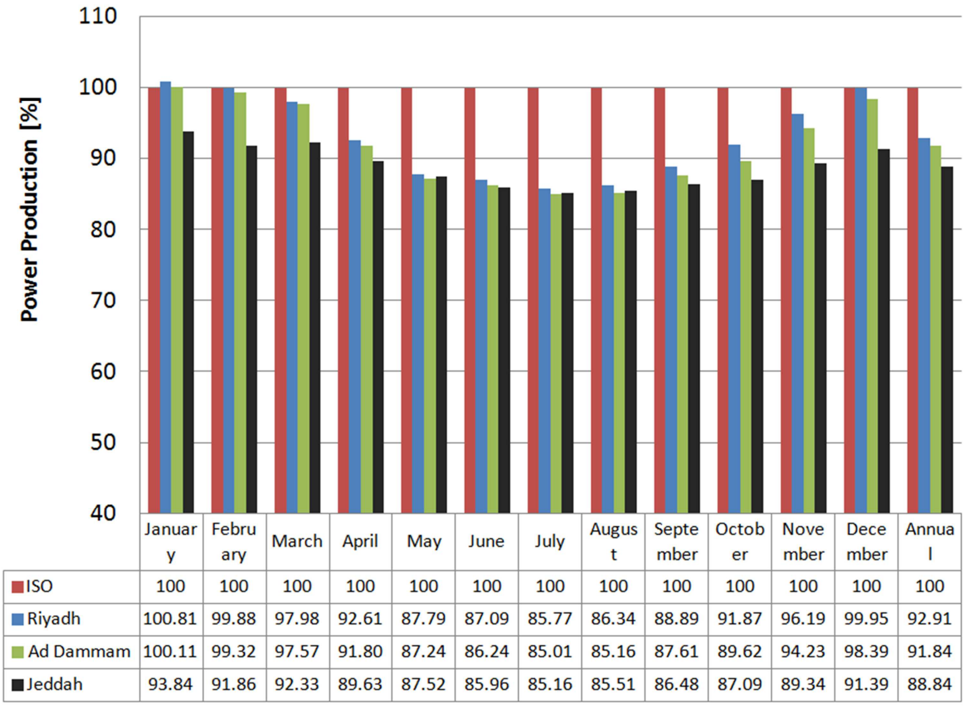


Figure 17. *Monthly and annual power production.*

Table 3. *Weather Data Comparison.*

Descriptions	**Operating Areas**	**Western Ad Dammam**		**Central Riyadh**		**Eastern Jeddah**	
		Month	**Value**	**Month**	**Value**	**Month**	**Value**
Weather Data	Max. temperature [°C]	July	45.19	July	43.87	July	39.47
	Min. temperature [°C]	January	10.15	January	8.9	January	18.9
	Max. relative humidity [%]	January	76.56	December	73.2	October	78.47
	Min. relative humidity [%]	June	7.77	June	6.91	July	29.1

4. Conclusion

The Kingdom of Saudi Arabia is divided into five geographical regions: Eastern, Central, Western, Southern, and Northern. The Eastern, Central, and Western regions almost have the same power demand, while the Connected (Eastern-central) Operating Area has almost double the of peak demand of the Eastern, Central, and Western regions, and the other regions have a lower power demand. Gas turbine power plants produce about 50% of the total capacity in the Kingdom. Their performance is clearly affected by the ambient air temperature and humidity. This study gives a general picture of the weather data variations of three main Saudi cities namely Riyadh, Jeddah and Al Dammam. It analyses systematically the effect of ambient air temperature and humidity on the performance of selected gas turbine units.

Table 4. *Gas turbine performance comparison.*

Descriptions	**Operating Areas**	**Western Ad Dammam**		**Central Riyadh**		**Eastern Jeddah**	
		Month	**Value**	**Month**	**Value**	**Month**	**Value**
Gas turbine performance	Max. production losses [kW]	July	16139	July	15246	July	14781
	Max. production gain [kW]	January	3028	January	4220	0	
	Max. thermal efficiency losses [%]	August	1.5	July	1.33	July	1.65
	Max. thermal efficiency excess [%]	January	0.25	January	0.4	0	
	Max. heat rate additional [kJ/kWh]	August	535	July	470	August	591
	Max. heat rate benefit[kJ/kWh]	January	85	January	135	0	
	Max. SFC additional [kg/kWh]	August	0.0107	July	0.0094	August	0.0118
	Max. SFC benefit[kg/kWh]	January	0.0017	January	0.0027	0	

In Ad Dammam, the maximum temperature is 45.19°C in July, while the minimum temperature and maximum relative humidity are 10.15°C and 76.56%, respectively; occurring in January. The maximum power loss, about 16139 kW occurring in July, represents about 20% of the ISO production and the maximum monthly power losses is in July and reaches 9.41GWh. The maximum annual power losses can be 8.2GWh.

In Riyadh, the maximum and minimum temperatures are 43.87 and 8.9°C, respectively. The maximum power loss is 15246kW which occurs in July and the maximum monthly power losses is 8.9GWh representing about 14.23% of the ISO production, while the annual power production loss is 7.1%.

In Jeddah; the temperature is higher than the ISO temperature while the relative humidity is fluctuated, for all months. The temperature is ranging between 39.47-18.9°C. The maximum power loss is 14781kW; about 17.5% of the ISO production and the maximum monthly power losses in Jeddah is 9.32 GWh which represents about 14.84% of the ISO production, while the annual power production loss is 11.2%. In general, the effect of weather conditions of the considered Saudi areas on the performance of gas turbine units can be significant. This would suggest the incorporation of additional components for inlet air cooling systems.

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Nomenclature

C_p : Specific heat at constant pressure [kJ/kg K]
f: Fuel to air mass ratio [kg_f/kg_a]
FLV : Lower Calorific Value of the fuel [kJ/kg]
h : Specific enthalpy[kJ/kg]
HR : Heat rate [kJ/kWh]
$\dot{m}$: Mass flow rate [kg/s]
N: Number of days in the month
P: Pressure [kPa]
Pr: Power output [kW]
Q_{in}: Heat added at combustion chamber [kW]
r_c: Pressure ratio […]
SFC: Specific fuel consumption [kg/kWh]
T: Temperature [K,°C]
$\dot{V}$: Volume flow rate of moist air [m^3/sec]
W: Work [kW]

Greek Letters

γ: Ratio of the specific heats […]
Δ : Difference, change
η : Efficiency [%]
ρ: Density of moist air [kg/m^3]
ϕ: Relative humidity [%]
ω: Humidity ratio [kg_w/kg_a]

Subscript

1, 2, 3 Number of state
a: Air
an: Annual
c: Compressor
com: Combustion chamber
f: Fuel
g: Flue gases
gen.: Generator
i: Time of the day
m: Month
th: Thermal
tu: Turbine
w: Vapor water, steam

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