Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2024;25(1):86–104

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI: 10.22363/2312-8143-2024-25-1-86-104
UDC 621.91.01
EDN: JDCYOB

Research article / Научная статья

Analysing the Feasibility of Adopting Gas Turbine Technology for Electric Power Generation in Iraq

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Article history

Received: July 15, 2023
Revised: December 4, 2023
Accepted: December 20, 2023

Conflicts of interest

The authors declare that there is no conflict of interest.

Authors' contribution

Undivided co-authorship.

Abstract. A study was undertaken to understand the status of electric power demand, generation and supply in Iraq and the feasibility for adopting gas turbine technology for generating electric power. Based on the climatic and weather data, it was found that Iraq in general experiences a hot and dry climate with cooler nights. Apart from the coastal regions of the country, the relative humidity is generally low. This was found to be an encouraging factor for adopting cost effective evaporative cooling systems for the air entering gas turbine used for power generation (GTPG). The higher frequency dust storms in Iraq can result in operational problems, shorter life span and higher maintenance costs for GTPG, making air filtration mandatory for efficient operation of GTPG. Taking into account the district wise climatic and weather conditions, the district of Nineweh was found to be more suitable for the establishment of gas turbine plant for electric power generation (GTPEG). Among the different cooling systems available taking into to account the cost effectiveness and the simplicity in design, construction, operation and maintenance, it was found that evaporative cooling system was more suitable. Further, it was found that the effectiveness of evaporative cooling system can be enhanced by taking advantage of the low night temperature and cooling the water to be used in the evaporative cooling system. Analysing the performance of the gas turbine, it was found that adopting the cooling system will result in reducing the power loss from 6.68–46.89 % to 2.77 to 21.17 %.

Keywords: gas turbine, cooling systems, Iraq, Nineweh region performance losses

For citation

Alaabidy WHS, Al-Rubaiawi MSS, Chertousov MA, Frolov MY. Analysing the feasibility of adopting gas turbine technology for electric power generation in Iraq. *RUDN Journal of Engineering Research.* 2024;25(1):86–104. http://doi.org/10.22363/2312-8143-2024-25-1-86-104

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Анализ целесообразности внедрения газотурбинной технологии для производства электроэнергии в Ираке

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История статьи

Поступила в редакцию: 15 июля 2023 г.
Доработана: 4 декабря 2023 г.
Принята к публикации: 20 декабря 2023 г.

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов

Нераздельное соавторство.

Аннотация. Проведенное исследование посвящено анализу состояния спроса, выработки и предложения электроэнергии в Ираке и целесообразности внедрения газотурбинной технологии для выработки электроэнергии. На основе климатических и погодных данных было установлено, что в Ираке в целом жаркий и сухой климат с более прохладными ночами. За исключением прибрежных районов страны относительная влажность, как правило, низкая. Это является обнадеживающим фактором для внедрения экономически эффективных систем испарительного охлаждения для воздуха, поступающего в газовую турбину, используемую для выработки электроэнергии (ГТВЭ). Более частые пыльные бури в Ираке могут привести к проблемам в эксплуатации, сокращению срока службы и увеличению затрат на техническое обслуживание ГТВЭ, что делает фильтрацию воздуха обязательной для эффективной работы ГТВЭ. Принимая во внимание климатические и погодные условия района, район Найнив был признан более подходящим для создания газотурбинной установки для выработки электроэнергии. Среди различных доступных систем охлаждения, принимая во внимание экономическую эффективность и простоту проектирования, конструкции, эксплуатации и технического обслуживания, было установлено, что система испарительного охлаждения является наиболее подходящей. Показано, что эффективность системы испарительного охлаждения может быть повышена за счет использования преимуществ низкой ночной температуры и охлаждения воды, которая будет использоваться в системе испарительного охлаждения. При анализе производительности газовой турбины было установлено, что внедрение системы охлаждения приведет к снижению потерь мощности с 6,68–46,89 до 2,77–21,17 %.

Ключевые слова: газовая турбина, охлаждающие системы, Ирак, регион Найнив, потери мощности

Для цитирования

Alaabidy W.H.S., Al-Rubaiawi M.S.S., Chertousov M.A., Frolov M.Y. Analysing the feasibility of adopting gas turbine technology for electric power generation in Iraq // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2024. Т. 25. № 1. С. 86–104. http://doi.org/10.22363/2312-8143-2024-25-1-86-104

Introduction

In this modern era, energy has become a vital component for the development of any human society and with the increasing population its demand is increasing day by day. Among the different energy sources, electrical energy stands as the primary requirement for humans. Taking into account the rate of increasing population for any energy supply systems to have a sustainable impact, it has to be designed taking into account the estimated population by 2050. Energy consumption analysis studies reveal that the energy demand is increasing by 2.9 % every year since 2010 and nearly 73 % of this demand is met from fossil fuel resources (FFR) [1]. Taking into account the environmental effects caused and its limited quantity available, the use of FFR is being reduced slowly by different countries [2]. In spite of all this, fossil fuel based technology (FFBT) cannot be completely ruled out as they are proven sources presently available for effective economic progress of developing economies [3]. This dependence of FFR will continue for many more years to come as making a sudden step back is practically difficult, especially for developing economies. This highlights the importance of researchers on improving the effectiveness of FFBT as researches on finding economic alternatives for FFR. This can bring twin benefits of not retarding the present economic progress of developing economies and at the same time having alternatives to FFR.

The energy sector of the economically developing countries have to tackle two major problems, the ongoing variations in the energy prices and the steadily increasing energy demand [4]. Among the various FFR considered for power generation, natural gas has proved to be more environment friendly, thus in the recent years natural gas fuelled gas turbines (NGGT) are being widely considered instead of steam turbines fuelled by coal and petro-fuel [5]. Using natural gas as fuel instead of coal and petro-fuel will result in huge reductions in CO_2, NO_x, and SO_2 emissions [6]. In fact, using natural gas instead of coal for power generation can result in nearly 50 % reduction of CO_2 leading to reduced environmental effects. In addition to this they are economical and have better thermal efficiencies than the other FFBT [5]. It is estimated that the natural gas demand will be increased by 40 % by 2050 than what was supplied in 2018 [7]. As gas turbines are simple in construction, operation and able to respond quickly to varying load requirements, they are being widely considered and recommended. But it should also be noted that both its thermal efficiency and the quantity of power produced is highly dependent on the ambient environmental conditions [8]. The important factors that affect the performance of GTPG are, the geographical location, inlet air temperature which decides the quantity of work by the compressor, ambient temperature, air density, air pressure, relative humidity and fuel [9–11].

Iraq is geographically divided into western desert region, northern mountainous region and fertile plains in the south and middle region. Iraq is the home for 0.57 % of the global population, with 70 % of its population living in the urban areas and have an annual population growth rate of 2.45 % [12]. Being the 5th largest oil reserve and 13th largest gas reserve, Iraq mainly depends on the energy sector for its development. In general, Iraq has a subtropical semi-arid type of climate, with the day temperature much higher than that of the night, so is the demand for electric power. Thus, for the sustainable development of the country's economy sufficient quantity electric power has to be produced effectively and economically. To achieve this suitable technology has to be adopted such that it is suitable for the conditions prevailing in the area, installed in the most appropriate geographical location such that it can operate with the highest possible efficiency producing power in an economic way and distribute the power with the minimum possible losses. This study analyses the present status of electric power generation and distribution in Iraq, the suitability of GTPG to the climatic and whether conditions prevailing in Iraq, identify the suitable area for establishing the GTPEG, the functional components required by GTPG for effective operation and further conduct a theoretical evaluation on the operating performance of GTPG.

1. Energy status of Iraq

Iraq is facing serious energy shortage and the gap between the demand and supply is increasing drastically since 2003 [14]. The repeated wars in Iraq have destroyed its economy, growth and infrastructure. The country now is facing huge electric power shortages both in production and distribution [15]. Iraq has a production of about 25GW which is 28.6 % less than its actual demand [13], in addition to this the demand is growing every year at the rate of 7 % [16]. It is estimated that Iraq has 8.5 % and 1.8 % of global oil and natural gas reserves respectively, placing the country in the 11th position globally in terms of oil and natural gas reserves. The southern region if the country holds about 71 % of the total FFR [7]. The country's economy and its electrical power generation sector mainly depends on these FFR. Despite sufficient fuel resource, Iraq imports power from Iran and Turkey at higher cost and supplies to its population at subsidised rates [14] due to inadequate generation capacity and huge losses in the distribution network. This is further adding economic burden on the country's economy which is trying to improve.

With aim of providing continuous power supply to its people, Integrated National Energy Strategy (INES) was launched by Iraq in 2013. The INES aimed to produce 40 % additional power by 2015 but was successful in achieving only 50 % of its estimated goal [18]. As the country was making steady progress, the invasion of Islamic State of Iraq and Syria (ISIS) during the period between 2014-18 caused huge damage to the power plants and destroyed the electricity supply lines. The total damage to the power sector caused by the ISIS invasion was estimated to be $ 7 billion [19]. In 2019, as the result of the fast-track programme by the ministry of electricity witnessed a 20 % increase in generation. During the same year a $ 16.3 billion project was set to upgrade 40 gas turbine plants and construct new power plants with an aim to add 1.6 GW to the existing production. In spite of all these the progress is slow and Iraq still remains as a country having the lowest electricity generation per capita in the Middle East [18] and is finding hard to meet the electric power requirements of its population. The government is making huge investments in this sector so as to meet the peoples demand. To make electricity affordable to the public, government is forced to supply it at subsidised rates. This in turn is putting huge economic burden on country and along with this the demand-supply gap is increasing every year [20].

2. Suitability of GTPG in Iraq

Electricity generation plants using gas turbines are considered to be more suitable for Iraq among the fossil fuel based technologies [21] as Iraq can effectively use the advantage of having about 81 % of its natural gas reserve as associated gas [7] and have lower water requirements that the other FFBT [14]. Using natural gas form associated sources which is usually burnt as flare [22] results in much lesser tapping cost [23], making power generation more economical. It is estimated that by using the associated gas for electricity generation instead of burning as flares can save about fifty million tonnes of CO_2 annually, thus benefiting the environment too [22]. Taking these facts into consideration Iraq is already trying to mainly depend on GTPG for power generation. In fact, 61 % to the total power production of the country is obtained from its 28 gas turbine power stations [16] but the matter of concern is that they are having lower production efficiency [24].

Among the climatic factors, ambient temperature affects the performance of GTPG the most [25]. The GTPG is designed such that they provide the best performance when operated in ISO conditions (typical thermal efficiency of GTPG when operated in ISO conditions is 30 %) and for every degree rise in the inlet air temperature above the ISO condition, there will be approximately a reduction of 0.64 % in the total power output [10] and 0.18 % in thermal efficiency [26]. Thus, in hot climatic regions like Iraq both the quantity of power produced and the production efficiency of GTPG will be highly affected, leading to increased production cost and pollution produced per kW of electric power generated [27]. In addition to the ambient temperature, GTPG operating in the Iraq will face problems related to higher filtration requirements for the air entering the GTPG due to the general dusty environment prevailing in the region [28]. Improper air filtration can affect the life, performance and frequent higher maintenance requirements for the GTPG. Relative humidity is the next important parameter that affects the performance of performance of GTPG. The thermodynamic property of the working medium (air-water vapour mixture) varies with the change in relative humidity, which in turn will affect the engine performance [29]. The relative humidity play a major role in accurately estimating the performance of GTPG when the ambient temperature is greater than 30 °C and relative humidity is above 70 % [30].

2.1. Climatic and geographical factors of Iraq hat influence the operational performance GTPG and the region suitable for the establishment of power plant

Among the countries of the Arab region, Iraq is the most vulnerable and experiences extreme weather events [31]. Though geographically located in the northern temperate zone, the country experiences continental and subtropical climate. Scarcity of sufficient and reliable metrological data from Iraq forms an hinderance while analysing the climatic conditions. It's clear from Figure 1 that 94.4 % of Iraq is experiencing arid to semi-arid climate and is considered as one among the fastest warming countries of the world [32]. Broadly Iraq can be classified into four climatic zones as (i) Mediterranean climatic zone: comprising of the mountainous region spread along the north and the north-east region occupying 21 % of the total land area, (ii) steppe climatic zone: occupying the 9.6 % of the area comprising of the undulating lands of the southern and western region, lies between the mediterranean and the desert zones having cold winter and very hot summer and receives about 200–400 mm of rainfall during winter season (ii) Desert zone: located in the western region of the country and occupies the largest share of land (39.2 %) and the (IV) semi-arid zone: occupying 30.2 % of the land area and is spread along the central and the southern region. It was clear that Iraq in general experiences a hot and dry climate apart from the cool and wet winter season starting from November to March with the rains extending up to April. During the winter the average day temperature reach about 16 °C and will go as low as 2 °C in the night. During the summer the day temperature can go over 43 °C, but the nights are usually cool with a temperature about 26 °C [33]. In general the country have more hotter days in a year, resulting in high ambient temperatures during the day time and much lower temperatures during the night time [34].

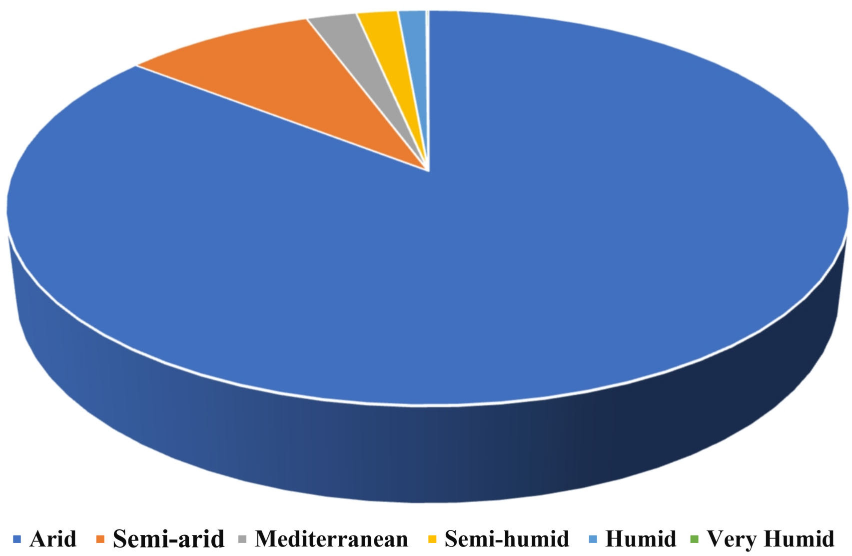

Figure 1. Area classification of Iraq based on aridity index [85]

To understand the climatic conditions of the different regions in Iraq, the climatological data from the year 1991 to 2020 obtained from the Climate Change Knowledge Portal of the World Bank Group [35] was analysed. The climatological analysis was done with the aim to find the most suitable region for the establishment of power plant in Iraq. Considering the month wise average maximum and minimum temperatures from the period between 1991–2020 (Figure 2), it was found that day temperatures from March to November were above 30 °C with the months April to October having an average above 40 °C. In fact the highest temperature (54 °C) of the Eastern Hemisphere was recorded in Iraq on 22nd July 2016 [36]. During the night the temperatures are too low with only the months June to August had temperatures above the optimum working temperatures of GTPG. Relative humidity also plays a major role in cooling air while using evaporative cooling systems. The extent of cooling depends on the relative humidity, under same temperature air having lower humidity will be cooled more than air with higher humidity. It was observed by Barakat et al. [8] that the temperature drop decreased by 22.8 % when the relative humidity changed from 20 to 80 %. Moreover, higher humidity results in increased heat consumption in the combustion chamber of GTPG. This is due to the high specific heat of water. The lower relative humidity (Figure 3) during the hotter months and higher humidity in the cooler months serves as a beneficial factor for the operation of GTPG. This helps in employing the cost-effective evaporative cooling system effectively [9; 37].

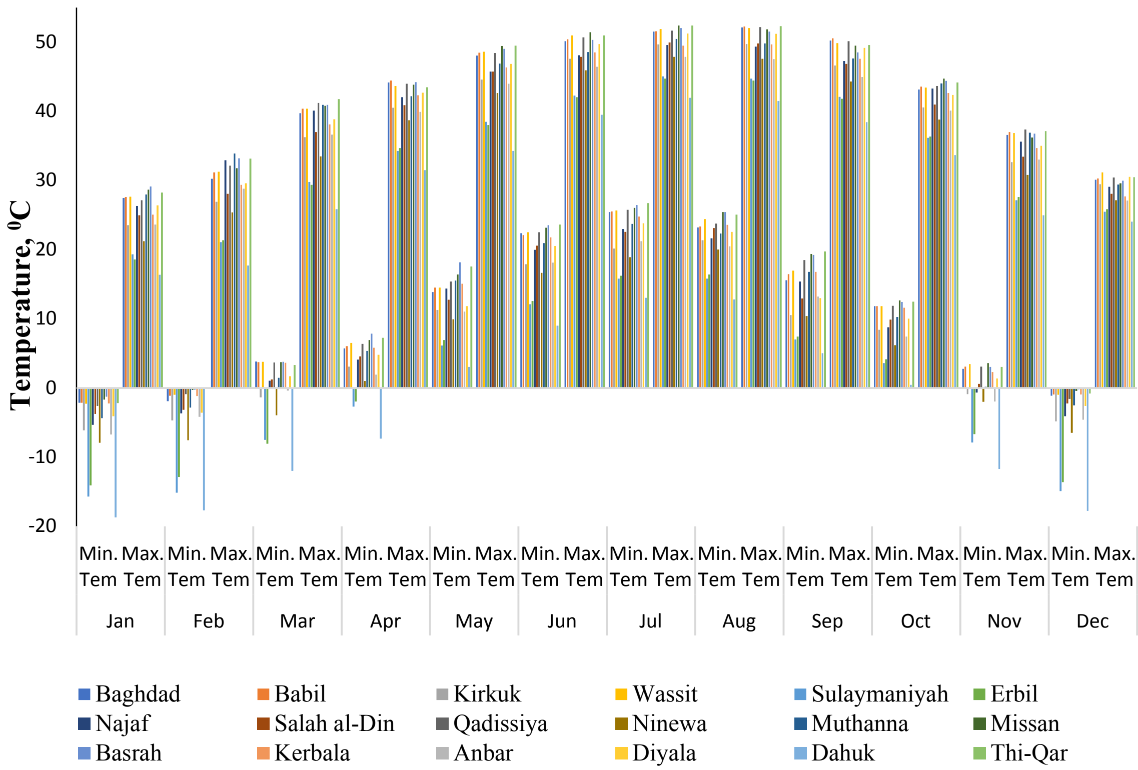

Figure 2. Monthly average maximum and minimum temperatures of different regions of Iraq [35]

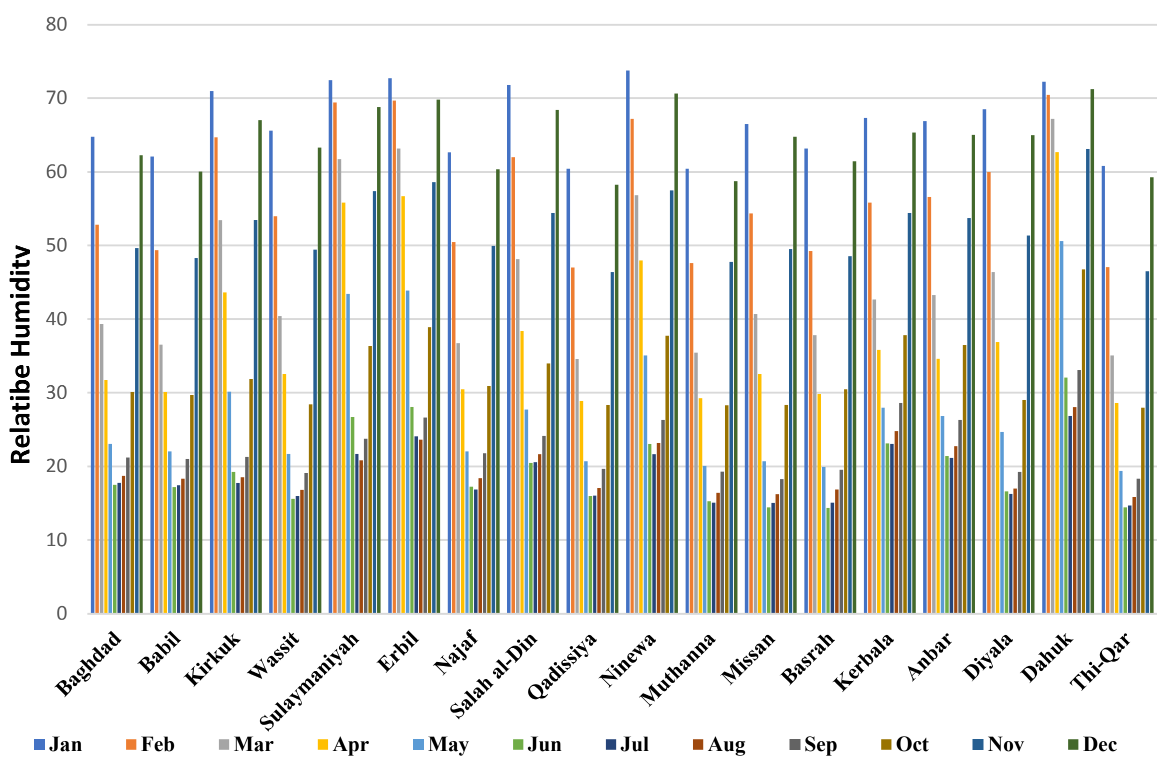

Figure 3. Monthly average relative humidity of different regions of Iraq [35]

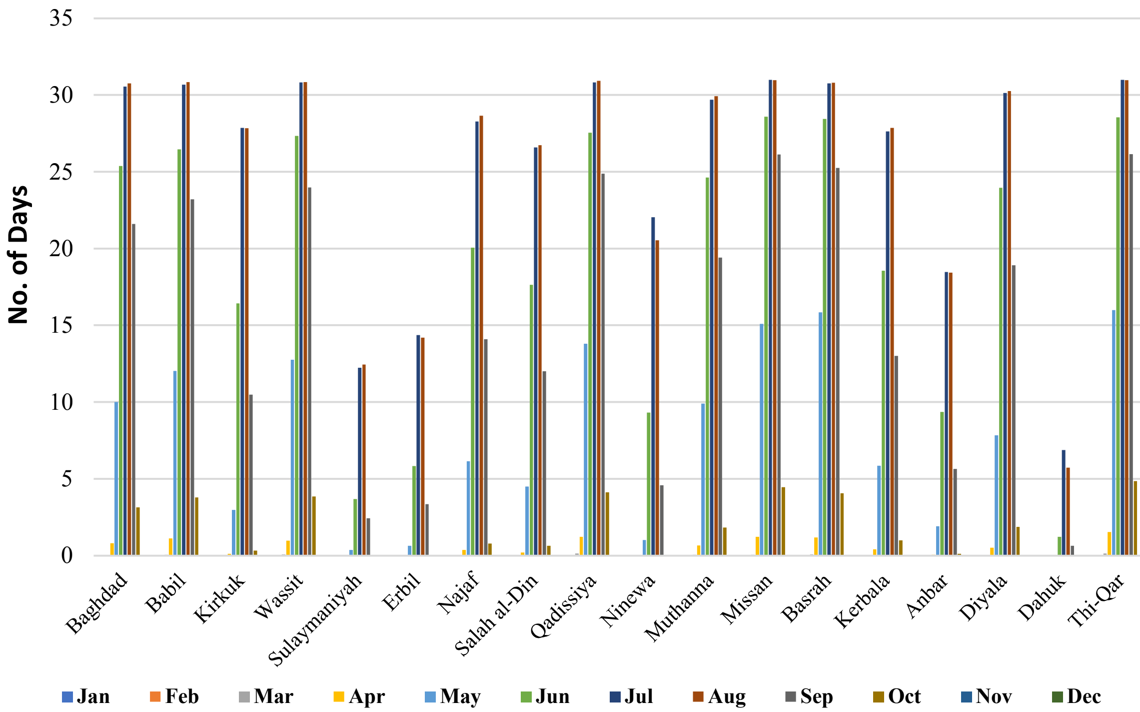

Figure 4. Number of days having day temperature above 40 °C (monthly average) on different regions of Iraq [35]

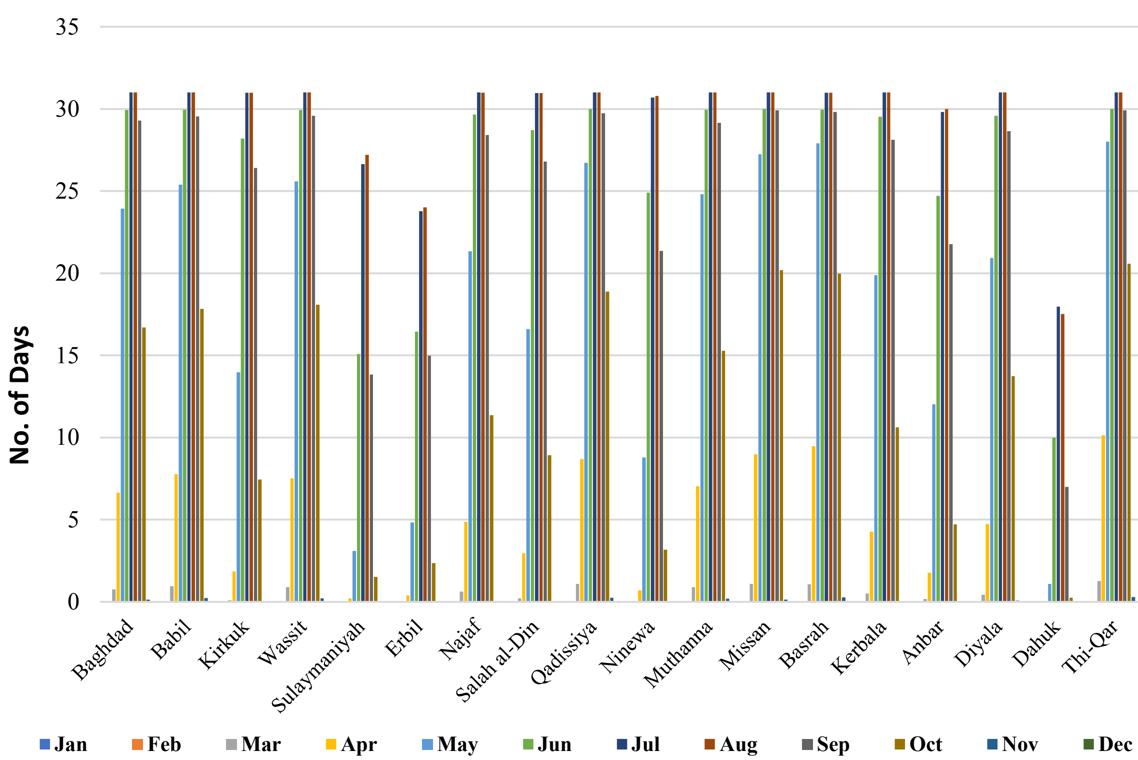

Figure 5. Number of days having day temperature above 35 °C (monthly average) on different regions of Iraq [35]

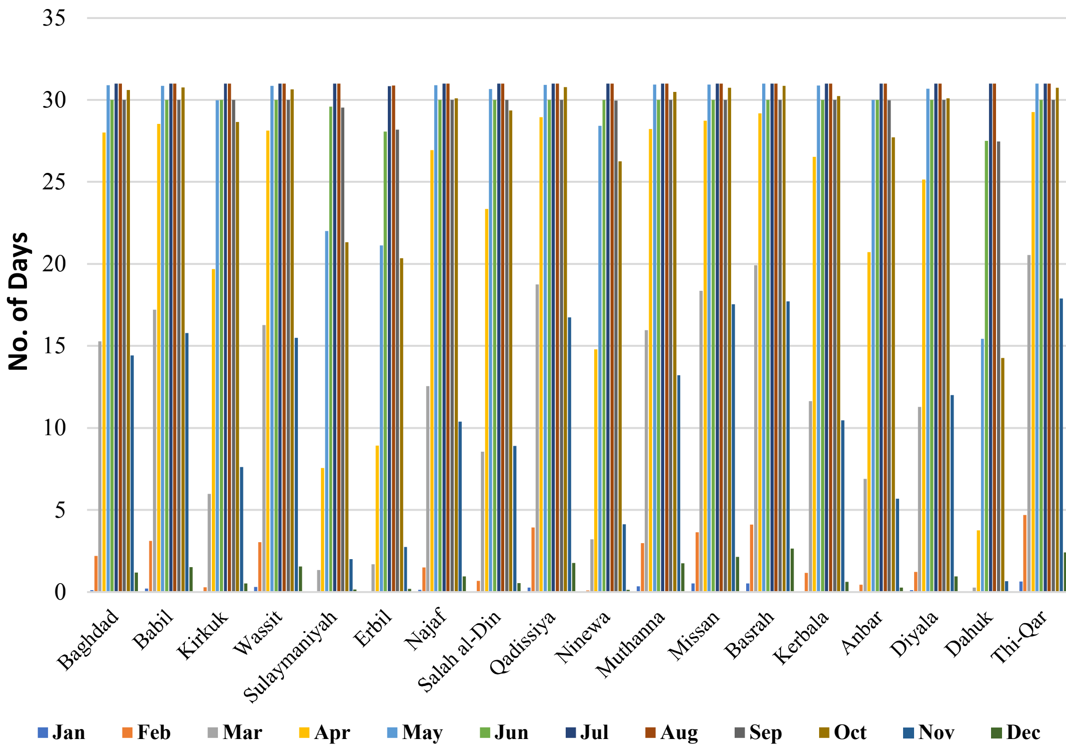

Figure 6. Number of days having day temperature above 25 °C (monthly average) on different regions of Iraq [35]

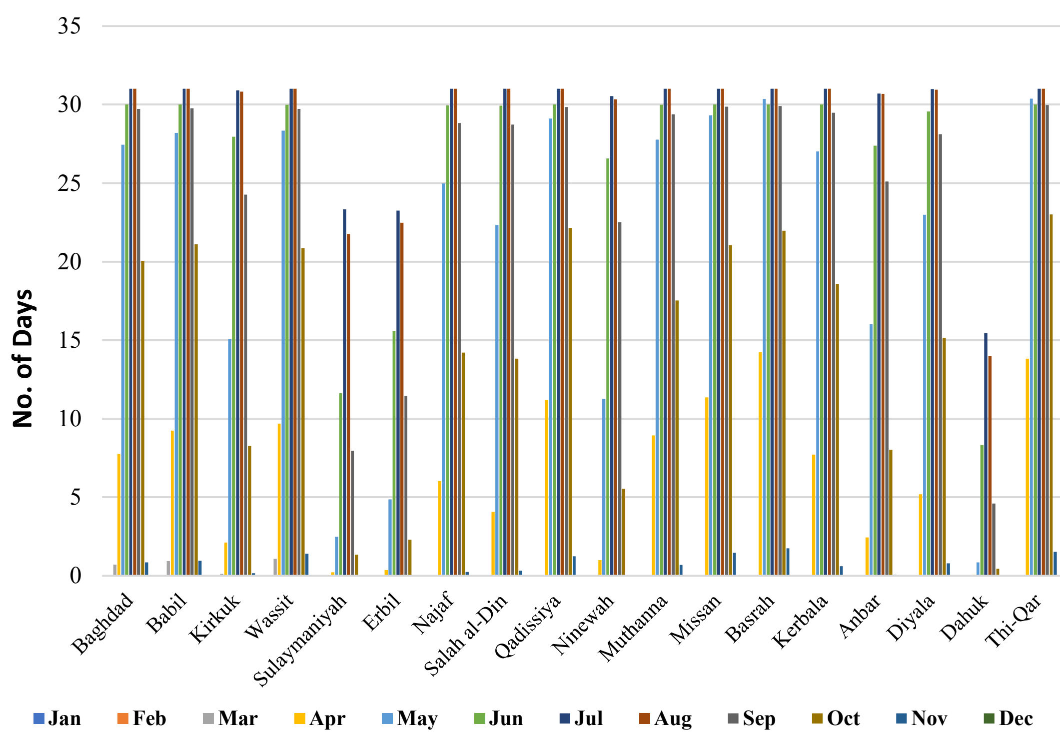

Figure 7. Number of days having night temperature above 20 °C (monthly average) on different regions of Iraq [35]

Considering the different districts on all climatic parameters considered, Dahuk had the most preferable conditions for the operation of GTPG followed by Erbil, Sulaymaniyah and Nineweh. But Dahuk, Erbil and Sulaymaniyah being mountainous regions will have lower air density affecting the mass flow rate of air and lower oxygen concentrations, thereby affecting performance of GTPG [38]. The number of days (month wise for each district of Iraq) during which the temperature is above 40 °C (Figure 4), 35 °C (Figure 5) and 25 °C (Figure 6) during day and 20 °C (Figure 7) during night is also an important factor to be considered. It was found that the district of Nineweh on average during the day time had 57.46 days above 40 °C, 120.41 days above 35 °C and 198.91 days above 25 °C and 127.75 days above 20 °C during night. This indicates that cooling load requirement is lesser for about 165 days in a year, adding better economic advantage than being placed in the desert regions of the country. In addition, the lower relative humidity of Nineweh helps in effectively adopting evaporative cooling system [39].

In addition to the climatological parameters the frequent dust storms in Iraq affects the performance and life of GTPG, imposing higher filtration requirements for the air entering the GTPG [28]. On an average about 38 dust storms happen in a year [40], most of them originating from the deserts of Iran, Iraq and Arabian Peninsula. The dust storms happen more frequently during the summer with few taking place during the winter season. It was found by Mohammadpour et al. [41] that between 2003–2012 there were 155 dust storm events with majority of them occurring during the months of April and May. The majority of the dust particles have diameter in the range 0.1–10 μm and requiring a minimum time of 14 hours to settle [42]. The dust storms carry small light weight particles of silt, clay and sand, the quantity and extent of dust load depends on the strength of the causing wind and shape, size and density of the particles. Studies have found that dust particles in a dust storm can be vertically lifted to a height of 6 km and carried horizontally to a distance up to 6000 km [43], not allowing even the mountainous region escaping from it. In Iraq majority of the dust storms takes place in the lower Mesopotamian plains. The Nineveh district is located in the north-western region of Iraq and is highly prone to dust storms [39] making air filtration requirements very essential of the GTPG located in the region.

3. Functional component requirements of GTPG for effective operation in Nineveh district of Iraq

The district of Nineveh selected for the establishment of gas turbine plant for power generation generally experiences a long hot and dry spell and short wet and cool spell (December–February) [44]. Thus, taking into consideration the geographic feature of Nineveh district and the prevailing weather conditions, the requirements of GTPG for effective operation is described in Figure 8. GTPG being constant-volume engines, their shaft power is proportional to the mass flow rate of air. As the temperature of the inlet air increases, its density decreases resulting in reduced mass flow rate and thereby increasing the work of the compressor. Reducing the temperature of the inlet air increases its density at constant pressure, increasing the mass flow rate and thereby the output power. Increase in inlet air temperatures above 15 °C results in the reduction of both thermal efficiency and power output [45]. It was found by Zeitoun [46] that a GTPG delivering 84.4 MW power at 15 °C dropped down to 69 MW at 45 °C. Further El-Shazly et al. [45] observed that by reducing the inlet air temperature by 10 °C from 40 °C can result in output power enhancement of 10 %. In addition to power and thermal efficiency enhancement, GTPG operating with lower intel temperature result in better heat rate and enhanced turbine life. Studies have shown that for every °C rise in temperature above 15 °C, the GTPG power output reduces by 0.77 %, thermal efficiency by 0.1 % and the air mass flow rate by 0.36 % [47]. This highlights the importance of cooling the inlet air when the GTPG is operating in conditions having high ambient temperature. Thus, for better performance of the GTPG, the temperature of the inlet air has to be 15 °C or brought down as close as possible. It was clear from the climatological and whether data of Nineveh that for better GTPG performance, inlet air cooling and air filtration systems are unavoidable components. The proper selection of the appropriate cooling system and the air cleaning system decides the operating and economic effectiveness of the GTPG.

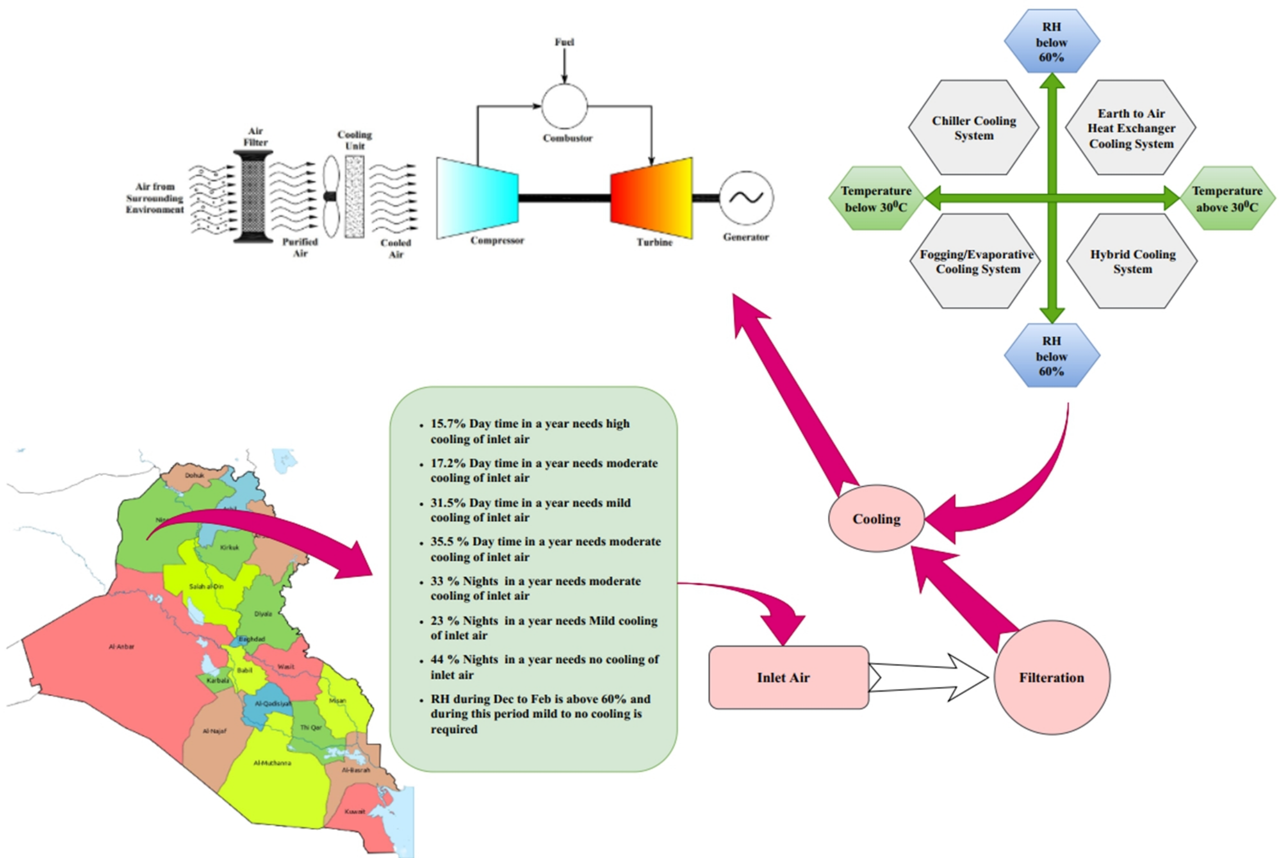

Figure 8. Pictographically representation of the GTPG requirements for effective operation in the Nineveh district Iraq
Source: made by the authors

3.1. Air cooling systems proven effective in GTPG

The different inlet air cooling systems used in GTPG can be broadly classified as systems lower temperature only and systems lowering the temperature along with increase in humidity of the incoming air. The systems that only cool the incoming air are absorption chiller cooling systems that cools the incoming air using heat exchangers [48], mechanical refrigerate cooling systems [37] and cooling systems using thermal storage options. While those increase the humidity of air along with cooling the air are systems that cools the air by absorbing the latent heat of evaporation commonly called as evaporative cooling systems [49] and using high pressure fogging system [50]. Each system has its own advantages and disadvantages [8] and a particular system has to be selected taking into consideration the economics, technical requirements and the extend of its suitability in handling the ambient conditions prevailing in the area.

Both high pressure fogging and cooling using media (evaporative cooling systems) are considered as better options for GTPG operating in hot and dry conditions [51]. Here cooling of air is achieved by the thermodynamic process called adiabatic saturation, in which thermal energy of the air is consumed by the water causing it to evaporate and the temperature of the inlet air is dropped to a value very close to the wet bulb temperature. Thus, wet-bulb depression is a deciding factor on the extend of temperature reduction and thereby the performance of the GTPG [52]. According to studies, the effectiveness of evaporative cooling method using media range between 0.85–0.9 while high pressure fogging system range between 0.97–1 [53]. Moreover its simplicity in design, easy to install, operate and above all cost effectiveness make the evaporative cooling method, cooling using high pressure fogging system being widely practiced [54]. The effectiveness of the fogging system can be enhanced by using cold water and reducing the spray droplet size (30–50 μm is considered as ideal droplet size) [56].

Inlet air cooling using mechanical compression and absorption cooling systems are usually considered as a second option next to evaporative cooling systems as they bring about change in only temperature of the incoming air. As they do not add moisture to the intake air, so the associated negative effects such as erosion, corrosion etc., on different parts of the turbine is avoided [58]. Both the systems are capable of producing better cooling effect than evaporative cooling systems, but are associated with parasitic losses in terms of more electricity consumptions for their operation [59], making it not that favourable option to be considered for Iraq now. Studies indicate that both mechanical compression and absorption cooling systems have a coefficient of performance above 6.0 [60]. In the study conducted by Santos and Andrade [57] it was found that absorption chillers are better than mechanical compression systems in providing higher energy increments at lower cost, but still costlier than evaporative cooling system. Absorption chillers are capable of reducing the temperature of the incoming air by 16.7 to 26.7 % more than evaporative cooling systems, increase the power output by 15 to 20 % and the thermal efficiency by 1–2 % [61] and decrease the electricity production cost by 2.97–5.04 % [27] regardless to the prevailing ambient conditions. Though the power output produced is 40 to 55 % more than that of high pressure fogging system [61], but the system is more complex and consumes more energy than cooling system using high pressure fogging system. Thus, making the operating cost much higher than the evaporative cooling systems [62]. In fact the payback period of evaporative cooling system is just 41.1 % of that of absorption chiller system [63].

In systems adopting stored thermal energy to cool the incoming air to the compressor, cooling is based on requirement [64]. The storage system is either sensible or latent heat type, with the latent type changing its phase while rejecting the stored energy to the incoming air. The latent type of system can store more energy than the sensible system [65]. The commonly used sensible thermal energy storage medium is water and ice as latent thermal energy storage medium, in addition glycol chiller and encapsulated phase change materials are also being widely used [66]. In the study conducted by Sanaye et al. [65] it was found that using the thermal energy stored in the ice was effective in increasing the power output by 3.9–25.7 %, the thermal efficiency by 2.1–5.2 %, but the payback period increased from 4 to 7.7 years. The increase payback period is due to the increased installation cost of the system.

Relative humidity is often considered by researchers that it does not affect the performance of GTPG significantly, but the thermodynamic property of the working medium (air-water vapour mixture) changes with the change in relative humidity, which in turn affect the engine performance [29]. Alasfour et al. [67] in their study found that both temperature and relative humidity are important parameters while determining the exergetic performance of GTPG. The relative humidity play a major role in accurately estimating the performance of GTPG when the ambient temperature is greater than 30 °C and relative humidity is above 70 % [30]. Especially while calculating the excess air requirement for the GTPG. Lugo-Leyte et al. [68] found that neglecting relative humidity can result in estimating excess air requirement over 5 % of what is actually required. An efficiency reduction of 6.28 % was observed in the study conducted by AL-Salman et al. [52] when the realative humidity of air was increased fron 10 to 60 % at constant ambient temperature. In addition to this relative humidity of air is an important parameter that decides the reduction in temperature of the air while using evaporative cooling systems. It was observed by Barakat et al. [8] that the temperature drop decreased by 22.8 % when the relative humidity changed from 20 to 80 %. Moreover, higher humidity results in increased heat consumption in the combustion chamber of GTPG. This is due to the high specific heat of water.

Results of the studies sited above indicate that evaporative cooling systems (both media and fog) are more suitable and economically effective solutions for hot and dry areas than the expensive absorption and vapour compression chiller methods [69]. As in the evaporative cooling system, sensible heat of the air is exchanged for the latent heat of evaporation from water is adiabatic, can result in enhancing the GTPG power output by about 12 %

in regions having a hot and dry climate [70]. This makes the adoption of evaporative cooling system as the most cost-effective method to enhance the power output of GTPG in regions like Iraq having a hot-dry desert type of climate. Based on these results of the various studies conducted on evaporative cooling systems, it could be concluded that adopting high pressure fogging system is a better method to increase the power output of gas turbines in region of Nineveh as area is characterised with higher ambient temperature and lower relative humidity. The basic disadvantage of this system is that it consumes huge amount of water and can be a problem in places having water availability problems. This will not be a major concern due to the presence of Khosr and Tigris rivers. Though the evaporative cooling system using media consumes about 10.15 % lower water than that of high pressure fogging system [61], the pressure drop while the air passes through the media and the need for regular media replacements results in increased operating cost of the system [69].

3.2. Air filtration systems for GTPG

The mass flow rate and quality of air is an important factor that decides the performance, useful life and maintenance requirements of GTPG. Iraq as a whole and Nineveh in particular have very poor air quality. Thus, the air entering the GTPG should be properly filtered and at the same time the filtration system should not negatively affect the mass flow rate of air. While selecting filter, air resistance and pressure drop induced, dust holding capacity and efficiency of filtration has to be taken into consideration [71]. Taking the results of Parolari et al. [42] into consideration, the filter selected should be able to filter out particles having diameters of 0.1 μm, but as per Schroth and Cagna [72] filters used for GTPG should be able to filter out particles sizes in the range of 0.01 μm to 3 mm. In addition, poor air quality can result in filters getting loaded fast, requiring frequent cleaning. Thus, to avoid frequent stopping of the GTPG for cleaning the filters, self-cleaning filters are more suitable. This saves a considerable cost of labour required for cleaning when compared to the non-self-cleaning type of filters [73]. More over due to the complex and harsh conditions prevailing in the desert type climate, often the filters used don't get in actual the useful life prescribed by the manufacturer [74]. Thus, for efficient operation and longer life of the GTPG, filtration of the incoming air is very essential and filter has to be selected by properly evaluating the information provided by the filter manufacturer, the prevailing operating conditions and taking into account the investment and maintenance cost required [75].

4. Case study: Performance analysis of a 25 MW GTPG operating in Nineveh region

The performance of a 25 MW GTPG proposed by Lebele-Alawa and Le-ol [76] was theoretical was theoretically analysed based on the climatic data for the Nineveh district of Iraq reported by the Climate Change Knowledge Portal [35] and The Global Historical Weather and Climate Data [77]. The Performance of the GTPG was compared both with and without cooling the inlet air to the compressor month wise for the maximum and minimum temperatures. It was assumed that the air into the compressor was cooled using evaporative (high pressure fogging) cooling system. The technical specifications and operating data at ISO condition of the GTPG as detailed in Table 1.

Table 1

Technical specification of the GTPG considered for the study

Parameter	Value	
Pressure of air interring the compressor	101.3	kPa
Pressure of air leaving the compressor	1000	kPa
Mass flow rate of air	122.9	kgs^{-1}
Turbine inlet temperature	1232	K
Isentropic efficiency of compressor	85	%
Isentropic efficiency of turbine	86.8	%
Combustion efficiency	99	%
Combustion chamber pressure loss	1.17	%
Thermal efficiency	26.6	%
Fuel	Natural Gas	
Calorific value of fuel used	48235.6	kJ/kg

4.1. Thermodynamic Model of a single shaft simple GTPG

While analysing the performance of the selected GTPG the following assumptions were taken into consideration:

a) It was assumed that the air is entering into the cooling unit was at ambient temperature.

b) The ambient pressure (P_a = 101.3 kPa) and it was assumed that the pressure of the air leaving the cooling system was same as the ambient pressure ($P_a = P_i$) [57].

c) The cooling process was adiabatic with no water loss while being injected and had an effectiveness of 90 %.

d) In the fogging chamber all the fog droplets were evaporated and the air from the fog chamber inters the compressor unit in saturated condition [78].

e) The air and the products of combustion behaves like ideal gases.

The equations used for calculating the performance of the selected GTPG was as follows.

Temperature of the air coming out of the cooling unit [78].

$$t_o = t_i - (t_i - t_{wb})\eta_c. \tag{1}$$

The cooling load of the cooling unit [57].

$$q_{cl} = m_{\text{air}}\, C_{\text{dap}}\,(t_i - t_o). \tag{2}$$

Pressure of the air while leaving the compressor [57].

$$P_1 = rP_i. \tag{3}$$

Considering the polytropic relations for gas ideal and isentropic efficiency of compressor, the temperature of air coming out of the compressor (t_1) was be obtained by [57]:

$$t_1 = \frac{t_o}{\eta_{\text{comp}}}\left[\left(\frac{P_1}{P_i}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + t_o. \tag{4}$$

By applying the first law of thermodynamics, the work done by the compressor was calculated [57]:

$$W_{\text{comp}} = m_{\text{air}}\, C_{\text{dap}}\,(t_1 - t_o). \tag{5}$$

The discharge pressure from the combustion chamber was calculated based on the pre-defined combustor pressure drop (P_{cpd}) [57]:

$$P_2 = P_1 - P_{\text{cpd}}. \tag{6}$$

Using energy balance in the combustion chamber, the heat delivered by combustion chamber was calculated as follows [57]:

$$q_{in} = C_{\text{flue gas}}\,(t_2 - t_1). \tag{7}$$

The mass flow rate of the natural gas used for combustion by the gas turbine was calculated based on the calorific value of the fuel gas used [57]:

$$m_f = \frac{q_{in}/CV_f}{\eta_{\text{compustor}}}. \tag{8}$$

The turbine discharge temperature was calculated as follows [57]:

$$t_3 = t_2 - \eta_t t_1\left[1 - \left(\frac{1}{P_2/P_a}\right)^{\frac{\gamma-1}{\gamma}}\right]. \tag{9}$$

The turbine power was calculated using the following equation [57].

$$W_t = m_t\, C_{f\text{lue gas}}\,(t_2 - t_3), \tag{10}$$

where

$$m_t = m_{\text{air}} + m_f \tag{11}$$

net power obtained from the gas turbine is given by [57]:

$$W_{net} = W_t - W_{\text{comp}}. \tag{12}$$

The specific fuel consumption was determined by [57]:

$$T_{sfc} = \frac{3600\, m_f}{W_{net}}. \tag{13}$$

The thermal efficiency of the gas turbine was determined by the following equation [57]:

$$\eta_{TH} = \frac{W_{net}}{m_f CV_f}. \tag{14}$$

4.2. Results

i Cooling effect. The comparison of monthly average maximum, minimum and wet bulb temperature, relative humidity and the temperature of air after cooling using evaporative cooling system is portrayed in Figure 9. It was evident from the generally the night temperatures are below the ISO rating expect during the months of June, July and August (respectively 10.9, 26 and 33.2 % above the ISO rating). While taking the day temperatures into consideration, cooling the inlet air is essential throughout the year and using evaporative cooling system ISO rating temperature of inlet air cannot be attained, indicating unavoidable power loss. The GTPG has to be operated with an air inlet temperature in the range between 18.19 to 30.97 °C during the day time. Thus, based on the finding of

Al-Ansary et al. [10] operating GTPG will be associated with a power output loss in the range between 4.8–9.6 % with the normal evaporative cooling system in use.

The temperature drops were calculated assuming the effectiveness of cooling system as 90 %, while Barakat et al. [8] reported 5 % higher and Hamedani et al. [79] 10 % lesser effectiveness than what was assumed in the present study. The finding of the present study, that evaporative cooling system while operating in high temperature conditions not able to lower the temperature below wet bulb temperature and thus unable to attain the ISO rated temperature was supported by the findings of Marzouk and Hanafi [21] in a study conducted in south-eastern Egypt, Zeitoun [46] in Riyadh, Sh. Alnasur and Al-Furaiji [24] in Baghdad and Dinc et al. [80] in Kuwait. Further as per the findings of Chaker et al. [55] that cooling using evaporative method can be attained below the wet bulb temperature range by using cold water can be effectively and economically implemented in the Nineveh district of Iraq as the night temperature is very low. The water used for the evaporative cooling can be cooled using the low night temperature, stored in thermal insulation and used for fogging as per the requirement. This will help to bring down the inlet air temperature close to the ISO rating.

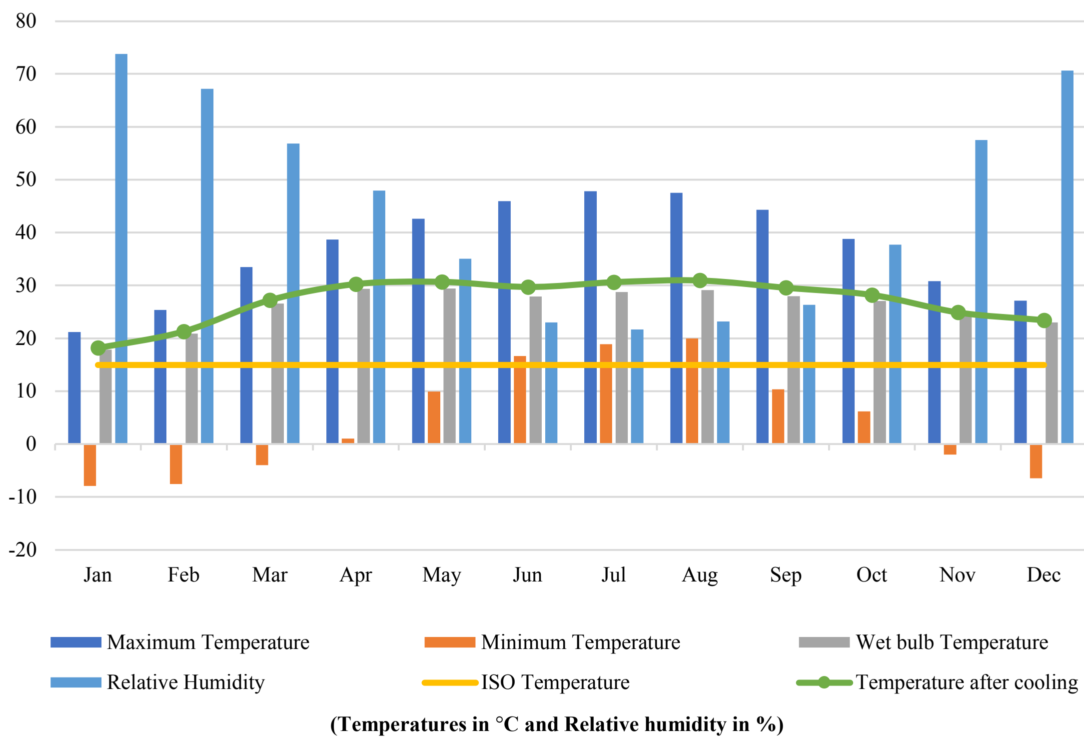

Figure 9. Comparison of monthly average temperatures (maximum, minimum and wet bulb), relative humidity and temperature of inlet air after cooling using evaporative cooling system [35]

ii Performance of GTPG. It was assumed that GTPG will be able to deliver its full capacity during the night time as the night temperatures of the Nineveh district of Iraq apart from the months of June, July and August are below the ISO rating (Figure 9). In addition, even during these three months the temperature are not that high, so it was assumed that the temperature of the air into the compressor could be cooled to the ISO rating. Thus, the performance of the GTPG was evaluated taking into consideration the day temperatures only and results are portrayed in Figure 10.

Taking into consideration the month wise performance, it was found that the power loss in the GTPG without cooling ranged between 6.68 to 46.89 % and with cooling a power loss was reduced to 2.77 to 21.17 %. As expected, the maximum power loss without cooling the air into the compressor

(38.5–46.89%) was observed during the months between May to September, out of which the months June-August had losses ranging between 43.19–46.89 %. It was also observed that the peak losses could be reduced by about 50% by adopting evaporative cooling and could be further enhanced if used colder water. It was also observed that as the temperature increased, there is a considerable decrease in thermal efficiency and increase in the specific fuel consumption. It was also found that cooling the inlet air temperature bought great improvements on both thermal efficiency and specific fuel consumption.

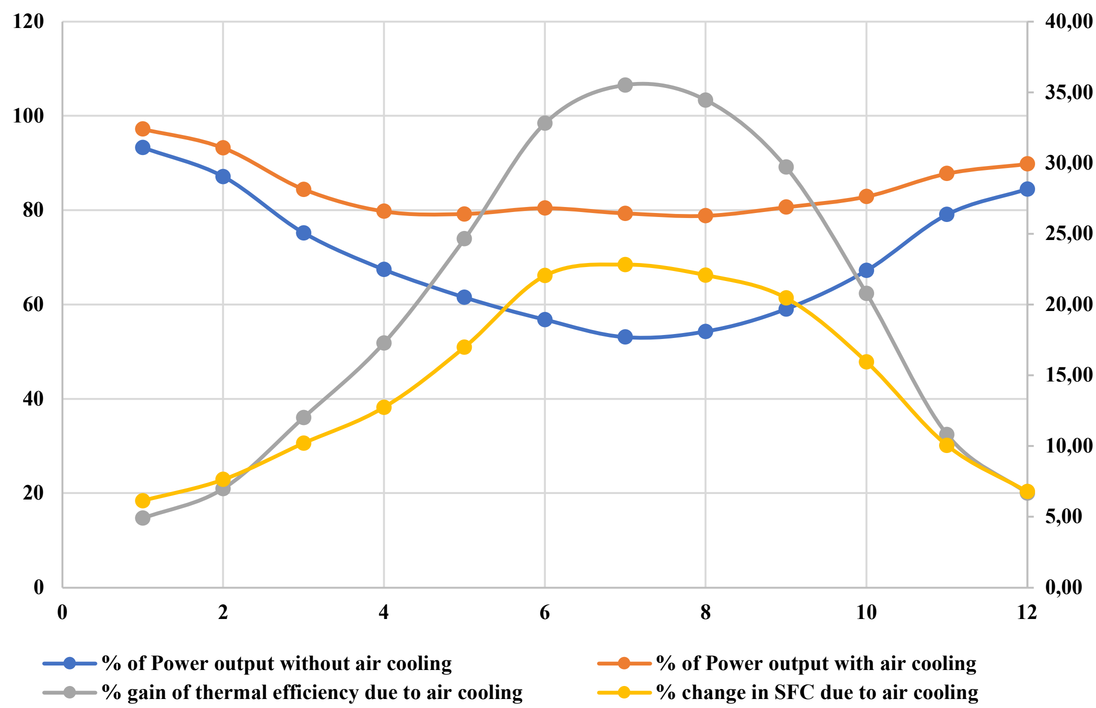

Figure 10. Effect of cooling inlet air on GTPG performance
S o u r c e: made by the author Wissam Huzam Salman Alaabidy

While operating GTPG in hot climatic conditions Punwani [81] experienced 30 % reduction in output power and 5 % in thermal efficiency. Karakas et al. [83] reported that there will be 10 % reduction in output power for every 10 °C increase ambient temperature. Chacartegui et al. [82] experienced 7 % output power reduction while operating the GTPG at 25 °C, which further increased to 15 % when the temperature increased to 36 °C. Hamedani et al. [79] experienced 12.5 % reduction in power output and 2 % reduction in thermal efficiency and Marzouk and Hanafi [21] experienced 20 % reduction in power output and 2 % reduction in thermal efficiency while operating their respective GTPG at 40 °C. While the study conducted by Dinc et al. [80] resulted in reduction of power output by 21.3 %, thermal efficiency by 3.6 % and increased SFC by 9.31 % while operating the GTPG at 55 °C. The results of these studies supports the power reduction outcomes of the present study. With regard to the improvements in power output as the result of cooling the incoming air, Oyedepo and Kilanko [84] using evaporative cooler obtained 5–10 % and 2–5 % and Marzouk and Hanafi [21] 6.84 % and 2 % enhancement is power output and thermal efficiency respectively.

Conclusion

The following conclusions were derived from the present study.

i. On the basis of the climatic data of the different districts of Iraq during the period 1991 to 2020, it was found that the district of Nineveh was more suitable for the establishment of gas turbine plant for power generation.

ii. The climatic data also explains that cooling of the inlet air to the GTPG is very essential for effective power generation. The climatic data of Nineveh supports the use of evaporative cooling system (either media or high-pressure fogging) as it has twin benefits of both reducing the temperature and increasing the relative humidity at a comparatively lower cost.

iii. As the night temperatures in the Nineveh region is very low, cooling the water used in the evaporative cooling system using the low night temperature can increase the cooling effect of the system.

iv. As the area experiences frequent sand storms air filtration is essential for both effective functioning and longer life of the GTPG.

v. Evaluating the performance of the cooling system, due to the limitations offered by the wet bulb temperature, it was found that the ISO rated temperature cannot be attained for ambient temperatures above 23 °C. Thus, power loss cannot be avoided but can only be reduced during the day time. As the nights and the early morning hours of the day are generally associated with lower temperatures, rated output power from the GTPG can be obtained for about 9–12 hour duration in a day.

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