Techno-economic assessments of advanced Combined Cycle Gas Turbine (CCGT) technology for the new electricity market in the United Arab Emirates

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Abstract

In this study, a dynamic cost model was constructed to compare the Levelised Costs of Electricity (LCOE) for advanced CCGT technology in comparison to traditional CCGT technology. The key technical and economic factors that affected the competitiveness of these CCGT units were evaluated. The results showed that advanced H-class CCGT technology has the lowest LCOE for the base case scenario at 4.93 US cents/kWh versus 5.32 and 5.71 US cents/kWh for F- and E-class technologies respectively. It is evident that the more advanced CCGT technology matches the major market drivers for the UAE energy transition, namely; competitive lifecycle costs, high thermal efficiencies which reduce fuel costs and limit CO_2 emissions and a high operational flexibility. The LCOE model outputs summarise the overall financial competitiveness of the different CCGT technologies for the UAE up to the year 2030 considering the future power generation demand profile. There are no H-class gas turbines installed in the UAE and this was one of the drivers behind this paper to show the benefits of the latest advanced CCGT technology. The study conveniently facilitates future discussions on the opportunities and challenges of the UAE's energy transition for developers, electricity suppliers and national policy makers.

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Key words: Combined Cycle Gas Turbine; Levelised cost of electricity; UAE; power generation; emissions

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1.0 Introduction

Electricity demand and supply growth has several drivers. These can include economic growth, fuel prices, peak loads and seasonal variances, energy intensity, industry structure, renewable policies and availability and security of supply (OME, 2007). In the United Arab Emirates (UAE), the annual energy demand has grown steadily over the last six years at an average of 4% (Strategy&, 2015) and the peak energy demand will double from 23GW in 2010 to 52GW by 2030 (Masdar Institute & IRENA, 2015).

The electricity demand and supply growth in the UAE are mainly due to its expanding economy and population, the hot desert environment, energy intensive industries and high personal incomes that translate into high levels of energy consumption (Sgouridis, et al., 2013). The high national energy demand is leading to two significant issues for the country; firstly the UAE has one of the highest carbon footprints in the world (IBP Inc., 2015) and second, the depletion of its natural gas reserves, on which it is almost entirely dependent on for electricity generation, is leading to an enormous energy shortage (Dargin, 2010). Both of these issues highlight the need for a sustainable energy transition strategy to reduce the environmental impact of electricity generation and to secure reliable and sustainable energy sources. In this regard, the UAE, despite having some of the largest reserves of oil and gas in the world, is currently diversifying its energy mix away from hydrocarbon-based electricity generation and is pursuing low carbon and renewable energy programmes (Jamil, et al., 2016). The UAE is aiming for nearly 20% of low-carbon electricity production from nuclear power plants and renewable energy by 2020.

Approximately 98% of the power generated in the UAE is currently from natural gas fired power plants (UAE MOE, 2014). Combined Cycle Gas Turbine (CCGT) technology is the most widely utilised and these plants traditionally operate continuously and at maximum efficiency to supply the base electricity demand (Troy, 2011). They therefore tend to have poor operational flexibility. If the UAE national energy policy continues as planned to 2030, renewable energy projects will account for more than 6.5GW of the power generation mix and will be predominantly derived from solar power with photovoltaic (PV) cells considered to be the highest potential technology (Jamil, et al., 2016). Nuclear power shall compromise of 5.6GW of generation capacity and clean coal shall compromise of 3.6GW. These new low-carbon power penetrations will demand a greater flexibility within the existing robust and heavily inclined base load CCGT power system.

The existing CCGT power plants will be required to operate on a more flexible basis to account for load variations and two shift operations caused by the solar PV generation which is intermittent and totally absent at night (Kirwan, 2014). Older and more inefficient CCGT plants, originally designed with base load dispatch characteristics, will become forced out of the market place by the new more efficient and lower cost merit plants. This will have a detrimental effect on the economic viability of older generators and in order to survive in the new marketplace, it is necessary that they adapt to more flexible operations (EPRI, 2004).

Cyclic operation via daily start/stops, fast loading and part-load operation for a CCGT plant introduce new mechanisms of damage and increase deterioration on CCGT plant's components. This can reduce the reliability and lifetime of the plant and increases maintenance and repair costs (Robertson, et al., 2010). Bullinger (2012) shows that by introducing advanced CCGT technology or by facilitating existing CCGT units to operate more flexibly, either though enhanced design features and components or through open-cycle operations, the impacts of cyclic operation may be reduced. CCGT plants will therefore have the opportunity to continue generating power and revenue during times when they would otherwise be shut down.

The study undertakes a techno-economic analysis of the operational flexibility of advanced CCGT technology to meet the UAE's changing power generation profile. By defining the technical and economic impacts of the introduction of low carbon and renewable energy on the existing power grid, the objective of this study is to qualify the technical and economic opportunities and challenges of the UAE's energy transition. In particular, the Levelised Costs of Electricity (LCOE) for traditional and advanced CCGT were examined as they are a useful measure for quick cost comparison between different power generation technologies. This is especially true in the UAE electricity market where production and selling prices are regulated by the government. The LCOE model outputs summarise the overall financial competiveness of the different CCGT technologies for the UAE up to the year 2030. The study aims to conveniently facilitate future discussions on the opportunities and challenges of the UAE's energy transition for developers, electricity suppliers and national policy makers.

2.0 Methodology

The operational benefits of advanced flexible CCGT technology for the future UAE energy market was performed by analysing LCOE results. The LCOE facilitated the comparison of the cost of producing one kWh by different technologies. The output of the LCOE calculation was reviewed against the major market drivers for the UAE energy transition, namely; low investment costs, high thermal efficiencies which reduce fuel costs and limit CO_2 emissions, high operational flexibility and high availability. The final output of the LCOE results in a specific cost that was calculated with a set of assumptions. Therefore a sensitivity analysis was conducted to provide a better understanding of the factors which may have a large impact on the LCOE calculation.

2.1 LCOE Model

The LCOE of a given technology is the ratio of the total costs (including capital and operating costs), to the total amount of electricity assumed to be generated during plant lifetime. Both the total costs and the amount of electricity are quantified in Net Present Value (NPV) terms. This means that the future costs and generation are discounted when compared to today's values. LCOE can be considered as the price at which the electricity must be sold at to break even over the lifetime of the asset. It is an essential economic concept that any power generation plant costs should be recovered by the useful energy it produces over its lifetime (Ramadhan, et al., 2013). The advantages of using a LCOE calculation is that standardises the units of measuring the lifecycle costs of producing electricity thereby easily facilitating comparisons of the competiveness between power generation technologies with different operating characteristics (World Energy Council, 2013). Given the structure of the electricity market in UAE where production and selling prices are regulated by the government, the LCOE is an excellent measure for cost comparison between different power generation technologies.

For this study an excel spreadsheet model was developed to calculate and compare the LCOE for different CCGT technologies. A key feature of the model is that it is flexible to allow the introduction of different scenarios and inputs upon which the impact in variation can be examined. Key inputs to calculating LCOE included capital costs, fuel costs, discount rate, fixed and variable Operation and Maintenance (O&M) costs, power output, plant efficiency, degradation rate and an utilisation rate for each technology. Figure 1 depicts how the LCOE was calculated in a flow chart format.

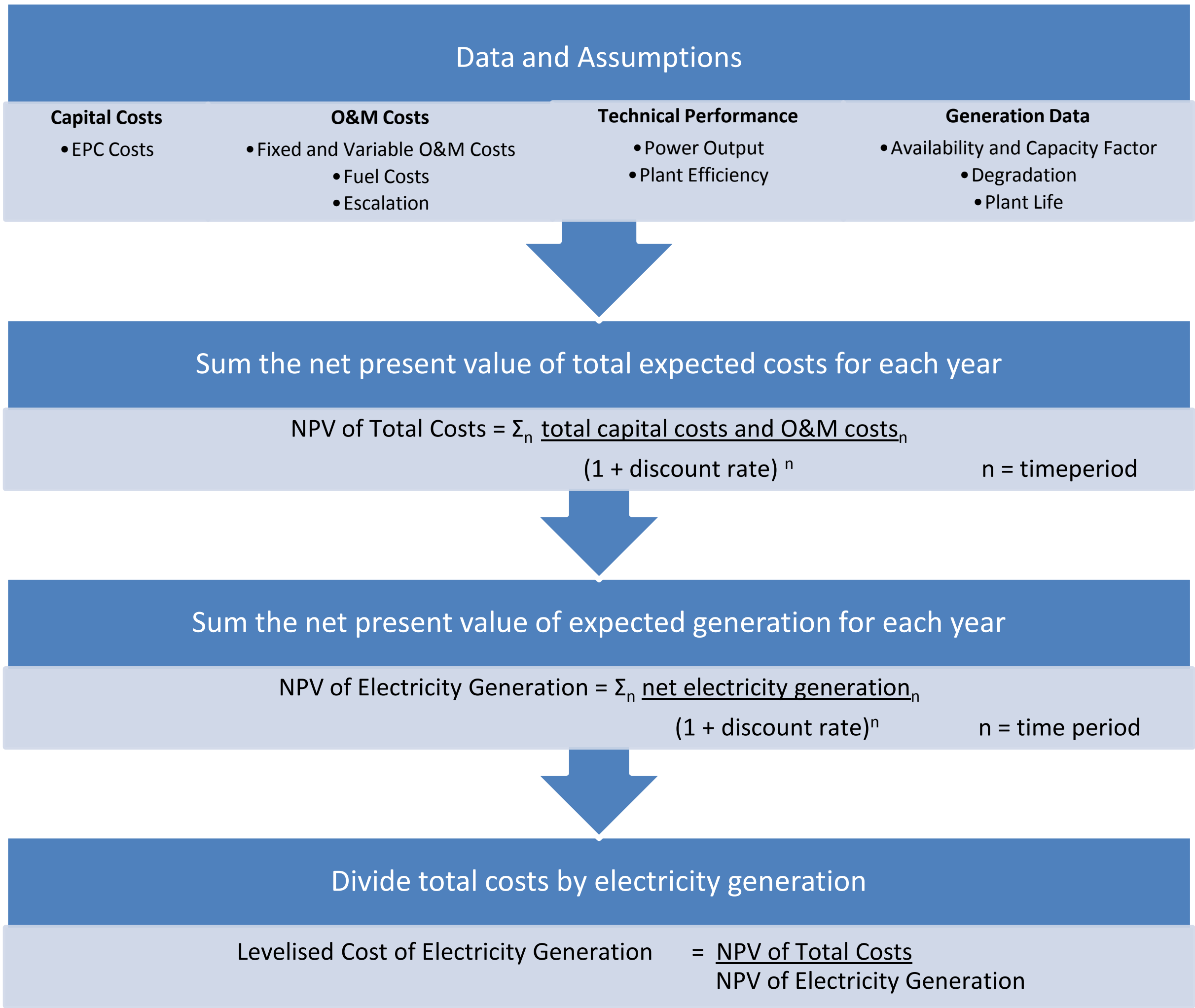

Figure 1 LCOE calculation flow chart

The LCOE was calculated using the formula described in Equation 1 and is denoted in US cents/kWh.

$$LCOE = \frac{CC \times PC + \sum \left[\frac{FC \times (1 + FE) + FO\&M \times PC + VO\&M \times MWh \times (1 - DF)^n}{(1 + DR)^n} \right]}{\sum \frac{[MWh \times (1 - DF)]^n}{(1 + DR)^n}} \quad [1]$$

Where,

CC: Capital Costs; PC: Plant Capacity; FC: Fuel Costs; FE: Fuel Escalation; FO&M: Fixed O&M Costs; VO&M: Variable O&M Costs; DF: Degradation Factor; DR: Discount Rate

The LCOE model output represents a minimum breakeven tariff in US cents/kWh for each CCGT technology. All costs presented in this paper are based on 2015 $. The exchange rate considered in the LCOE model is 1 UAE Dirham (AED) = 0.27220 US Dollar ($). It is important to note that the AED is pegged to the $ so the currency exchange rate is fixed (Marsh, 2015).

2.2 Factors that influence the LCOE

Fossil fuel technologies such as CCGTs which have significant fuel costs over the plant lifetime are significantly affected by both the fuel costs and capital costs in the LCOE calculations. The use of fuel subsidies that lower the fuel price and any other incentives or taxes, such as tax credits or emissions taxes, can also impact the LCOE calculation. As with any assumption, there is an element of uncertainty and the actual values will change across different regions and also with time as technologies advance and fuel prices change (NREL, 2010).

The capacity factor is also influential and it depends on the power generation mix and the load characteristics of the locality. Since power generation output is a core piece of a LCOE calculation and is inversely proportional to the total costs, the higher the capacity factor the lower the generation cost. It is also noted by the EIA (2015) that since load must be continuously balanced; flexible units whose output can be varied to follow demand typically are more valuable than less flexible units such as base-load thermal plants or intermittent renewable energy sources.

2.3 Sensitivities

LCOE calculations are highly sensitive to the underlying data and assumptions used including those on capital costs, fuel prices, operating costs, discount rates and the capacity factors. As such it is often more appropriate to consider a range of cost estimates rather than point estimates. In order to illustrate some of these sensitivities a high, medium and low case of ranges are considered.

2.4 LCOE boundaries and exclusions

Determining the LCOE costs of a power generation technology is not straightforward and depends heavily on the assumptions made and the boundaries and exclusions for costing. The study aims to facilitate a quick comparison of the total costs of different CCGT technology on an equal basis, and it does not necessarily represent the actual costs in the market. For this study the boundary limits for costing were considered as being within the fence of the generation assets and the energy transmitted was at the export side of the main transformer. Only the costs borne in relation to the plant operation asset were considered and excluded all subsidies and support mechanisms (e.g. minimum capacity payments). The assumed costs excluded the expense of connecting to the electrical grid and did not include any transmission and distribution costs. No revenue streams selling electricity nor from any ancillary support markets are considered (e.g. spinning reserve).

The LCOE model utilises basic financial assumptions as the purpose of this study was to compare CCGT technology costs and performance characteristics. Therefore no taxes, tax incentives, no costs associated with environmental emissions and carbon taxes or detailed financing arrangements were considered.

3.0 Power Generation Demand Forecast

The UAE's energy sector is decentralised and ruled independently by each emirate. Abu Dhabi and Dubai are the two dominant emirates for electricity production in the UAE. As such the published information related to future power demand forecasts from the electricity authorities (ADWEA and DEWA) are used as the basis of this study. SEWA and FEWA which are the smaller utility authorities that govern power sectors in the northern emirates have no published data and only a small share of the UAE generation capacity at approximately 10% and 3% respectively. Further ADWEA provides around 57% of the electricity demand for SEWA and around 90% of the demand for FEWA and has committed to cater for any future energy demand growth (Juaidi, et al., 2016).

The two most recent published documents that detail ADWEA's and DEWA's future energy forecasts are the ADWEC Statistical Report (2015a) and the Dubai Energy Outlook 2020 (Access, 2015). These two documents are used to forecast the combined UAE power generation demand and are further complimented by other sources of information such as;

- Policy on the Evaluation and Potential Development of Peaceful Nuclear Energy (ADEC, 2008),
- Renewable Energy Prospects: United Arab Emirates (Masdar and IRENA, 2015),
- State of Energy Report (DSCE, 2014), and
- DEWA Electricity Statistics (DEWA, 2016), etc.

3.1 Data and assumptions

The Abu Dhabi peak demand forecasts up to 2030 are taken from the ADWEC statistical report 1998-2014 (ADWEC, 2015a). The Dubai peak demand forecasts up to 2020 taken from the Dubai Energy Outlook 2020 (Access, 2015).

The annual peak demand for Dubai from 2020 to 2030 is calculated by assuming that the planned 5GW of solar power will form 25% of the generation capacity as announced under Dubai's current energy policy and that a reserve margin of 25% is applied.

The peak demand forecasts for the UAE are presented in Figure 2 and Table 1. The total UAE peak demand for 2030 is calculated as 40,093 MW with an installed capacity of 51,366 MW and this is assumed as the basis of this study.

The installed capacity mix for Abu Dhabi and Dubai is assumed as follows;

<u>Abu Dhabi</u>

- Nuclear shall comprise of 5,600MW installed capacity as currently envisaged under national policy,

- Renewable energy shall comprise of 1,500MW as currently envisaged under its energy policy,
- CCGT shall make up the remainder of the installed capacity,
- None of the existing CCGT capacity shall be decommissioned during the period up to 2030, and
- The forecast ADWEC peak demand is assumed to have an average capacity margin of 25% year on year based on recent historical margins which have been typically ranged between 14-40%.

<u>Dubai</u>

- Renewable solar energy shall rise incrementally to 7% by 2020 and to 5,000MW by 2030 in line with current policy announcements,
- Nuclear imports shall comprise 7% of peak demand as currently envisaged under national policy,
- Coal fire power plants shall compromise of 2,400MW by 2023. It is assumed that the second phase of 3,600MW will be operational by 2030.
- Gas fired shall comprise the remainder of the installed capacity and will reach 10,800MW by 2020 and progressively lower by 2030 as per current energy policy,
- The installed capacity is derived from the peak demand with a 25% margin assumed based on recent historical margins which have been typically ranged between 20-27%.

The calculated additional required UAE CCGT generation capacity in 2030 is 10,394MW. A breakdown of the assumed UAE future power generation capacity is detailed in Table 2.

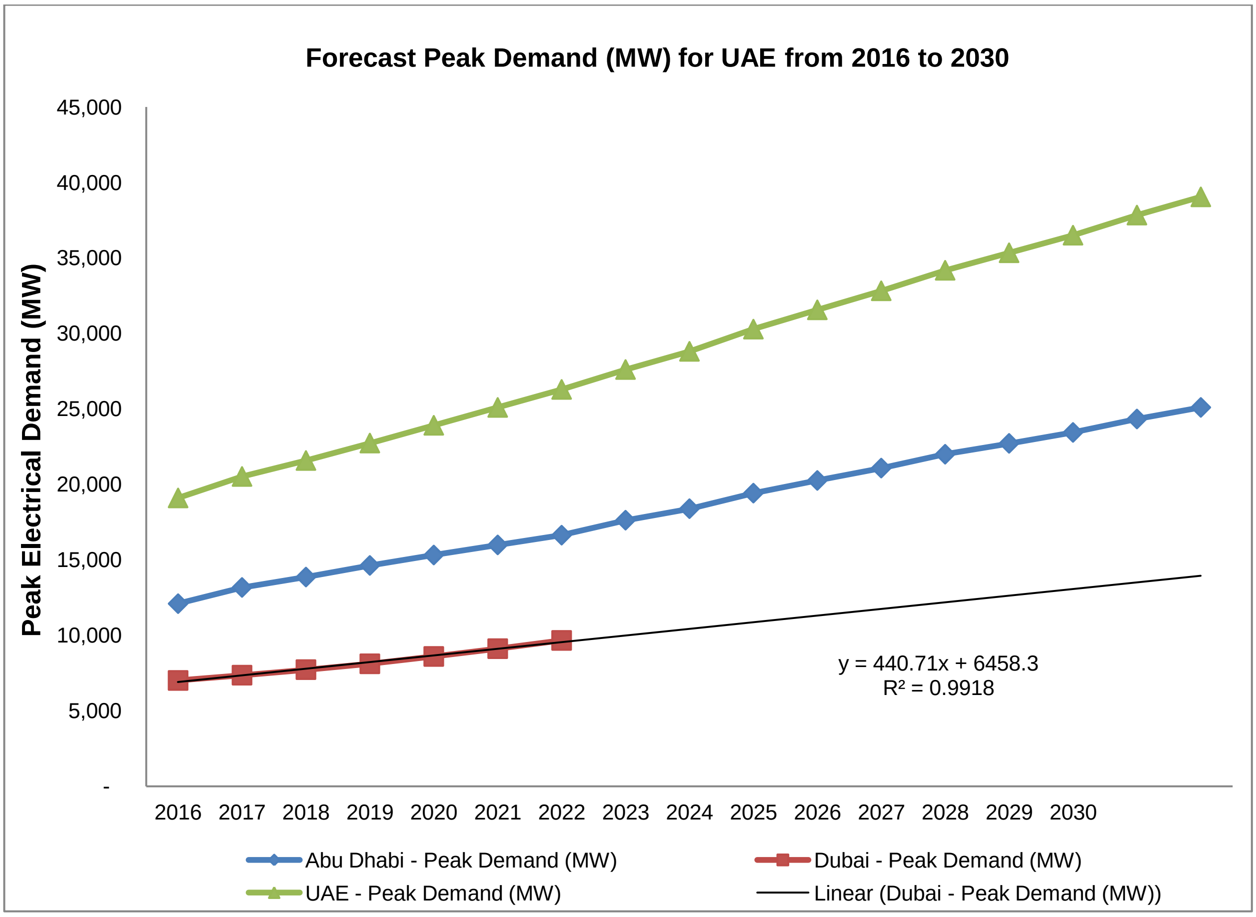

Figure 2 Peak Demand Forecast (MW) for Abu Dhabi and Dubai from 2014 to 2030

Peak Demand (MW)	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Abu Dhabi	13,856	14,625	15,316	5,984	16,630	17,622	18,385	19,416	20,254	21,074	21,992	22,712	23,436	24,327	25,093
Dubai	7,722	8,108	8,594	9,110	9,656	10,190	10,425	10,725	11,259	12,328	12,862	13,397	13,931	14,466	15,000
Total	**21,578**	**22,733**	**23,910**	**25,094**	**26,286**	**27,812**	**29,110**	**30,675**	**32,048**	**33,402**	**34,854**	**36,109**	**37,367**	**38,793**	**40,093**

Table 1: Peak Demand Forecast (MW) for Abu Dhabi and Dubai from up to 2030

Capacity (MW)	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Abu Dhabi (CCGT)	17,270	16,831	15,945	15,380	14,363	15,641	16,632	17,958	19,043	20,105	21,290	22,228	23,170	24,321	25,666
Abu Dhabi (Nuclear)	-	1,400	2,800	4,200	4,924	4,887	4,849	4,812	4,774	4,737	4,700	4,662	4,625	4,587	4,200
Abu Dhabi (Solar)	50	50	400	400	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Dubai (CCGT)	9,700	9,800	9,900	10,200	10,800	9,812	9,055	9,086	8,916	9,574	9,378	10,008	9,839	9,869	10,000
Dubai (Solar)	13	213	213	213	676	1,013	1,800	1,800	2,600	2,600	3,400	3,400	4,200	4,200	5,000
Dubai (Nuclear Imports)	-	-	-	-	676	713	751	788	826	863	900	938	975	1,013	1,400
Dubai (Coal)	-	-	-	-	600	1,200	1,800	2,400	1,200	1,200	1,200	1,200	1,200	3,000	3,600
Total UAE	**27,033**	**28,294**	**29,258**	**30,393**	**33,539**	**34,766**	**36,387**	**38,344**	**40,060**	**41,753**	**43,568**	**45,136**	**46,709**	**48,491**	**51,366**

Table 2: Generation Capacity Forecast (MW) for Abu Dhabi and Dubai up to 2030

4.0. Technical Parameters

The technical parameters that are inputs to the LCOE calculation are discussed in this section.

4.1 CCGT Technology

Large industrial and utility scale GTs use a letter designation to identify the machine's technology class which are differentiated by volumetric air flow, its compressor pressure ratio, and most importantly the turbine inlet firing temperature (Zachary, 2008). D and E-class engines dominated the 1980's with firing temperatures of around 1,100°C. F-class engines with firing temperatures of around 1,300°C became available in the early 1990s and rapidly rose to become the market leader for the next twenty years (Ducker, 2015). More recent and advanced GT classes (G, H and J) with firing temperatures of up to 1,600°C have been steadily developed and operationally validated since then (Mitsubishi Heavy Industries, 2014).

There are wide ranges of industrial GTs that are commercially employed in various configurations, ranging from aero derivative units with power outputs up to about 100 MW, through E-class units rated at around 200 MW, to the larger F-class machines rated at around 300 MW and finally H-class machines with power outputs of over 400MW. F-class industrial machine are the market leaders in the CCGT industry. In the UAE, the industry currently favours building multiple units of multi-shaft shaft blocks with two or more GTs coupled to one ST. This is commonly referred to as a two on one multi-shaft plant. The block capacity of such an F-class two on one arrangement is around 900MW, although the outputs vary between OEMs. E-class machines are still used especially in instances where there is a lower power requirement. H-class machines are recently gaining more interest and market share due to their superior efficiencies and as the technology gains more operating hours and proven experience. For this study three CCGT technology classes are evaluated namely; E-, F- and H-class. In this study the Alstom/GE 13E2, Siemens SCC5-4000F and GE 9HA.02 models are considered for E-, F- and H-class gas turbine, respectively.

4.1.1 Power plant arrangement

In order to provide a consistent evaluation approach for the three GT technologies, the same power plant arrangement of two GTs and one ST in a multi-shaft configuration was assumed. A multi-shaft configuration was chosen as it is the most common arrangement in the UAE market. The multi-shaft arrangement is favoured as combined steam headers can be utilised for the production of water in distillation plants and further the GTs can be installed and operated in a simple cycle mode prior to the finalisation the steam cycle in an early power arrangement. These two factors are a dominant feature of the UAE electricity sector whereby electricity production is entwined with water production and there is a continuously large demand for power. Multi-shaft arrangements can also offer cost savings through sharing of the common auxiliary systems such as, fuel storage and forwarding systems and closed cooling water plant etc.

4.2 Power output

Power output is dependent on the technology class and on the arrangement of the plant. The calculated additional required UAE CCGT generation capacity in 2030 is 10,394MW. The most likely range of power output for future CCGT plants in the UAE would be between 500 and 1,600MW. Larger plants are more attractive with lower comparative specific costs but land availability, fuel sources and transmission network capacity may hamper the deployment. Smaller plants are also feasible but not as common in the UAE due to the significant energy demand growth. The assumed power outputs for each GT technology in a two on one multi-shaft configuration is shown in Table 4. The required number of CCGT units (within ±2% tolerance) to meet the forecast power generation requirements of 10,394MW at ISO conditions by 2030 for each technology are shown in Table 6.

4.3 Heat rate

The performance of a power plant is expressed in terms of plant net heat rate and it is defined as the ratio of the heat input to the plant net power output. The heat rate is related to the thermal efficiency ($\eta_{thermal}$), can be calculated using the formula in Equation 2 and is denoted in kJ/kWh.

$$Heat\ rate = \frac{3600}{\eta_{thermal}} \qquad [2]$$

The average thermal efficiency for a CCGT is approximately 50% (or 7200 kJ/kWh) but this varies for each plant and is heavily dependent on the GT technology and regional parameters (Tamvakis, 2015). The world record for CCGT efficiency was recorded by a GE H-class plant at 62.2% with an electrical output of 605MW (BusinessWire, 2016). The heat rate for each GT technology in a two on one multi-shaft configuration is shown in Table 4.

4.4 Degradation

The performance of CCGT power plants deteriorates over time as the main hot gas path components degrade with use. The GT efficiency is the most important parameter in CCGT efficiency. The primary drivers for GT performance degradation are fouling, erosion, corrosion, foreign object damage, thermal distortion and material losses in the turbine section (Zwebek & Pilidis, 2003). Typical capacity and heat rate degradation rates of 3% and 1.9% respectively, are assumed over each of the plants life (PA Consulting, 2014). As with all parameters, system degradation rate is treated as a single value in LCOE calculations despite the fact that it is known that even within a single power plant installation, individual GT's will degrade with substantially different rates.

4.5 Capacity factor

The capacity factor of a power plant is defined as the ratio of its actual power output, to its potential maximum power output over a defined period of time. The electricity demand in the UAE displays an irregular profile with demand during the winter months as low as 40% of the annual peak. Coupled with the high reserve capacity margins the actual capacity factors of CCGT plants in the UAE are low. The average monthly capacity factor for ADWEC during the period 2009 –2014 was calculated as 49.3% (ADWEC, 2015b).

Quantifying a capacity factor for intermittent generation technologies is a challenge as the capacity factor varies with environmental conditions (Kovacevic, et al., 2013). For this study the annual average capacity factor (%) was calculated on the assumed monthly power generation load profile to 2030 and on the Abu Dhabi published data from 2009 - 2014. The assumed calculated figures are presented in Table 3.

Year	2017	2018	2019	2020	2021	2022	2023
Capacity factor	33.5%	31.1%	29%	26.6%	26.1%	25.7%	25.6%
Year	2024	2025	2026	2027	2028	2029	2030
Capacity factor	25.9%	26.3%	26.6%	26.9%	27.1%	26.9%	26.8%

Table 3 Annual average capacity factor calculated on the assumed monthly UAE load profile 2030

4.6 Availability factor

The availability factor is defined as the amount of power a plant is able to deliver as a ratio of what it would provide if it operated continuously at full output. The availability factor is inclusive of time for forced outages caused by plant trips or failures and for scheduled outages to complete any maintenance or major overhauls. The availability factors for the CCGT technologies considered in this study are shown in Table 4. The basis of these figures is the 'Electricity Generation Cost Model – 2012' by Parsons Brinckerhoff (2012) who detail the low, medium and high availability factors for CCGT technologies whether 1st of a kind or N_{th} of a kind. E-Class is chosen with the lowest availability as it is the oldest technology and has the lowest ramp rates, lowest turndown and longest start-up times of the three technology classes. Conversely, H-Class is chosen with the highest availability as it is the latest and most advanced technology of the three with the highest ramp rates, highest turndown and the shortest start-up times. F-class availability therefore lies between the E- and H-class availabilities.

Technical parameters for the plant performance specifications two on one multi-shaft configuration are detailed in Table 4.

Parameters	E-Class	F-Class	H-Class
Model	Alstom 13E2	Siemens 4000F	GE 9HA 0.2
Net power output (MW)	581	890	1552
Net plant efficiency (%)	55.1	58.7	62.8
Plant heat rate (kJ/kWh)	6522	6133	5732
Average availability (%)	91.9	92.8	93.7
Turndown (%)	56	36	18
Star time (Minutes)	80	30	30
Ramp rate (Minutes)	28	55	140
Average power degradation rate (%)	3.0	3.0	3.0
Average heat rate degradation (%)	1.9	1.9	1.9

Table 4 Base Case LCOE Model – Summary of the Technical Inputs and Assumptions

5.0 Economic Parameters

The costs are one of the two core pieces of any LCOE calculation. The economic parameters that influence the LCOE are discount rate, capital costs, fuel costs, and O&M Costs (fixed and variable). Narbel, et al., (2014) detail that for a LCOE calculation for a CCGT, the overall costs can typically be made up of capital costs (14 – 31%); fuel costs (61 – 80%) and O&M costs (2 – 11%).

5.1 Discount rate

The discount rate considers the time value of money and is typically related to the rate of return that could be earned on comparable investments. A discount rate is used in LCOE calculations to translate future costs and power generation outputs to present values and to calculate the costs per unit of energy produced (SI Ocean, 2013). Typical discount rates for LCOE calculations are between 5% and 10% and the rates can have a significant impact on LCOE calculations (Nicholson, 2012). A 7% discount rate is assumed across all of the cash-flows and all of the energy production over the life of the plant. This approach allows the estimates to be viewed as neutral in financing and risk terms.

5.2 Capital costs

For a CCGT the capital costs are those costs considered in the EPC price and those include the main equipment (GT's, HRSG's, ST's, condensers and cooling system), construction and commissioning costs, transport, contractor's fee, and contingency.

The main OEM equipment (the GT, ST and the generator) is the biggest cost component of an EPC price and typically account for around 40-50% of the overall price. The HRSG, condenser and cooling system usually accounts for around 20%, the balance of plant and electrical equipment around 15% and the civil works around 15% (Mott MacDonald, 2010). The contracting scheme for procuring EPC services for power generation projects in the UAE is typically implemented with a single contracting entity at a fixed, lump-sum price.

The capital costs does not include any other costs such as development costs, financing costs, insurance or legal fees, land costs or gas and electric interconnections.

For CCGT power plants the capital costs can range anywhere between 400 and 1300 US $/kW. Determining the capital costs of new CCGT plants is challenging as it is dependent on several variables including; the technology and scale, numbers of units ordered, suppliers selected, market conditions (commodity prices, supply chain bottlenecks etc.) and the ability of the owner to effectively manage the costs (Mott MacDonald, 2010).

The economic slowdown in the UAE after the spectacular crash in 2008 and more recently due to the collapse of global oil prices has had a significant declining effect on the capital cost of new entrant CCGT plants in the local market. EPC prices have fallen over the last two years as the economic slowdown has increased market pressures on EPC suppliers and transferred negotiating power towards buyers. There have been a number of recent EPC transactions in the Middle East most of which are understood to have been done at around 500

$/kW. For reference the Gas Turbine World Handbook details that CCGT EPC prices have varied between 400 and 600 $/kW during the period 2007 to 2013 (PA Consulting, 2014). This data is not geographically specific however the CCGT prices presented in Gas Turbine World are only estimated budget prices for specific 1x1 and 2x1 combined cycle configurations. It does provide benchmarks though which can be used to estimate the price of comparably sized plants, after making allowances for different generation technology designs.

It is expected that as the UAE economy stabilises and investment in major infrastructure follows, specific costs would return to more normal levels of around 600 - 700 $/KW. It is assumed that the capital costs will exhibit economies of scale and that the smaller E-Class plants will have a higher capital cost than the much larger H-Class plants. The specific capital costs for the CCGT technologies used for the LCOE analysis is shown in Table 5. As capital cost data is provided on the basis of specific costs per unit capacity, or as overall costs rounded to the nearest dollar an error of up to 5% could be considered.

Due to the variability in capital costs and the impact that it has in a LCOE calculation, any assumed capital cost of a CCGT plant must be justifiable. A prudent approach is to analysis a range of cost estimates rather than a single cost estimate. A sensitivity analysis is therefore carried out which investigates the potential changes and impacts of the capital costs on the LCOE calculation.

5.3 Fuel costs

Fuel costs are one of the most important factors in a LCOE for a CCGT as they can make up to 80% of the total costs. The high fuel costs are compensated in a LCOE calculation by low capital costs which is in comparison to renewable energy technologies such as hydro, solar, and wind have very high capital costs but no fuel costs (Narbel, et al., 2014).

In this study only natural gas is considered as the fuel source and there is no back-up fuel such as distillate or heavy fuel oil. The fuel gas cost is expressed in AED per Million Metric British Thermal Units (MMBTU). As of February 2016, the natural gas spot price was around 8 AED/MMBTU (Index Mundi, 2016). However in February 2014 the price was nearly triple this at around 22 AED/MMBTU. Gas production in the GCC has historically cost between 4–11 AED/MMBTU and the recent drop in oil and gas prices has reduced the pressure demand side markets (IRENA, 2016). The natural gas production cost in the UAE is calculated as low as 4 AED/MMBTU by the Abu Dhabi National Oil Company (ADNOC) due to the fact that it is largely an associated by-product (Boersma & Griffiths, 2016). A fuel cost of 11.02 AED/MMBTU (or 3 $/MMBTU) is assumed for this study.

Due to the volatility in gas prices and the impact that it has in a LCOE calculation, the assumed cost of fuel over the economic life of a CCGT plant can be challenging. A sensitivity analysis is therefore carried out which investigates the potential changes and impacts of the fuel costs on LCOE calculation. Due to the variability of gas prices the sensitivity analysis considered high and low price escalations of 5% and 1% per annum respectively.

5.4 O&M costs (Fixed and Variable)

O&M costs for a CCGT are subject to a wide variation and are dependent on the technology and scale of a plant, the operating regime and on the type of fuel used (Parsons Brinckerhoff, 2009). Fixed O&M costs, defined in US $/kW/year typically include spare parts, planned maintenance activities and any owner's costs such as wages, leases, insurance etc. Fixed costs for CCGT are low in comparison to other thermal generation technologies given the low levels of staff required and the costs should not vary significantly with changes in electricity generation levels (Mott MacDonald, 2010). Variable O&M costs defined in US $/MWh are more significant than fixed costs as GTs require considerable maintenance in order to ensure availability. This is especially significant in energy markets where there is a large penetration of intermittent renewable energy sources which cause increased CCGT cycling regimes. Variable O&M depends on factors including conditions include the number of operating hours, number of starts and number of trips (Rodilla, et al., 2012).

The O&M costs assumed for this study are derived from the 'US EIA Annual Energy Outlook Report' (2015). For this study, E-Class technology is chosen as the basis for conventional CCGT technology and H-Class is assigned as the advanced CCGT technology. F-class figures for Fixed and Variable O&M costs therefore lay between the E- and H-class figures. An O&M escalation rate of 2.38% per annum is assumed for both the fixed and the variable costs as the inflation rate in the UAE averaged 2.38% from 1990 until 2015 (Trading Economics, 2016).

5.5 Plant life

Current IPP models in the UAE typically implement project terms from 20 to 25 years as specified in the relevant power/water purchase agreements (Booz & Co., 2010). The plant term is assumed as 25 years in the LCOE model.

For the base case the economic parameters used for the LCOE analysis is summarised in Table 5. The base case results are calculated on the basis of current published market data e.g. the technical assumptions use the most recent published GT data and the economic assumptions use current market EPC prices and current Henry Hub natural gas spot prices.

Parameters	Alstom 13E2	Siemens 4000F	GE 9HA.02
Specific capital costs ($/kW)	700	650	600
Fixed O & M Costs ($/kW/year)	13.16	14.26	15.36
Variable O&M costs ($/MWh)	3.6	3.44	3.27
Discount factor (%)	7	7	7
Plant life	25	25	25
O & M Price escalation (%)	2.38	2.38	2.38
Gas price escalation (%)	2	2	2
Gas price (AED/MMBTU)	11.02	11.02	11.02

Table 5 Economic input parameters for base case LCOE model

6.0 Results and Discussions

6.1 Base case results

A high level summary of the results of the LCOE calculation is presented in Table 6. In order to aid comparison, the total LCOE costs are also shown in Figure 3 as 100% stacked costs on a US cents/kWh for the three CCGT technologies with the LCOE for each technology shown broken down by the three main cost components – capital costs, fixed and variable O&M costs and fuel costs. The plant efficiencies and fuel costs are based on lower heating value (LHV).

Summary	Alstom 13E2	Siemens 4000F	GE 9HA.02
Required CCGT Capacity by 2030 (MW)	10,394	10,394	10,394
Net Power Output (ISO) of Block (MW)	581	890	1,552
Required CCGT Blocks (2x1)	19	12	7
Net Total Power Output (MW)	11,039	10,680	10,864
Capital Costs (Million $)	7,727	6,942	6,518
O&M Costs - Fixed and Variable (Million $)	2,940	2,740	2,680
Fuel Costs (Million $)	16,151	14,838	14,245
Total Costs for Power (Million $)	26,819	24,520	23,443
Net Electrical Energy (GWh)	594,949	581,237	596,985
LCOE (US Cents/kWh)	5.71	5.32	4.93

Table 6 High level summary-comparison of LCOE for each CCGT technology

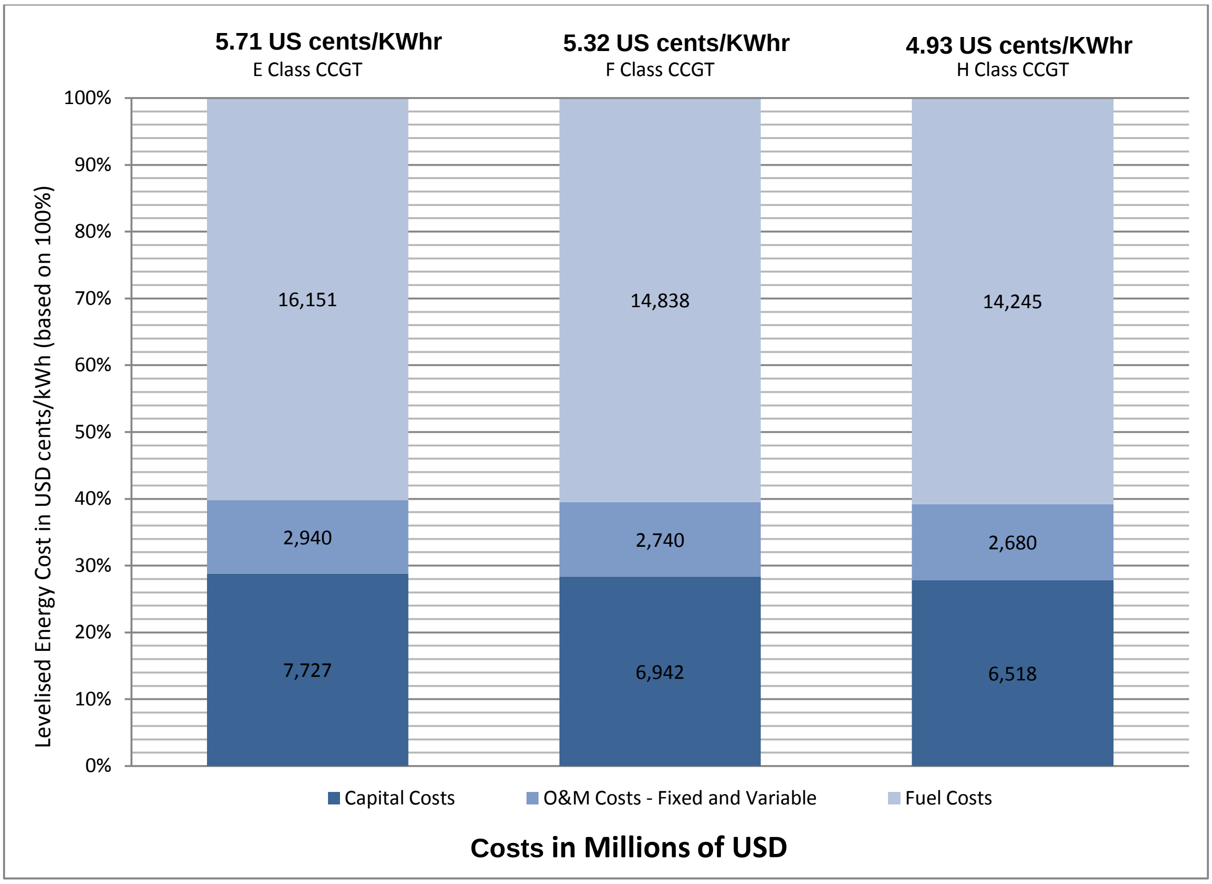

Figure 3 LCOE for each CCGT Technology in $ cents/kWh (based on 100%)

As expected, the LCOE model calculation details that H-class, as the most advanced CCGT technology on the market, has the lowest LCOE at 4.93 US cents/kWh. The F-class lies behind the H-class with an LCOE at 5.32 US cents/kWh which is an increase of approximately 8%. The most expensive CCGT technology is shown as E-class with an LCOE of 5.63 US cents/kWh which is approximately 16% more expensive on a LCOE cost basis than the H-class technology.

The biggest contributor to the overall costs for power for all cases is the fuel cost at around 60% for each technology. The next largest cost component is the capital cost which accounts for around 29% and finally the O&M cost is the smallest contributor at around 11%.

6.2 Sensitivities

For CCGT technologies the fuel costs are a major driver of the levelised cost. In order to demonstrate this, sensitivities which explore uncertainty over the fuel costs are provided. The base case fuel costs are assumed at 8 $/MMBTU with an escalation rate of 2% per annum. For the sensitivity analysis a low and high fuel price escalation of 1% and 5% per annum, respectively were applied.

O&M costs for a CCGT are subject to a wide variation and are dependent on the technology and scale of a plant and the operating regime. For the sensitivity analysis an O&M cost escalation range of ± 50% was applied.

The capital cost sensitivity range represents the uncertainty around capital costs for the given technologies. Due to the variability in capital costs and the impact that it has in a LCOE calculation a sensitivity analysis range of ±25% is applied.

In the base case, a 7% discount rate is applied across all of the cash-flows and energy production over the complete term of the plant. As the discount rate will determine the balance of weight given to the cash flows and energy production, a low and high discount rate of 3% and 10%, respectively were considered for the sensitivity analysis.

Levelised costs are sensitive to assumptions on capacity factors. A sensitivity analysis was therefore explored on high and low ranges of the assumed capacity factor at ± 25%.

The assumed estimates for base case and the high and low ranges for the sensitivity analysis are presented in Table 7.

	Base Case	**Low Range**	**High Range**
Fuel Price Annual Escalation Rate	2%	1%	5%
O&M Annual Escalation Rate	2.38%	1.19%	3.57%
Capital Costs	100%	75%	125%
Discount Factor	7%	3%	10%
Capacity Factor (Average Annual)	26%	20%	33%

Table 7 Summary of the sensitivity analysis range of estimates

6.2.1 Sensitivity analysis results

Table 8 shows the results of the sensitivity analysis for the three CCGT technologies with the LCOE ranges stated in US cents/kWh. The range of LCOE for each CCGT technology is graphically shown in Figure 4.

	LCOE (US cents/kWh)		
	E-Class	F-Class	H-Class
Capital Costs	4.98-6.32	4.65-6.11	4.33-5.94
Fuel Price Annual Escalation Rate	5.41-6.62	5.04-6.17	4.69-5.75
O&M Annual Escalation Rate	5.60-5.71	5.22-5.32	4.85-4.96
Discount Factor	4.91-6.23	4.58-5.87	4.27-5.45
Capacity Factor (Average Annual)	5.31-6.85	4.95-6.36	4.61-5.91

Table 8: Sensitivity Analysis Results on LCOE for each CCGT Technology

The ranges of LCOE costs (in US cents/kWh) from the sensitivity analysis relative to the base case for each CCGT technology are shown in Figures 5-7.

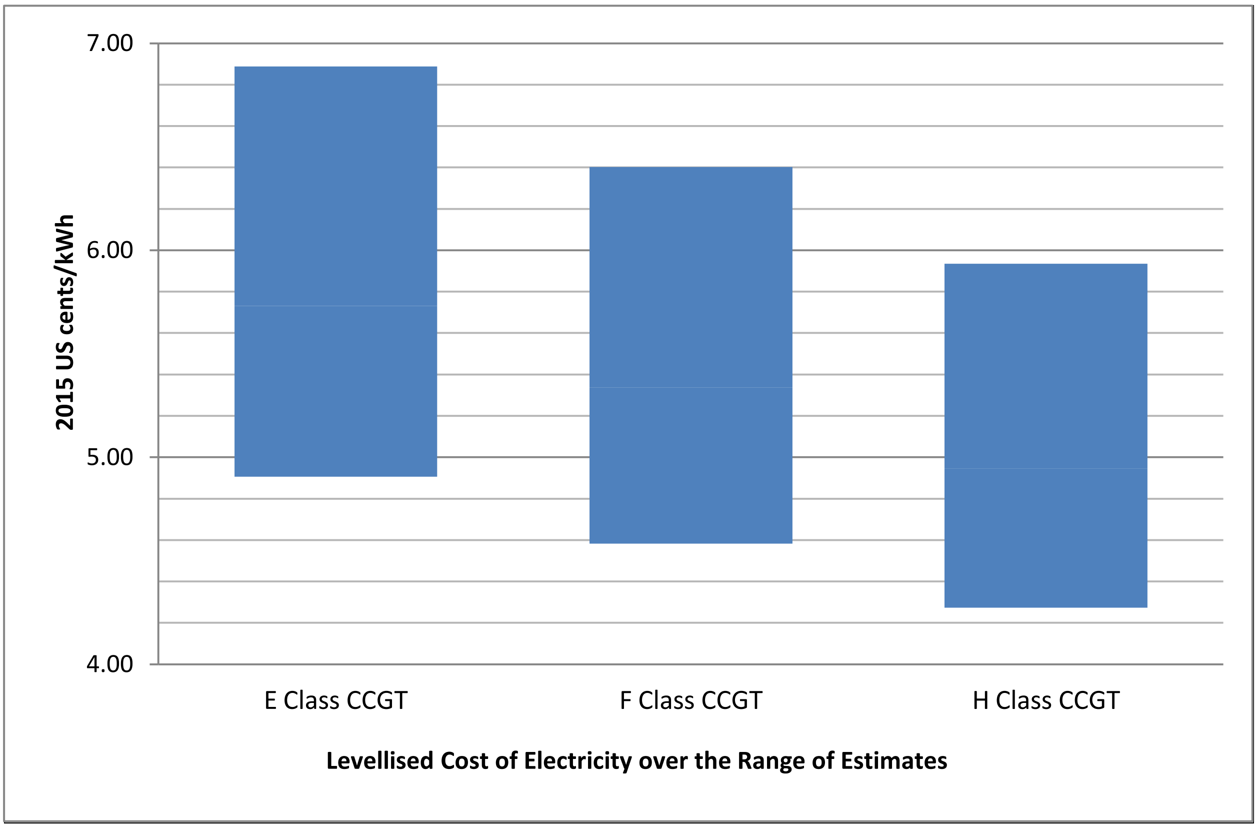

Figure 4 Sensitivity analysis range of LCOE for each CCGT Technology

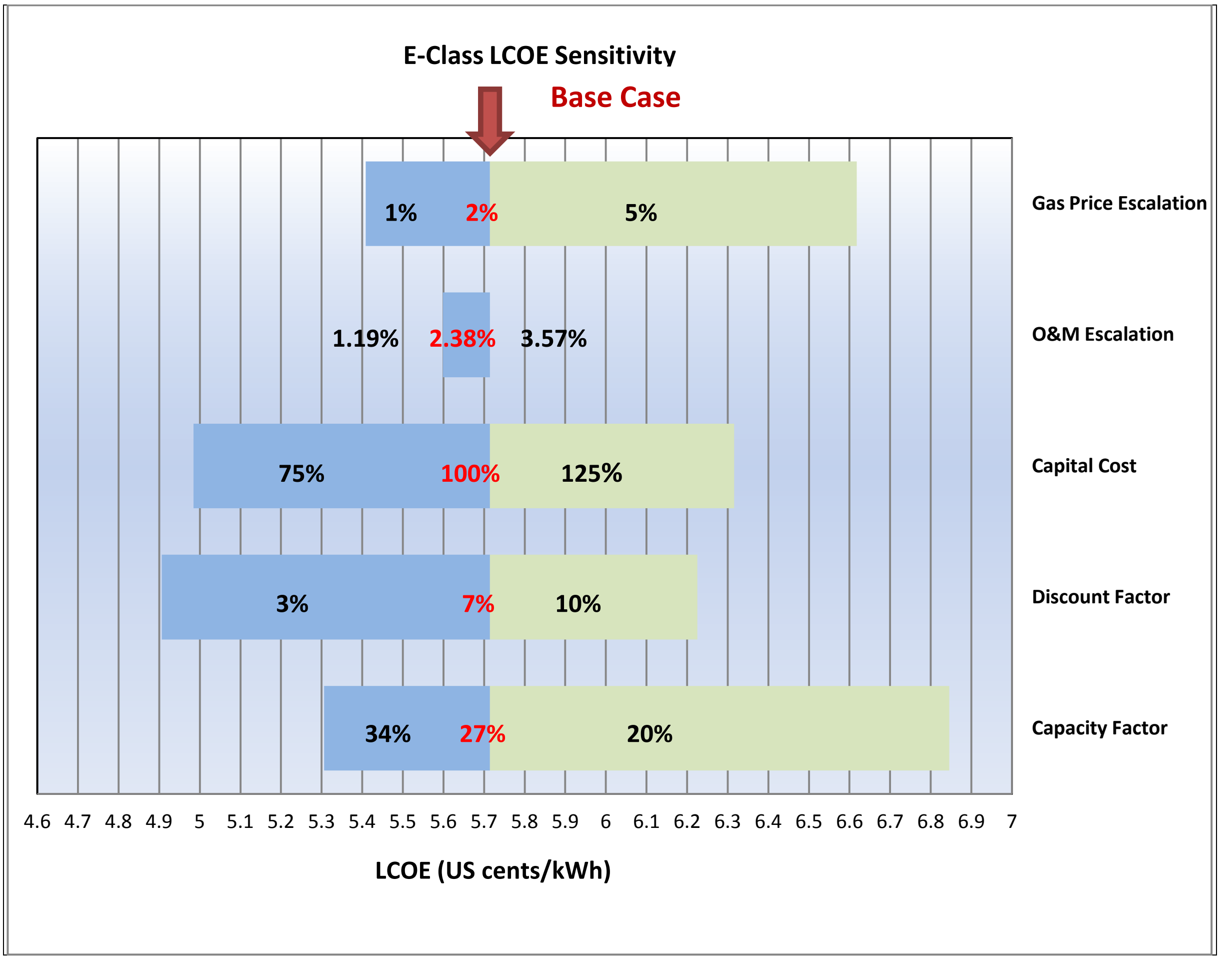

Figure 5 E-Class Sensitivity Analysis Results

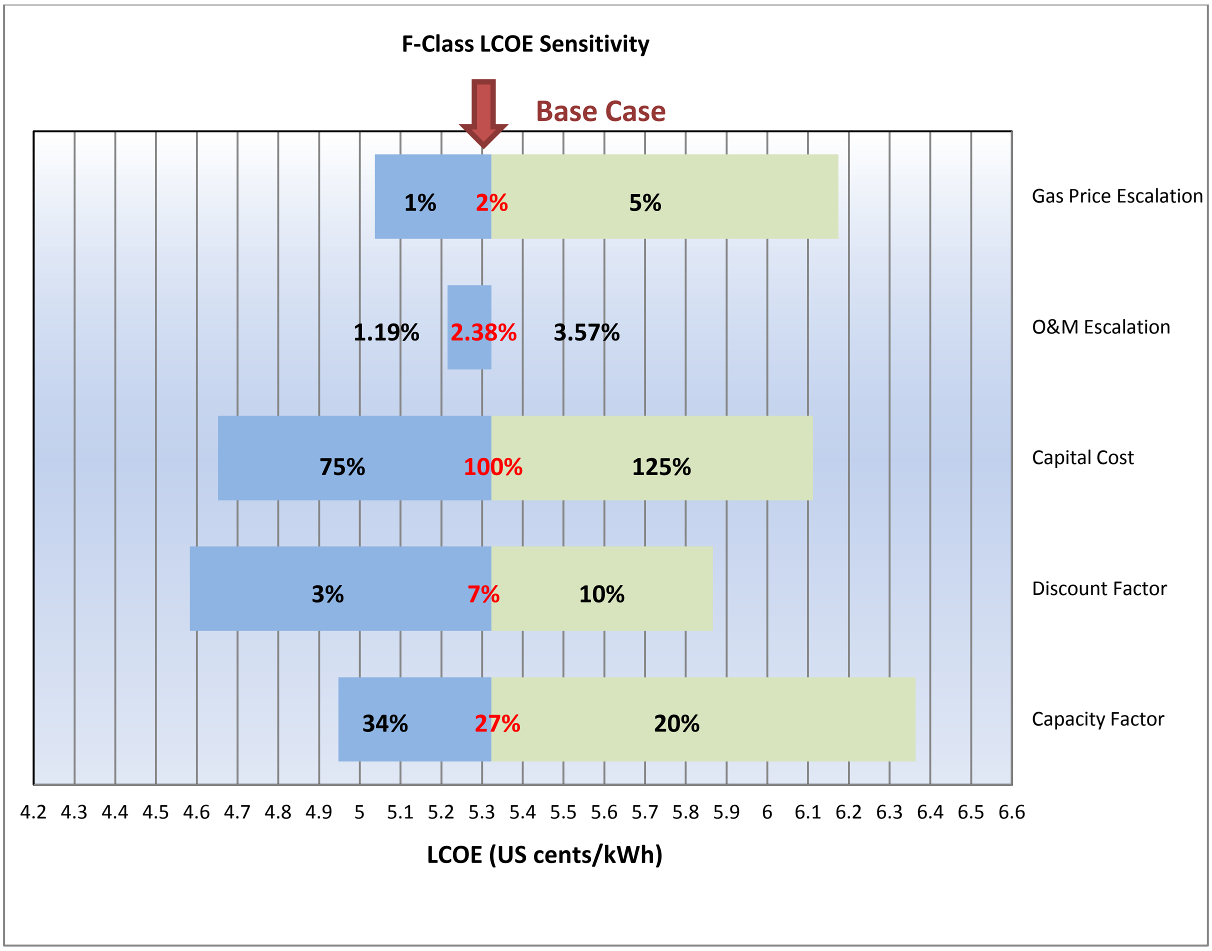

Figure 6 F-Class Sensitivity Analysis Results

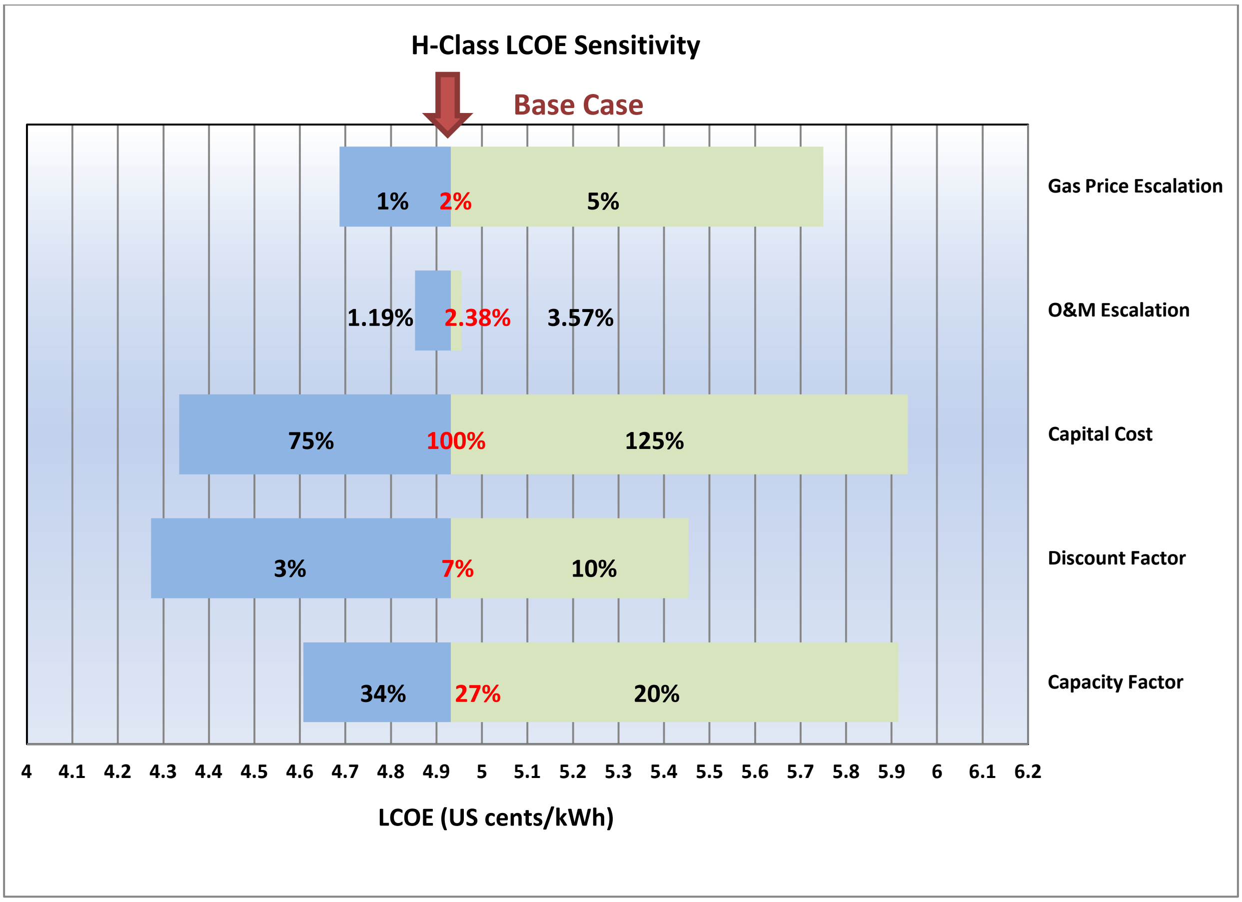

Figure 7 H-Class Sensitivity Analysis Results

The sensitivity analysis on fuel price escalation shows that the assumed fuel cost has a large impact on the LCOE for all technologies. This impact is more pronounced for the less efficient E-class with the high gas price escalation resulting in an LCOE of 6.62 US cents/kWh which is approximately 17% more than the base case LCOE. The affects are not as pronounced for the more efficient F- and H-classes where capacity factor and capital costs have more of an influence respectively.

The sensitivity analysis shows that a low capital cost scenario results in the second lowest LCOE for all the CCGT technologies after the discount factor. The low capital cost has a strong influence on the LCOE because when the upfront investment costs are lower, the NPV of total costs will decrease significantly. The high capital cost scenario does not assert as much influence on the LCOE for the lower efficiency E class. In this scenario, the LCOE of 6.32 US cents/kWh is lower than the LCOE for the high gas price escalation scenario and the low capacity factor scenario at 6.62 and 6.85 US cents/kWh respectively. This can be attributed to the impacts of higher fuel costs. Conversely for the most efficient H-class, the high capital cost scenario has the most detrimental effect on the LCOE with a cost of 5.94 US cents/kWh calculated.

The ± 25% range between the plausible low and high scenarios results in similar outcomes for the different CCGT technologies. For E-class, the low capacity factor has the biggest impact on the overall LCOE at 6.85 US cents/kWh. The high capacity factor at 5.31 US cents/kWh is third in its impact behind capital costs and discount factor. The lower efficiencies and power outputs of the E-class drive it LCOE costs and when the capacity factor is low there is further reduced cost competiveness.

Similarly for the F-class, the low capacity factor has the biggest impact on the overall LCOE at 6.36 US cents/kWh. The high capacity factor is also third in its impact behind capital costs and discount factor and is calculated at 4.95 US cents/kWh.

The high capacity factor scenario for H-class is similar to E- and F-class in that the LOCE at 4.61 US cents/kWh is third in its impact behind capital costs and discount factor. However the low capacity factor for the H-class results in a different outcome when compared to E- and F-class. The LCOE at 5.91 US cents/kWh is second to the high capital cost scenario at 5.94 US cents/kWh. This may be attributable to the much larger power and efficiencies and the generation outputs and costs offset the reduced running hours in comparison to the E- and F-classes.

In all cases the low discount rate of 3% resulted in the lowest LCOE for each technology. The lowest LCOE calculated over all scenarios was at 4.27 US cents/kWh for H-class at a 3% discount rate. The high discount rate analysis shows less of an influence and the resulting LCOEs were lower for all technologies than the scenarios of high capital costs, high fuel price escalation and low capacity factor.

A low discount rate represents a low risk investment and as such the full benefits of power production are realised at this case. This is especially evident as there are no revenue streams considered in the LCOE model and it is only the fuel and O&M costs which are discounted. The discounting is applied over the economic life of the plants which is assumed to be somewhat longer than typical financing terms. This approach allows the estimates to be viewed as neutral in financing and risk terms and the high discount rate affect is somewhat reduced.

In all cases the O&M escalation had the least amount of influence on the LCOE for all technologies. For E-class the LCOE range only diverged from the base case of 5.71 US cents/kWh to 5.60 US cents/kWh at the low rate of escalation and the effect of a high escalation rate was negligible (<0.05%). The effect on the F-class was similar in that the base case of 5.32 US cents/kWh only moved noticeable for the low escalation rate to 5.22 US cents/kWh. Lastly the H-class was somewhat similar with a LCOE range of between 4.85 – 4.96 US cents/kWh against a base case LCOE of 4.93 US cents/kWh.

The impacts of O&M cost escalation is considered to be so small due to the fact that the O&M cost is the smallest cost factor in the LCOE and only accounts for less than 11% of the total base case costs for each CCGT technology.

6.3 LCOE comparisons

The LCOE (in US cents/kWh) of utility-scale electricity generation technologies in the GCC as calculated by IRENA (2016) is presented in Figure 8 for comparison purposes. The LCOE of gas fired generation technologies is shown to range approximately between 3-7 US cents/kWh for fuel gas prices between 1-8 USD/MMBTU. This correlates with the calculated LCOE for the base case which is between 4.93 - 5.71 US cents/kWh at 3 USD/MMBTU. For the sensitivity analysis the range is 4.27 – 6.85 US cents/kWh for fuel prices starting at 3 USD/MMBTU and increasing to over 10 USD/MMBTU.

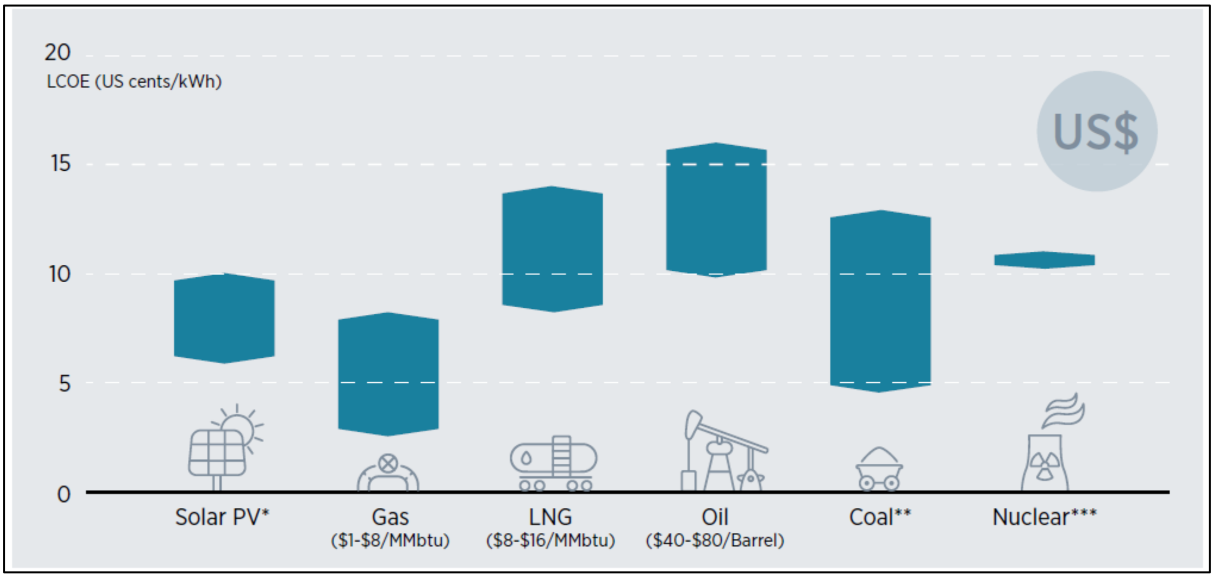

Figure 8 LCOE of utility-scale electricity generation technologies in the GCC (US cents/kWh) (IRENA, 2016)

Recent market developments in the UAE have put the region on the global map with some of the lowest LCOE recorded from solar PV. The recent tender in September 2016 for a 350MW solar power plant to be built on an IPP basis in Sweihan, in east Abu Dhabi resulted in the lowest bid at 2.42 US cents/kWh (The National, 2016a). This PV price is one of the lowest in the world and it is stated by IRENA (2016) that this price level is more competitive than oil and gas plants in the GCC region.

Another reference is the first phase of the 3,600 MW Hassyan coal power plant awarded by DEWA in October 2015 which it was estimated to have a LCOE of 4.501 US cents/kWh under a 25 year power purchase agreement (ACWA Power, 2015). It is also noted that estimates for the cost of nuclear power in the UAE are around 11 US cents/kWh (IRENA, 2016).

It is evident from the LCOE calculation that the more advanced the CCGT technology, the greater its competitiveness. The H-class technology, with its significantly higher power outputs and efficiencies has the lowest LCOE calculated at 4.27 US cents/kWh at a 3% discount rate. This LCOE is more competitive than most of the recent solar PV and coal fired plants awarded in the UAE in 2015. However the strong influence of gas prices and capacity factor on the LCOE could reduce the competitiveness of advanced CCGT technology. This is possible in the scenarios where gas prices were to rise in the short term or if the penetrations of other power generation technologies were to increase further to a point where CCGT plants would operate less and less.

Given the current UAE transition away from natural gas fired power plants, it is likely that in the long term, solar, coal and nuclear power plants will be on top of the merit order for dispatch and that CCGT plant may be displaced and forced offline especially during periods of low demand. Power is dispatched in accordance with a least cost merit order. The basis of the merit order includes amongst others, the plant availability, start-up prices, fuel priority and efficiency. Solar or nuclear power could be a least-cost option for base load power generation under a wide range of scenarios due to the very low costs of electricity production. If however the majority of the substantial fixed and variable costs for the nuclear plants in the UAE will be carried by the national government and the running costs are incorporated into electricity tariffs, then the economics of nuclear power may not be cost effective against CCGT plants in the short-term. Possible merit order effects on the installed CCGT capacity are shown in Figure 9.

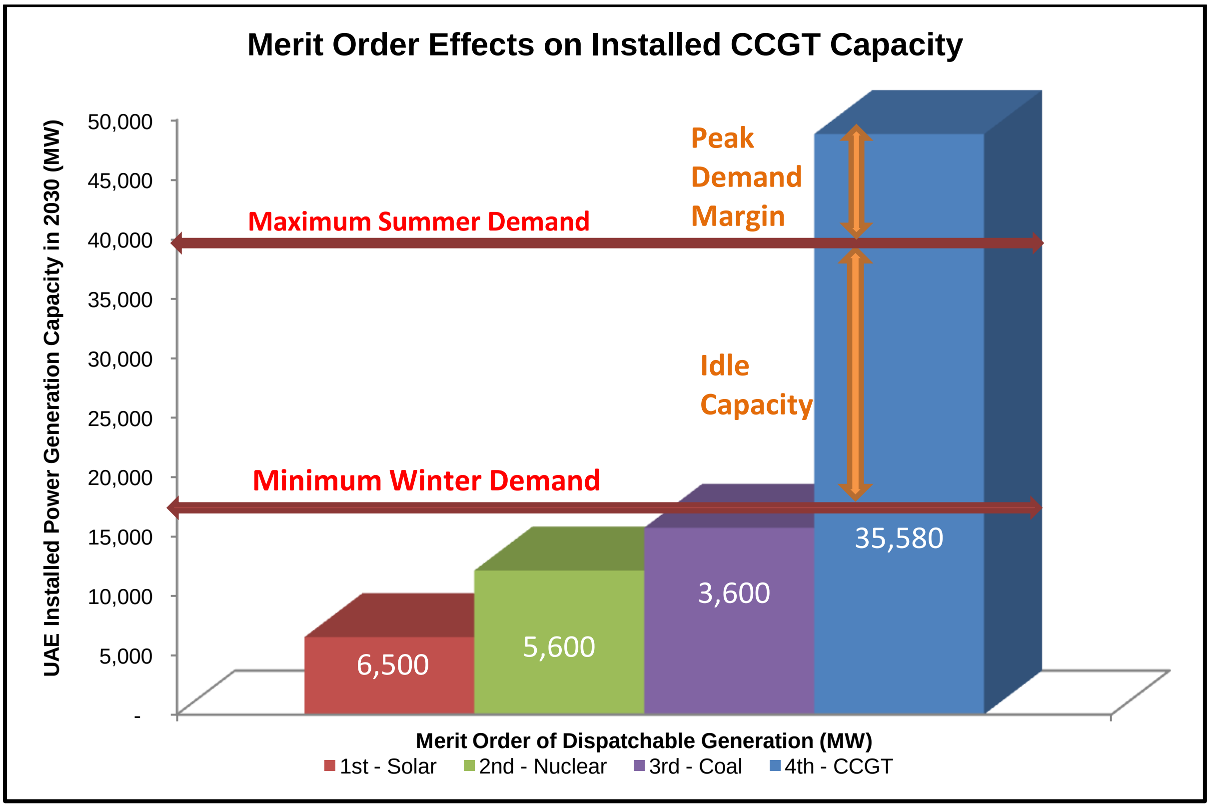

Figure 9 Merit order effects on installed CCGT capacity

Another future potential factor to the competitiveness of CCGT technology in comparison to nuclear and solar power are carbon emissions costs. The introduction of carbon emissions schemes and a rise in CO_2 costs may have a significant impact on the contest between coal, gas, renewable and nuclear power. The UAE renewable energy policies and the goals to reduce GHG emissions are on a voluntary basis however and there are no obligations or legally binding targets to reduce its significant GHG emissions.

6.4 Long term implications for existing CCGT plants

The new power generation market in the UAE poses challenges to existing CCGT plants who wish remain in operation and for network operators who need to preserve a reliable grid. A major constraint in the UAE power generation market is the predisposition in IPP development models towards building base load power plants that are required to be available to operate at all and any time to provide cheap electricity. An efficient electrical system must be balanced with several power generation technologies that are flexible to meet base-, part- and peak-load demands. To achieve this balance there must be a change in strategy and system planners should consider the development of more flexible capacity in addition to building large scale base load IPPs. Future IPP tenders could be specified in such a way as to allowing developers to design a flexible plant for various load regimes.

The introduction of intermittent solar and base load nuclear and coal power generation technologies in the incumbent CCGT power market may complicate the existing IPP models and private investors could have future additional risks to consider and manage. IPP generators may not be able to adequately recover the costs from increased cycling operations as a result of the increased daily and seasonal fluctuations in demand.

The long-term off-take contracts for IPPS are typically between 15 and 25 years and certain costs such as the O&M, interest rates, currencies and fuel prices are fixed at financial close. In a typical UAE IPP structure there is only 40% equity for the foreign investor, but this foreign investor takes all of the operational responsibility. Investors considering increased risks from increased cycling operations as part of their investment strategy decision may increase the rates of return.

Another issue for existing IPP's is that less than 5% of an IPP's income actually depends on power production, and this is a pass-through cost. The main income is based on maintaining a target availability figure. Maintaining this target availability is of key importance to ensuring the expected rate of return to the investor. If there are increased cycling operations which result in increased downtime or decreased efficiencies or availabilities, then the risk of maintaining the targets is increased. Private investors' required real rates of return may be higher than the 3%, 7% and 10% discount rates used in this study and the time required to recover the invested capital may be shorter than the assumed 25 years.

The contractual terms of IPPs may need to be reviewed and dealt with by policy makers prior to any future reforms to the existing UAE electricity market. While advanced CCGT plants can be more suitable for flexible operation, current installed units may still be required to operate for many more years. Any imbalances to existing IPP structures may deter future foreign investment and increase electricity generation and transmission costs over time. There is also the risk of creating stranded generation assets if electricity demand growth slows down.

Additional costs to existing IPPs resulting from cycling operations could be recuperated through Capacity Remuneration Mechanisms (CRMs). Such mechanisms could remunerate the fixed/capital costs of IPP plants which are suddenly required to operate in a fast ramping and fast cycling manner. Such methods are already seen in more mature diversified markets in Europe. In order to successfully utilise CRMs in such manner, it is first necessary that existing CCGTs adapt to more flexible operations.

7.0 Conclusions

This study set out to investigate the future UAE power generation profile and to evaluate the competitiveness of CCGT technology for the new electricity market. Traditional and advanced CCGT technologies were examined in detail and the key technical and economic factors that affect the competitiveness of these CCGT units were evaluated.

In examining the forecasted power generation profile it was identified that the utilisation rate of CCGT units will initially decrease significantly as penetrations of solar, clean coal and nuclear power increase. However to meet the forecasted energy demands of the UAE approximately 11 GW of new CCGT units will be required to bridge the gap that low-carbon technologies do not provide. The merits of incorporating advanced CCGT technology into the future power system to meet this demand were investigated. The results showed that advanced H-class technology has the lowest LCOE and as such matches the major market drivers for the UAE energy transition, namely; competitive lifecycle costs, high thermal efficiencies which reduce fuel costs and limit CO_2 emissions and a high operational flexibility.

The results indicate the important challenges that older CCGT technologies face due to their lower thermal efficiencies and their lesser ability to operate on a more flexible basis to account for load variations and two shift operations caused by the intermittent solar generation.

This study conveniently facilitates future discussions on the opportunities and challenges of the UAE's energy transition for developers, electricity suppliers and national policy makers. It highlights the importance of investing in flexible generation and of upgrading existing plant to be more efficient and capable of cycling operations.

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Acronyms and Abbreviations

ADWEA: Abu Dhabi Water and Electricity Authority

ADWEC: Abu Dhabi Water and Electricity Company

AED: United Arab Emirates Dirham

CCGT: Combined Cycle Gas Turbine

CRM: Capacity Remuneration Mechanism

DEWA: Dubai Water and Electricity Authority

FEWA: Federal Electricity and Water Authority

GCC: Gulf Cooperation Council

GE: General Electric

GHG: Green House Gas

GT: Gas Turbine

GW: Gigawatt

HRSG: Heat Recovery Steam Generator

IPP: Independent Power Producer

kJ/kWh: kilojoules per kilowatt-hour

kW: Kilowatt

kWh: Kilowatt Hour

kt: kilotons

LCOE: Levelised Cost of Electricity

MMBTU: Million Metric British Thermal Units

MOE: Ministry of Energy

MW: Megawatt

NPV: Net Present Value

O&M: Operation and Maintenance

OEM: Original Equipment Manufacturer

PV: Photovoltaic

ST: Steam Turbine

SEWA: Sharjah Electricity and Water Authority

UAE: United Arab Emirates

USD: United State Dollars