An Economic and Environmental Analysis of a Combined Cycle Power Plant, Improved by Using a Gas Turbine Inlet Air Cooling

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Abstract: – The economic and environmental impacts of gas turbine inlet air cooling were investigated for Nubaria (around 130 k m south East of Alexandria, Egypt) combined cycle power plant as a case study. Thermodynamic model was developed to simulate the combined cycle before and after the integration to the proposed single stage Li Br and H_2O absorption cooling system. Inlet air-cooling by 10 ^oC can increase the annual power generation by 6.4 %. The 20-year Life Cycle Cost Analysis of the proposed integration indicates a net present value of MM$ 20 for each generation module with payback period of 3.5 years. Sensitivity analysis was conducted for potential changes in both fuel and electricity prices. Despite of the overall increase of the plant fuel demand by 6.5%, the specific fuel consumption has been decreased by 0.5 g / kWh from 164 g /kWh to 163.5 g/kWh. This decrease means an improvement of the combined cycle heat rate by 0.3%. This decrease in heat rate means a considerable reduction in CO_2 emissions (30 kton / year) hence improving the plant environmental footprint.

Keywords: Absorption Chiller, Turbine Inlet Air Cooling, Economic, Payback, Environmental Analysis

1 Introduction:

Thermal power plants supply 90% of total electricity demand in Egypt where, the average generation efficiency is 40% [1]. Still the remaining 60% is emitted to the atmosphere as waste heat and greenhouse gases GHGs without further use or recovery. This fact stimulates the need to search for opportunities to benefit from these waste energy, especially in light of what the country is witnessing from growing demand for electricity and unprecedented strict environmental regulations. On the other hand, there are more than 130 gas turbine GT contributing nearly 35% of the total generation capacity. Despite of their numerous advantages, GTs are nevertheless negatively impacted by high ambient temperature. On hot days, power demand increases while gas turbine power and efficiency fall. A significant decrease in the generation efficiency occurs at high ambient temperature due to lower air density and the resulting increase in compressor specific work. Depending on the type of the gas turbine, the output power will decrease by 6% to 10% for every 10˚C of intake-air temperature increase. At the same time, the specific heat consumption increase by a percentage between 1.5% and more than 4% Zhang [2]. Both combined cycle CC and simple GT power plants represent 50% of the country's installed capacity. Achieving substantial improvement in CC performance by adding gas turbine inlet air cooling GTIAC system has become an approved and well recognized technology. The option of integrating an absorption chiller to the existing Nubaria CC power plant has been thoroughly investigated as a case study. A unique steady-state model for the overall integrated cycle was developed and results analyzed. As a first step, the energy and exergy analysis of its impacts on the plant performance was conducted and presented in separate paper [3]. Although, many researches have been conducted to investigate different aspects of GTIAC, only, very few have considered the Egyptian specific climatic and economic conditions. The current study is a complementary part for the previous work. It investigates the economic and environmental impacts of GTIAC for the same plant, hence, filling this scientific gap. References [4-10] represent over view and comparative studies about the different used technologies and their applications in specific countries. Gareta et al [11] presented an accurate procedure to calculate the profitability of air cooling systems in combined cycle plants. Boonnasa et al [12] proposed a steam absorption chiller to cool GT intake air in Bangkok. The annual GT Power has increased by 10.6% and the CC power plant by 6.24%. In economic analysis, the payback period was about 3.81 years, internal rate of return 40%. Ameri [13] investigated the application of GTIAC in Iran, where this technique will increase the output power by 11.3%. The economic study has shown the internal rate of return IRR will be 23.4% and the payback period is estimated to be around 4.2 years. Yazdi [14] investigated the utilization of a heat pump. Results suggested that mean output power increases during hot seasons by 11.5% and 10% for Yazd and Tehran, respectively, and the costs of power generation decreased by 11% and 10% respectively. Suneetha et al [15] conducted an experiment of inlet air cooling for a gas turbine of 102.19MW rated power. Air temperature was decreased from 33˚C to 15˚C by using water chiller of 4717.45 TOR capacity. Turbine output increases to 114.94 MW with percentage increases of 12.47%. Murugavel et al [16] studied the life cycle cost analysis of waste heat operated VAM and compared it to the conventional VCM same capacity. The initial cost of the VAM was 125 % higher than VCM, while its operating cost was 78.2% lower. The life cycle cost of VAM was found to be 71.5 % low compared to VCM. In addition, VAM will result in GHG reduction of 2.85×10^6 kg/year. Barigozzi et al [17] presented a techno-economical parametric analysis of GTIAC for a combined cycle power plant. Three cases have been analyzed, supposing the plant operating in different sites, Phoenix, New Orleans, and Abu Dhabi. De Lucia et al [18] GTIAC using absorption chiller can enhance power production by 5-10 % on a yearly basis, depending on site climate, and up to 18% in the warmest months. These benefits are double those supplied by evaporative cooling. The system simple payback period is nearly 2 years. Grace et al [19] used special software that integrates performance, cost, and financial analysis capabilities into a single product, combining them with a flexible data input structure that allows the user to optimize the plant design to technical and financial criteria. Kodituwakku et al [20] investigated the option of GTIAC using absorption chiller for 20 MW (GE MS5001 R) gas turbine in Sri Lanka. Up to 20% extra power can be achieved annually by cooling ambient air from 30 ^{o}C to 15 ^{o}C. The direct payback period for this case was estimated to be 11 years. Tehrani et al [21] has investigated the feasibility of different GTIAC systems and the best case selected by both technical and economic consideration. Sherif et al [22] performed life cycle cost analysis (LCCA) to compare a novel high-pressure regenerative turbine engine (HPRTE) to conventional one. This novel turbine is integrated with a vapor absorption refrigeration system. The HPRTE showed life cycle cost savings of 7% over turbines with a similar power capacity. Marzouk, et al [23] studied the chiller cooling and evaporative cooling thermally and economically for 264 M W gas turbine plant located at Korymat – South of Egypt, the results indicates that the gas turbine annual power gained by cooling by chiller is 117027 MWh, and the net cash flow is MM$ 3.8, while the gas turbine annual power gained by cooling by evaporative is 86118 MW, and the net cash flow is MM$ 4.5.

2 Methodology application

The methodology is based on the thermodynamic simulation of the GT, CC as described in the plant manual [24] and the inlet air cooling equipment to predict the performance of the newly integrated cycle at different operational scenarios. On the other hand, effect of the ambient conditions, environmental impacts, the economic variables (gas and electricity prices, investment and maintenance costs) has been taken into consideration in the process of GTIAC system sizing and type selection. The following stepwise procedure has been systematically followed in order to investigate and analyze all important and controlling parameters needed for the integration of GTIAC into Nubaria CC plant.

1. Technical data analysis: investigate all relevant design and operational details of the plant's different equipment.
2. Site climatic data analysis: calculate climate data (temperature and relative humidity) of an average day, month, and year as shown in figures 1, 2, 3.[25]
3. Tariffs and prices of utilities: i nvestigate the prevailing electricity tariffs to and fuel pricing scheme in local market. Conduct sensitivity analysis for the additional fuel cost and augmented electricity sales revenues on annual basis.
4. Simulation of the CC performance without the air cooling system, according to historical climate data.
5. Simulation of the CC performance with the air cooling system and new inlet conditions. Parametric study with energy and exergy analysis of the CC.
6. Comparison of the previous results, in order to elucidate power output improvements and fuel consumption variation for each scenario.
7. Select the optimum size of the absorption cooling system to achieve the best results. Selection is normally based on both the achievable augmented power and the corresponding generation efficiency.
8. Evaluation of the extra power output by multiplying the electricity price and the number of hours to obtain the incomes.
9. The payments are calculated by multiplying the extra fuel consumption for augmentation by the fuel unit cost.
10. Calculation of the profit, making the difference between incomes and payments, and subtracting also cooling system operation and maintenance costs.
11. Conduct life cycle cost analysis for the integrated CC and GTIAC system.
12. Environmental impacts of the proposed integration is calculated by comparing the GHGs emitted to the atmosphere before and after considering the GTIAC system.

3 Results and Discussion

Thermodynamic model using Engineering Equations Solver EES [26] has been developed to simulate the above mentioned IES. The model has been configured for the steady state condition only. The 750 MW module was assumed as the investigated unit. The augmented power, change in fuel consumption and thermal efficiency have been estimated and presented in a separate work. For example, figure (4) indicates effect of ambient air temperature on the plant generated power. The effect of ambient air temperature on fuel consumption rate and power generated in the two cases of working with and without GTIAC is shown in figure (5). Parametric study was carried out to predict the CC performance at different ambient temperatures both with and without GTIAC. 412 GWh could be augmented due to GTIAC with percentage increase of 6.85%. The change of fuel consumption at specific ambient temperatures is explained in figure (6). Despite of the annual consumption increase by 65.4 k Ton of gas with percentage 6.5%, the specific fuel consumption has been decreased by 0.5 g/kW power generated. This means a slight improvement in thermal efficiency.

The estimated cooling capacity is 4000 TOR/module. However, it is assumed to be 150% in the economic calculations as a safety margin. The following economic and environmental analysis is based on the previously obtained results and the pre-selected values of some calculation variables as assumed in table (1). Two economic key indicators to evaluate the modification's cost benefit analysis, namely, NPV and payback period are selected. The NPV was calculated by the application of equation (1).

$$NPV = \frac{R_1 - C_1}{1+r} + \frac{R_2 - C_2}{(1+r)^2} + \frac{R_3 - C_3}{(1+r)^3} + \ldots\ldots + \frac{R_n - C_n}{(1+r)^n} \quad (1)$$

i is related to specific year which is under study, Ri and Ci is the income and cost of a same pointed year, r is a discount rate and finally n is a life plan. An annual inflation rate of 3% was taken into consideration for all calculations. The life cost cycle analysis LCCA of the additional power augmented by the proposed inlet air cooling system can be estimated using equation (2) for life span of 20 years.

$$C_t = \sum (C_i + C_o + C_f - C_s) \quad (2)$$

According to the literature review, the capital cost of the absorption chiller is based on the size and capacity. Normally, the cost figures covers only the chilling coil and does not consider the installation, transportation, pumping, piping equipment and construction costs. However, in this case the overall installation cost of GTIAC was considered [27]. Figure (7) indicates the sensitivity analysis of the extra fuel consumption, where, GTIAC cannot be economically justifiable if the fuel price becomes hire than $5 for MMBTU Figure (8) represents the sensitivity analysis for electricity prices and indicated that the modification will be less attractive if the sales price of augmented electricity becomes less than $.04/kWh. The LCCA of GTIAC is explained in table (5) for one generation module of 750 MW rated power. NPV of about MM$20 with payback period of 3.5 years can be achieved. In addition to the mentioned positive NPV the proposed change will bring some surplus benefits to Nubaria CC plant. For example, 54 ton/hr/ plant harvested fresh water as separated during cooling process. This water is nearly demineralized and can be used for boiler make-up saving nearly k$ 100/plant / year. Another benefit with positive economic impact is the saving of k$ 250/plant / year as a result of improvement in the maintenance costs of filter package due to longer life time.

Also, the environment will benefit from the proposed modification. Despite of overall increase of the plant fuel demand by 6.5% due to additional power generated, the specific fuel consumption has been decreased by 0.5 g / kWh from 164 g / kWh to 163.5 g / kWh. This decrease means an improvement of the combined cycle heat rate by 0.3%. What looks minor decrease in the consumed fuel simply means saving of 3000 ton of natural gas / year. The saved fuel reduced the GHGs emitted to the atmosphere by around 30 kton CO2/ year.

4 Conclusion:

The application of GTIAC has become very well recognized technology. It has become a must for a country like Egypt which targets higher rate of economic and sustainable development, Inlet air-cooling by 10 ^{o}C can increase the annual power generation by 6.4 %. The 20-year Life Cost Analysis of the proposed integration indicates a net present value of MM$ 20/ module. The payback period is 3.5 year. Despite of the overall increase of the plant fuel demand by 6.5%, the specific fuel consumption has been decreased by 0.5 g / kWh from 164 g / kWh to 163.5 g / kWh. This decrease means an improvement of the combined cycle heat rate by 0.3%. This decrease in heat rate means an annual reduction of 30 kton of CO_2 emissions hence improving the plant footprint.

Nomenclature:

CC	Combined Cycle
C_f	Fuel Cost
Ci	Cost at specific year i
C_o	Operation and Maintenance Cost
CO_2	Carbon Die Oxide
C_s	Salvage Value
C_t	Total Cost
GHGs	Green House Gases
GT	Gas Turbine
GTIAC	Gas Turbine Inlet Air cooling
HPRTE	High-Pressure Regenerative Turbine Engine
HRSG	Heat Recovery Steam Generator
I	Specific year
IES	Integrated Energy System
LCCA	Life Cycle Cost Analysis
LHV	Lower Heating Value
MM$	Million United States Dollar
N	Life span "year"
NPV	Net Present Value
R	Financial discount rate
Ri	Revenue at specific year i
ST	Steam turbine

TOR Ton Of Refrigeration
VAM Vapour Absorption Machine
VCM Vapour Compression Machine

Table (1) Values of some financial variables

Item Description		Value
C_t	Total Cost	Throughout the life time
C_i	Investment Cost	$1500/ TOR [27]
C_o	Operation and Maintenance Cost	3 % C_i
C_s	Salvage Value	5 % C_i
C_f	Fuel Cost	$ 4 / MMBTU [28]
	Absorption Cooling Capacity/ unit	6000 TOR
	Augmented Power kWh	412,245,500
	Electricity Tariff $/kWh	0.04
	Additional fuel demand MMBTU	3270392.034
	Financial interest rate	10%
	Inflation rate	3%
	Base year 2016 Costs ($)	$= 16 Egyptian Pounds LE
	Annual working hours (hr)	8000
	Project lifetime (year)	20

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Annex 1

Figure (1) Site Temperature Profile Measured in Hourly Intervals [25]

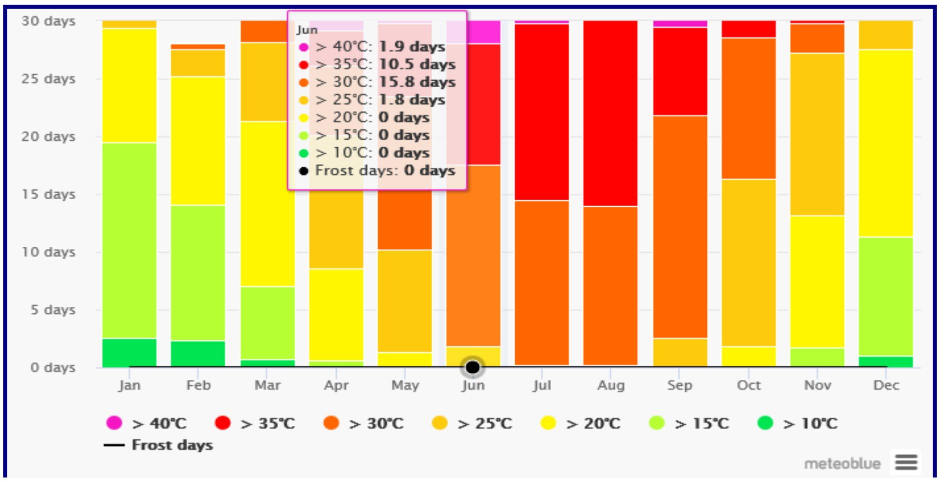

Figure (2) Daily Maximum Recorded Temperature Diagram [25]

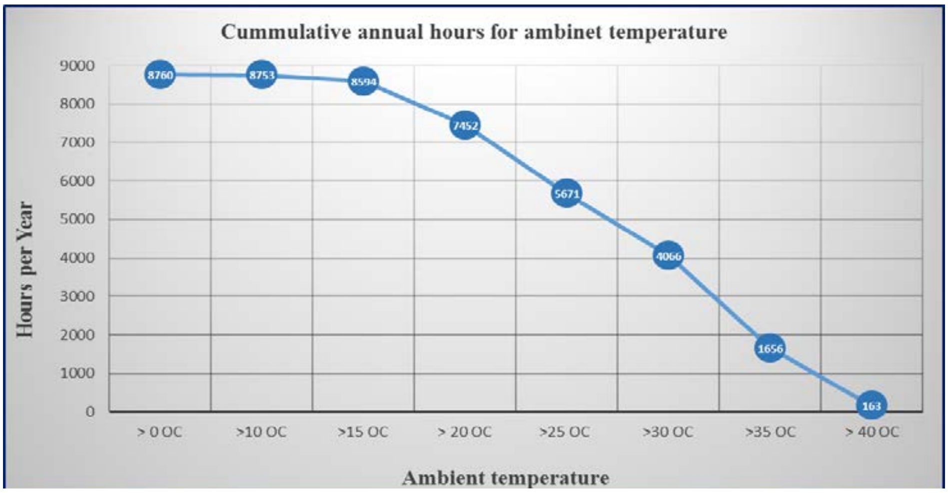

Figure (3) Cumulative annual hours for ambient temperature

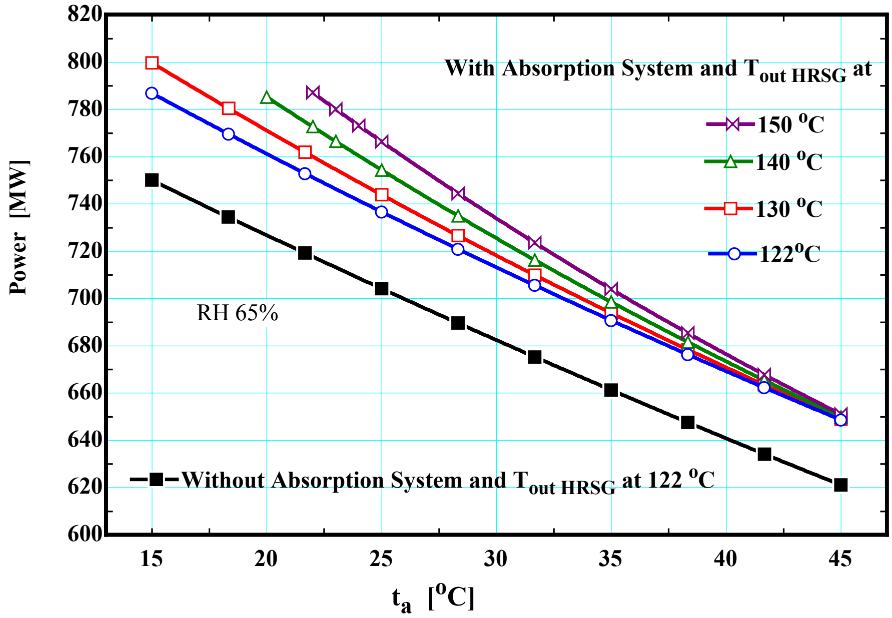

Figure (4) Effect of ambient air temperature on the plant generated power

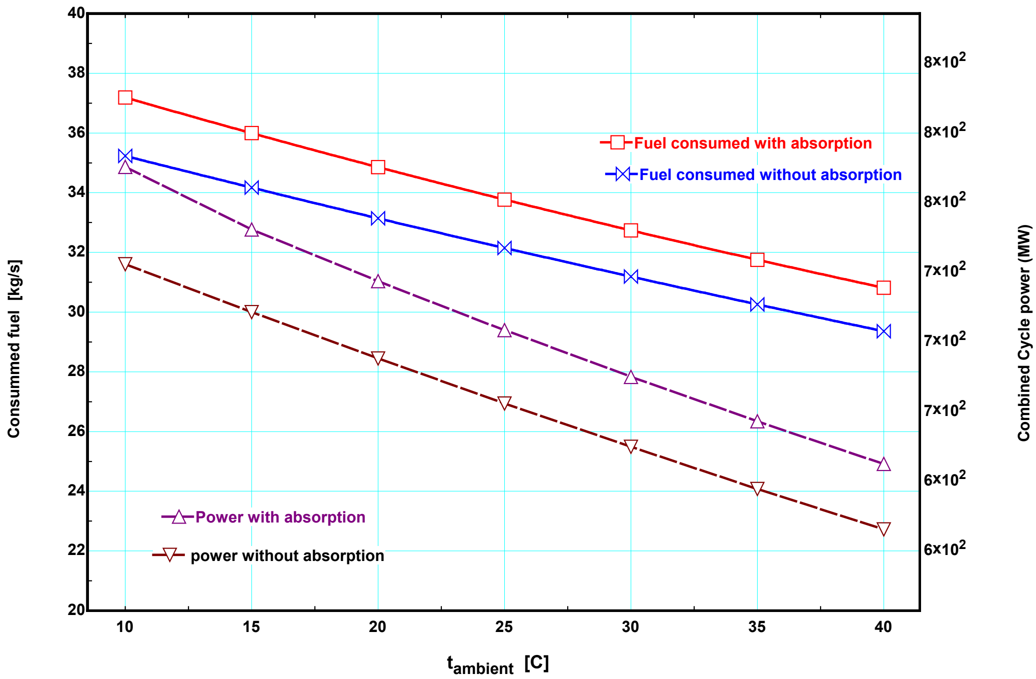

Figure (5) Effect of ambient temperature on fuel and power generated with and without GTIAC

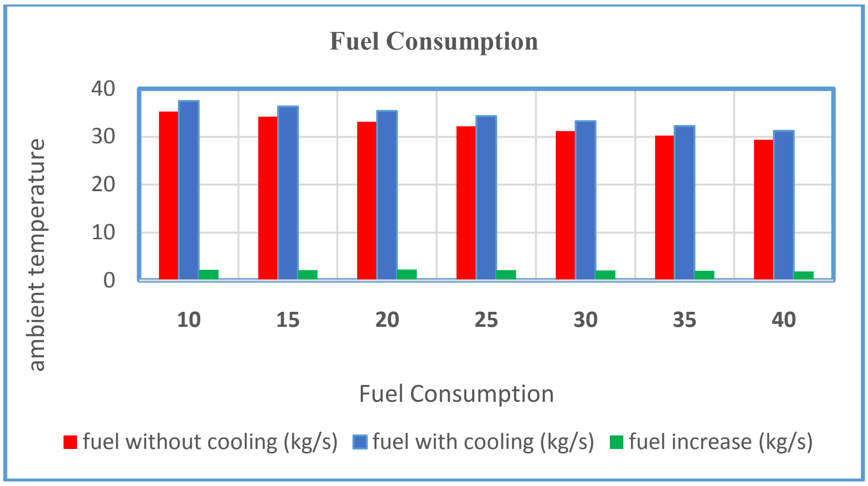

Figure (6) Change of Fuel Consumption Due to GTIAC

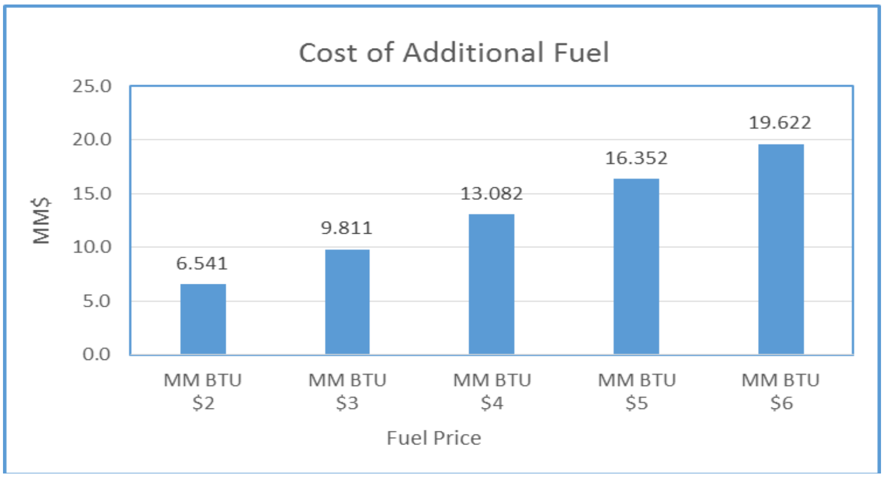

Figure (7) Sensitivity analysis of the Cost of Additional fuel demand

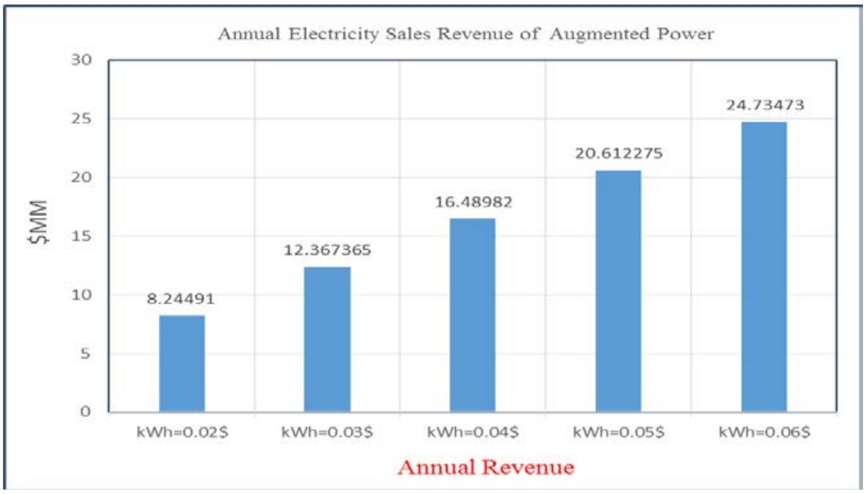

Figure (8) Sensitivity Analysis of Electricity tariff and Annual Revenue