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Energy economics and optimal generation mix of selected power plants technologies in Ghana

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A B S T R A C T

Currently most countries in Africa are plagued with a persistent trend of inadequate power supply, which has a ripple effect on all sectors of the economy. Governments needs to expand electricity generation and supply and manage the existing generating facilities efficiently and effectively to make electricity accessible and less expensive. In this study eleven power plant technologies were analyzed in terms of fuel type, fuel cost and carbon dioxide emissions. Economic analysis of each power plant was analyzed. With the help of screening and load-duration curves, the optimum generation mix was determined. The paper therefore concludes that SGT-400 Technology of 80 MW with 3, 6% contribution to the current load should be used as peaking power plant. Orenda OGT25000 Technology of 220 MW rated capacity which contributes 10% to the load should be used for Mid-load generation, while Coal Supercritical Technology of 1500 MW capacity should be used as Base-Load power plant. However, the other technologies considered in the analysis were found to uneconomical and cannot be advice to be used in power generation.

Introduction

Thermal generation is the hope for solving the energy problems in Ghana looking at the water levels of our Hydro Dams in Ghana, it is important as a country to identify which type of thermal technology will be much more beneficial and economical. Efficient and economical use of our existing power plants is very paramount. Moreover, measures are not only needed to make more energy resources available but also to make efficient use of what we have now. Obviously, this calls for extensive studies to explore the various thermal power plant conversion technologies as well as sustainable fuel alternatives to augment the current stock. It is in the light of this that this research is been conducted to determine the economic assessment of the various Thermal Power Plant in Ghana and also to determine the best technology that would give a maximum output. The growing trends of industrialization and population increase have brought increasing demands on energy resources worldwide, a situation from which Ghana is not exempted. Currently, the country is faced with a persistent trend of inadequate power supply, which has a ripple effect on all sectors of its economy. Efforts are

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being made at the national level via the Ministry of Energy, Ministry of Power and Ghana Energy Commission to arrest the current situation, through policies and agreements with multinational investors. In line with the national vision of attaining energy sufficiency for sustainable economic growth, the Government of Ghana (GoG) has created the Power Ministry from the Ministry of Energy to focus mainly on electric power generation, transmission and distribution. The new ministry has instituted measures in the short term to buy and hire some thermal power plants and power barges to generate electricity to help reduce the current shortage in the country.

Also, it is foreseeing the rapid completion of existing thermal power plants projects under construction in the country such as the 230 MW Kpone Thermal Power Plant and 110 MW TICO expansion. Measures are not only needed to make more energy resources available but also to make efficient use of what we have now. Obviously, these calls for extensive studies to explore the various thermal power plant conversion technologies as well as sustainable fuel alternatives to augment the current stock [11]. Since thermal generation is said to be the hope for solving the energy problems, it is important as a country to identify which types of technologies will be much more beneficial. As a developing nation, we need more megawatts to develop all sectors of the economy by making efficient use of our existing power plants and acquiring new reliable and efficient power plants. Taking into consideration the sources of fuel for the running of the plants. Even though most of the existing plants are generating, we still have shortage in our system. Some may attribute it to Government's failure to forecast and construct new power plants to meet the annual increase in demand. Another factor is the failure to do due diligence in the selection of the suitable technology. This is because, most of the power plants brought into the country either by the Energy Ministry, Volta River Authority (VRA) or Independent Power Producer (IPP) do not perform at their maximum efficiency. They are most of the time acquired whenever the nation is in crisis. This consequently leads to a rush and not taking our time to do a better selection of the technology. Also, some of these power plants were given to the Government as grants or loans (example is the Takoradi-T3 plants). This project will serve as a guide to help these organizations in the selection of the appropriate, efficient and environmentally sustainable technology for generating power in the country. Energy forms the backbone and the core support on which every economy thrives.

Like many developing countries, Ghana has to reckon with a perennial trend of energy insufficiency especially with electricity supply. The Ghana Energy Commission indicated a supply shortfall of 2700 GWh for the year 2010 [2]. Currently, the nation is shedding load due to shortage in generating about 600 MW to 700 MW [3]. The discrepancy between the overall national demand of energy and the generating supply being made available now yields a deficit that cripples many sectors of the economy. The rationing of load (Load Management) in the country has led many manufacturing companies to lay off workers to help reduce production cost in order for them to still stay in business. For instance, Coca Cola bottling company had to shut down its branch in Kumasi in May 2015 (Metrofmonline.com 2015). Also, a plastic manufacturing company in Accra sent nearly 200 staffs home just to reduce the cost of production since the running of their diesel generators has increase their production cost. VALCO, a major producer of aluminum products for both local and international markets has a regrettable trend of shutting down or working below capacity due to shortfalls in national electricity supply [5]. A look at our daily schedules reveals how indispensable electricity has become as far as the very execution of most of our routines at work is concerned; ranging from simple word processing to complex automated manufacturing and processing activities. Therefore, abrupt outages in power supply result in increase in production cost, reduced productivity, loss of revenue, and occasional accidents, with a possible damage to both life and property. Thus, a guide to help in the selection of power plant technology and their suitable source of fuel for optimum efficiency utilization that would afford Ghanaians the luxury of uninterrupted electricity supply need to be developed and harnessed as a matter of urgency, if the country is to achieve its millennium development goals.

Sustainable electric power is a basic requirement for the development of many countries and to make their aspirations for higher living standards to be achieved. (Energy Center, KNUST, 2008). The objective of this paper is to analyze the costs of generating electricity in Ghana with the main aim of determining the optimum generation mix and the most efficient thermal power plant technology.

Power plant technology analysis

Fuel rate

Table 1 shows the various installed, on-going and future thermal power plants for the country and the types of fuel used in generation.

The amount of fuel required by a power plant to generate a kWh of electrical energy can be given by:

$$m_f = \frac{h_R}{h_V} \tag{1}$$

m_f: Quantity of fuel used to generate electric energy, m^3/kWh or kg/kWh
h_V: Heating values, kJ/m^3 or kJ/kg
h_R: Heat rate of technology, Btu/kWh or kJ/kWh.
(Source: [13])

Table 1
Technology, fuel type used and ISO rating capacity of Thermal Power Stations in Ghana.

Generating Stations	Installed Unit Capacity, MW	Number of Unit	Technology/Model	Heat Rate, kJ/kWh	Fuel Type
TTPS (T1)	110	2	GE Frame 9E.3	10,960	Gas/DFO/LCO
TTPS- TICO (T2)	110	2	GE Frame 9E.3	10,960	Gas/DFO/LCO
TTPS (T3)	25	4	Orenda OGT 25,000	9480	Gas/DFO/LCO
TT1PS (Station 2)	126	1	GE Frame 9E.4	10,650	Gas/DFO/LCO
TCTPP (Station 2)	126	1	GE Frame 9E.4	10,650	Gas/DFO/LCO
TT2PS (Station 3)	7.9	4	SGT-300	11,773	Gas/DFO
TT2PS (Station 3)	12.9	4	SGT-400	10,355	Gas/DFO
KTPP	115	2	Alstom GT11N2	10,619	Gas/DFO
APR ENERGY	25	10	TM2500	9755	Gas/DFO
VRA/SHENZHEN (Feasibility Studies)	350	2	Supercritical	23,027	Coal
VRA/SHENZHEN (Feasibility Studies)	600	2	Supercritical	23,027	Coal

(VRA Project & System Monitoring Department, 2012)
(Energia, 2013)

Table 2
Low heating values of the various types of fuel for electric power generation.

TYPE OF FUEL	LOW HEATING VALUE
Natural Gas (Ghana Gas)	38,956.84 kJ/m^3
Light Crude Oil (LCO)	42,327 kJ/kg (Bonny Fuel)
Distillate Fuel Oil (DFO)	43,400 kJ/kg
Bituminous Coal (South Africa)	25,120.8 kJ/kg

(Source: [8])
(Source: [12])
(Source: [10])
(Source: [9])

Table 3
Prices of fuel as of July 2015 for electricity generation.

TYPE OF FUEL	PRICE
Natural Gas (Ghana Gas)	US$ 8.84/MMBTU
Light Crude Oil (LCO)	US$ 54.285/barrel
Distillate Fuel Oil (DFO)	US$ 1.0239/litre
Bituminous Coal (SA)	US$ 57.42/ton

(Source: [7])
(Source: [9])

Table 4
Price of the various fuels per their energy content.

TYPE OF FUEL	PRICE	PRICE PER ENERGY CONTENT, US$/MMBTU
Natural Gas (Ghana Gas)	US$ 8.84/MMBTU	8.84
Light Crude Oil (LCO)	US$ 54.285/bbl	9.359
Distillate Fuel Oil (DFO)	US$ 1.0239/litre	27.96
Bituminous Coal (SA)	US$ 57.42/ton	2.893

Table 5
Heat Rate conversion, kJ/kWh to BTU/kWh.

Generating Stations	Installed Unit Capacity, MW	Technology	Heat Rate, kJ/kWh	Heat Rate, BTU/kWh
TTPS (T1)	110	GE Frame 9E	10,960	10,388.08
TTPS- TICO (T2)	110	GE Frame 9E	10,960	10,388.0757
TTPS (T3)	25	Orenda OGT 25,000	9480	8,985.31
TT1PS (Station 2)	126	GE Frame 9E	10,650	10,094.25
TCTPP (Station 2)	126	GE Frame 9E	10,650	10,094.25
TT2PS (Station 3)	7.9	SGT-300	11,773	11,158.65
TT2PS (Station 3)	12.9	SGT-400	10,355	9,814.65
KTPP	115	Alstom GT11N2	10,619	10,064.87
APR ENERGY	25	TM2500	9755	9,245.96
VRA/SHENZHEN	350	Supercritical	23,027	21,825.38
VRA/SHENZHEN	600	Supercritical	23,027	21,825.38

(Source: [6])

Fuel rate for GE Frame 9E.3 technology using natural gas fuel is:

$$m_f = \frac{10{,}960\ kJ/kWh}{38{,}956.84\ \text{kJ/m3}}$$

$$m_f = 0.281\ \mathbf{m^3/kWh}$$

The results for the **amount of fuel** of the different types of fuels used to produce 1 kWh for each technology is shown in supplementary sheet **S1**.

Fuel cost

The world market prices of the various fuels used in power generation are shown in the table below.
The cost of fuel required by a power plant to generate a kWh of electrical energy can be given by equation below:

$$\mathrm{C_F} = \frac{P_F\ x\ h_R}{10^3} \tag{2}$$

$\mathrm{C_F}$: Cost of fuel used to generate electric energy, US$/MWh
P_F: Price of fuel used to generate electric energy, US$/MMBTU
h_R: Heat Rate of technology for generating power, BTU/kWh
(Source: [13]), (Source: [4])
Fuel cost for GE Frame 9E.3 technology using natural gas fuel is;

$$\mathrm{C_F} = \frac{8.84\ \frac{\text{US\$}}{\text{MMBTU}} \times 10{,}388.08\ \text{BTU/kWh}}{10^3}$$

$$\mathbf{C_F = 91.83\ US\$/MWh}$$

The results for the **cost of fuel** of the different types of fuels used to produce 1 kWh for each technology is shown in supplementary sheet **S2**.

Power plant CO_2 emission

The quantity of CO_2 emitted by any power plant depends on, carbon content of the fuel used, efficiency or heat rate of the plant, heating value of the fuel used, amount of electrical output produced To calculate the CO_2 emission from a fuel, the carbon content of the fuel must be multiplied with the ratio of the molecular weight CO_2(44) to the molecular weight Carbon (12) = 44 / 12 = 3.67 kg/kg. The amount of CO_2 produced by a power plant per kWh of energy generated can be given by Eq. (3) below:

$$m_{CO2} = f_c\ x\ m_F\ x\ 3.67 \tag{3}$$

Determination of the fraction of carbon in Natural gas:

$$f_c = \frac{P\ x\ M_c}{T\ x\ \rho_{NG}} \sum_i \left(\frac{f_i}{M_i\ x\ R_i} \right) \tag{3a}$$

Density of natural gas ρ_{NG} in kg/m^3 can be given by;

$$\rho_{NG} = \frac{P}{T} \sum_i \left(\frac{f_i}{R_i} \right) \tag{4}$$

where;
m_{CO2}: Amount of carbon dioxide produced, m^3/kWh
m_F: Fuel rate, kg/kWh
f_C: Fraction of carbon in natural gas, kg/kg
f_i: Fraction of the i-th component of natural gas, m^3/m^3
P: Standard pressure (101.3 kPa), kPa
T: Standard temperature (273 K), K
R_i: Gas constant of the i-th component of natural gas, kJ/kg-K
M_C: Molecular weight of carbon, kg/kmole
ρ_{NG}: Density of natural gas at standard conditions, kg/m3
M_i: Molecular weight of the ith component of natural gas, kg/kmol
(Source: [13])

$$\rho_{NG} = \frac{101.3}{273} \times \sum_i \left(\frac{100}{8.3145} \right)$$

$$\rho_{NG} = \frac{101.3}{273} \times 12.02718$$

$$\boldsymbol{\rho_{NG} = 4.46283}$$

Therefore, the fraction of carbon in Natural Gas fuel (Ghana Gas)

$$f_c = \frac{101.3 \times 12.0107}{273 \times 4.46283} \times 0.67789$$

$$f_c = 0.9986 \times 0.67789$$

$$\mathbf{f_c = 0.677\ kg/kg}$$

(Source: [10])
(Source: [1])
Calculation of $\sum_{\mathbf{i}}(\frac{\mathbf{f_i}}{\mathbf{M_i\ x\ R_i}})$ is shown in supplementary sheet **S3**.
The amount of CO_2 emitted for GE Frame 9E.3 technology using natural gas fuel is:

$$m_{CO2} = 0.677 \times 0.281 \times 3.67$$

$$\mathbf{m_{CO2} = 0.698\ m^3/kWh}$$

The results for the **carbon dioxide emission** of the different types of fuels used for each technology is shown in supplementary sheet **S3**.

Summrery results

Graphical representation (i.e. bar and pie chart) of the fuel cost for each technology is show below;

Economic analysis of power plants: cost of electricity/service

The cost of production of electricity of technology i that uses fuel type j, $P_o(i, j)$ in \$/MWh, can be given by Eq. (5) below:

$$P_o(i,j) = \frac{C_{cpi}\,x\,C_{RFi} + f_{OMi}}{8760\ x\ \eta_{AVi}\,x\,C_{Fi}} + v_{OMi} + p_{Fj}\,x\,\frac{h_{Ri}}{1000} + C_{EPijm} \tag{5}$$

Fixed Cost Variable Cost
Where
C_{cpi}: Capital (capacity) cost of technology i (\$/MW)
C_{RFi}: Capital recovery factor of technology i (fraction per year)
C_{Fi}: Capacity factor of technology i
η_{AVi}: Availability of technology i
f_{OMi}: Fixed O&M cost of technology i (\$/MWy)
v_{OMi}: Variable operating and maintenance (O&M) cost of technology i (\$/MWh)
p_{Fj}: Price of fuel j (\$/MMBTU or \$/GJ)
h_{Ri}: Heat rate of technology i (Btu/kWh or kJ/kWh)
C_{EPijm}: Environmental penalty that a CO_2-emitting technology i using fuel type j must pay if environmental policy is m (\$/MWh)
(Source: [14])
Furthermore, C_{EPijm} can also be expressed as

$$C_{EPijm} = \begin{cases} 0,\ if\ m = 0 \\ m_{CO2ij}\,x\,C_{TX},\ if\ m = 1 \end{cases} \tag{6}$$

Where:
m_{CO2ij}: Amount of CO_2 emitted by technology i using fuel type j (t/MWh)
C_{TX}: Carbon tax on CO_2 emission (\$/tons, (Source: [14]),
The type of environmental policy in the economy $m = 0$, if no carbon tax is required, and $m = 1$, if carbon tax is required.
Currently in Ghana, there is no carbon tax charged by the Environment Protection Agency. Therefore, C_{EPijm} component of the variable cost is 0.

Input data

Table 12 shows the estimated capital cost, fixed and variable operating and maintenance cost for the technologies including their recovery cost factors.

$$Fixed\ cost = \frac{C_{cpi}\ x\ C_{RFi} + f_{OMi}}{8760\ x\ \eta_{AVi}\ x\ C_{Fi}} \tag{7}$$

Assuming Availability efficiency of 95% and Capacity factor of 100% for all technologies. Fixed cost for GE Frame 9E.3 is;

$$Fixed\ cost = \frac{1,270 \times 10^3 \$/MWh \times 0.2/yr + 79.5 \times 10^3 \$/MWyr}{8760 \times 0.95 \times 1}$$

$$Fixed\ cost = \$40.07/MWh$$

$$Variable\ cost = v_{OMi} + p_{Fj}\ x\ \frac{h_{Ri}}{1000} \tag{8}$$

Variable cost for technology, GE Frame 9E.3 and fuel type, Natural gas is;

$$Variable\ cost = 52.7\$/MWh + 8.84\$/MMBtu \times \frac{10,960kJ/kWh}{1000}$$

$$Variable\ cost = \$149.59/MWh$$

The results for the **variable cost calculations** of the different types of fuels used for each technology is shown in supplementary sheet **S4**.

Graphical representation (bar and pie chart) of the cost of electricity for each technology is show below;

Base-load, mid-load, and peaking power plants

Demand for electricity can vary considerably from day to night. Weekly patterns of demand for electricity indicate higher demand during the week than on weekends. On a seasonal basis, demand is normally at their highest point during the dry and sunny seasons than in the wet or rainy seasons.

These demand fluctuations signify that higher output will be required during peak demand while there will be some idle capacity during off-peak periods. Certain power plants are very expensive to install but relatively cheap to operate. These types of plants are therefore supposed to run continuously and are often referred to as base-load plants. Examples of base-load power plants include coal-fired plants, nuclear plants, combined-cycle plants and hydroelectric plants. On the other hand, some power plants are less expensive to install but very expensive to operate. As such, they must operate during peak demand or periods of highest demand, and are referred to as peak generators or power plants. They include simple-cycle gas-turbines. Between these two extremes are power plants that are operated during most part of the day. These are the intermediate load power plants. The biggest challenge for utility planners is the optimum combination of power plants that will meet the hour-by-hour power demands of their clients i.e. the combination that offers the best economic incentive. The screening curves and load-duration curves will be used to determine the economic characteristics of different types of power plants and how they relate to the loads they must serve to determine the optimum combination.

Screening curves

The total capital costs of power plants may be divided into: Fixed Costs and Variable Costs. The Fixed costs component of power plants, consist of the charges that must be paid even if the plant does not operate. They include: Capital of procuring of equipment and installation. Fixed operating and maintenance (OM) costs.Variable costs are the costs associated with operating the power plant. These costs are mainly Fuel Costs, Variable OM costs. Finding the optimum mix of power plants begins with the development of screening curves. Screening curves are actually curves that relate the annual total cost required to pay both fixed and variable costs to the annual operating hours or capacity factor of the power plant.

$$\text{Total Cost (TC)} = \text{Fixed cost} + (\text{Variable cost x Capacity factor}) \tag{9}$$

(Source: [13])

Load-duration curves

A plot of the power demand (load) against time in an equal hourly interval per year will result in a load-time curve, with the area of each column or slice representing the energy demand in that particular hour. When such a curve is rearranged in decreasing power demand (i.e. ordering them from highest load to lowest load over the entire period (in this case one-year), the resulting curve is known as the load-duration curve.The total area under the curve is the total annual energy demand.

Table 6
Natural gas results.

Natural Gas (NG)				
Technology	Heat Rate, kJ/kWh	Fuel Rate, m^3/kWh	Fuel Cost, US$/MWh	CO_2 Emission, m^3/kWh
GE Frame 9E.3 (110MW)	10,960	0.28	91.83	0.699
GE Frame 9E.4 (126MW)	10,650	0.27	89.23	0.679
Orenda OGT 25,000 (25MW)	9480	0.24	79.43	0.605
SGT-300 (7.9MW)	11,773	0.30	98.64	0.751
SGT-400 (12.9MW)	10,355	0.27	86.76	0.660
Alstom GT11N2 (115MW)	10,619	0.27	88.97	0.677
TM2500 (25MW)	9755	0.25	81.73	0.622

Instead of using histogram, a smooth curve is normally used to represent the load-duration.This curve can now be used to answer such question as how many hours per year the load is equal to or above a certain value, for instance.

The country's base load and peak load demands for 2015 are 1200 MW and 2200 MW, respectively. Source: [3]

Determining the optimum generation mix

The screening curves and the load-duration curve are very important curves that can be used to determine the optimal generation mix of each power plant technology in the energy markets. The points where different power plant technologies intersect each other on the screening curves can be used to determine the fraction of hours per year that each technology can optimally be operated. These intersections when plotted on the load-duration curve then determine the optimal capacity of each generating unit in the energy mix. (Plot screening/load-duration curves together)

Discussion of result: fuel to technology analysis

Natural gas analysis

Almost all the thermal plants in the can use natural gas as fuel to generate electricity. From Table 6, considering the two GE technologies that is GE frame 9E.3 and GE frame 9E.4 with their ISO ratings of 110 MW and 126 MW, respectively. The fuel rate of GE frame 9E.4 is 0.2734 m^3/kWh which is about 1.4% less than that of GE frame 9E.3 (0.2813 m^3/kWh). These can also be seen to reflect by almost the same percentage difference in the fuel cost and carbon dioxide emissions of the two technologies. Based on these assessments, it is economically and environmentally right for government and other investors to invest in the GE frame 9E.4 technologies which gives a higher output than GE frame 9E.3 technologies. GE frame 9E.4 uses lesser fuel (natural gas) to produce power thus reducing its fuel cost and cost of generation. As compared to GE frame 9E.3, the GE frame 9E.4 saves about US$2.6/MWh in fuel cost (US$91.83/MWh – US$89.23/MWh). Indicating a savings of US$327.6 for the 126 MWh of output energy. This implies a US$7862.4 savings per day and about US$2,869,776 savings annually.Also comparing the two 25 MW plants that are Orenda OGT25000 and TM2500 technologies.

The amount of fuel used to generate 1 kWh of electric energy with Orenda OGT25000 (0.2433 m^3/kWh) is also 1.4% less than TM2500 (0.2504 m^3/kWh). The fuel cost and carbon dioxide emission also shows almost the same marginal percentage difference of the two technologies. The analysis shows that for the same power output of 25 MW, it is more economical to install or generate with the Orenda OGT25000 technology as compared to TM2500. These will save the country or any investor about US$2.3 of natural gas fuel cost for every megawatt generated. Meaning, a savings of US$57.5 for the ISO rating of 25 MWh of energy and US$1,380 per day and about US$503,700 per annum. With the Siemens thermal plant technologies, that is SGT-300 with an output of 7.9 MW and SGT-400 also with an output of 12.9 MW. It can be seen from Table 6, that the SGT-400 technology consume 0.2658 m^3 of natural gas as compared to SGT-300 which consumes 0.3022 m^3 to produce 1 kWh of electric energy. This means a 6.4% less of fuel used by SGT-400 and almost the same percentage difference in the cost of fuel to generate 1 MWh of energy. It also emits much less carbon into the atmosphere, making it environmentally compliant and friendly. The analysis shows that the SGT-300 technology with its low ISO rating of 7.9 MW is costlier in generating power. With these two technologies, the SGT-400 has an advantage of reducing fuel cost of about US$11.88 for every megawatt produced. For its ISO rating of 12.9 MW, it is estimated at reducing the fuel cost to US$153.25. Therefore, making a daily savings of US$3,678 and US$1,342,488 per annum.

Light crude oil analysis

Economically, Orenda OGT25000 as compared to GE frame 9E.3, when both technologies use LCO as fuel to generate 1 MW of energy, Orenda OGT25000 saves about US$13.13 for cost of fuel.

This implies a savings of US$328.2 for the 25 MW rating of the technology. This indicates another savings of US$ 7,877.1 per day and translating into about US$2,875,147 annually.

Distillate fuel oil analysis

Distillate fuel oil (DFO) is one of the fuels used to generate or run our thermal plants to produce electricity. Table 8 above gives the various values of fuel rate, fuel cost and CO2 emissions for the existing thermal plants technologies when they are

Table 7
Light crude oil results.

Light Crude Oil (LCO)				
Technology	Heat Rate, kJ/kWh	Fuel Rate, kg/kWh	Fuel Cost, US$/MWh	CO_2 Emission, m^3/kWh
GE Frame 9E.3 (110MW)	10,960	0.2589	97.22	0.6652
GE Frame 9E.4 (126MW)	10,650	0.2516	94.47	0.6464
Orenda OGT 25,000 (25MW)	9480	0.224	84.09	0.5754

Table 8
Distillate fuel oil table of solution results.

Distillate Fuel Oil (DFO)				
Technology	Heat Rate, kJ/kWh	Fuel Rate, kg/kWh	Fuel Cost, US$/MWh	CO_2 Emission, m^3/kWh
GE Frame 9E.3 (110MW)	10,960	0.2525	290.45	0.797
GE Frame 9E.4 (126MW)	10,650	0.2454	282.24	0.7745
SGT-300 (7.9MW)	11,773	0.2713	312.00	0.8562
SGT-400 (12.9MW)	10,355	0.2386	274.42	0.7531
Alstom GT11N2 (115MW)	10,619	0.2447	281.41	0.7723
TM2500 (25MW)	9755	0.2248	258.52	0.7094

Table 9
Coal Supercritical table of solution results.

Coal				
Technology	Heat Rate, kJ/kWh	Fuel Rate, kg/kWh	Fuel Cost, US$/MWh	CO_2 Emission, kg/kWh
Supercritical (350MW)	23,027	0.92	63.14	236.173

powered with DFO. Comparing GE frame 9E.3 and 9E.4, with their fuel rate of 0.2525 kg/kWh and 0.2454 kg/kWh. This gives a percentage difference of 1.43%, making GE frame 9E.4 more efficient in fuel consumption. These translate to about another 1.4% of less fuel cost to produce 1 MWh of electric energy and less carbon dioxide emission. Resulting from the analysis, the fuel cost difference for 1 MWh of energy is US$8.22. Considering the output of GE frame 9E.4 of 126 MW gives US$1,035.15 less cost of fuel of GE frame 9E.3. These will imply a daily cost reduction of savings of US$24,843.6 and an annual difference of US$9,067,926.Similarly, when SGT-300 and SGT-400 are analyzed, it can be realized that SGT-300 fuel rate of 0.2713 kg/kWh is 6.4% higher than SGT-400 fuel rate of 0.2386 kg/kWh. This reflects in the same percentage difference of their cost of fuel per MWh and amount of carbon dioxide emitted per kWh of electric energy produced. From the analysis, the cost of DFO for SGT-400 is US$37.58 per MWh less cheap than SGT-300 for electricity generation. For the 12.9 MW rating of the technology, gives US$484.8 reduction in the fuel cost. This then gives an amount of US$11,634.2 savings of fuel per day and an annual savings of about US$4,246,491.

Technology to fuel analysis

To determine for each technology, which of the three sources of fuel is best suited to be used as main fuel for generation to reduce generation cost and maximize profit.

GE frame 9E.3 technology

With the GE frame 9E.3, from Tables 6, 7 and 8, it has a high fuel rate of 0.2813 m3/kWh on natural gas as compared to LCO of 0.2589 kg/kWh and DFO of 0.2525 kg/kWh. In terms of fuel cost per MWh for GE frame 9E.3, natural gas recorded the lowest amount as compared to LCO and DFO. With emission of carbon dioxide for GE frame 9E.3, DFO has the highest emission then that of natural gas and LCO in that order. Although NG, recorded high figures in fuel rate and CO_2 emissions, but the cost of fuel is the lowest and that reduces the cost of generation. It makes a difference of US$5.39 per MWh less with LCO and US$198.62 per MWh less with DFO. This makes a daily reduction or savings in the cost of generation by US$129.4 and US$4,766.9 with LCO and DFO respectively. And an annually savings of US$47,234.3 with LCO and US$1,739,917.5 with DFO.

GE frame 9E.4 technology

With this technology, the above Tables 6, 7 and 8, shows a high heat rate when it is run on natural gas than LCO and DFO. But it records high CO_2 emissions when run on DFO. For the cost of fuel which has a direct relation to the cost of generation, the technology consumes less fuel when on natural gas (US$89.23) followed by LCO (US$94.27) and lastly DFO (US$282.24). This translates into a savings of US$5.24 with LCO and US$193.01 with DFO. Giving a daily savings of US$125.81 with LCO and US$4,632.13 with DFO and an annually difference of US$45,921 with LCO and US$1,609,726 with DFO.

Table 10
Overall summary of results.

TECHNOLOGY	Fuel Cost, US$/MWh	CO_2 Emission, m^3/kWh
GE Frame 9E.3	Average = 159.83	0.72
NG	91.83	0.699
LCO	97.22	0.6652
DFO	290.45	0.797
GE Frame 9E.4	Average = 155.31	0.70
NG	89.23	0.6792
LCO	94.47	0.6464
DFO	282.24	0.7745
Orenda OGT 25,000	Average = 138.25	0.62
NG	79.43	0.6046
LCO	84.09	0.5754
DFO	251.23	0.6894
SGT-300	Average = 205.32	0.80
NG	98.64	0.7509
DFO	312.00	0.8562
SGT-400	Average = 180.59	0.71
NG	86.76	0.6604
DFO	274.42	0.7531
Alstom GT11N2	Average = 185.19	0.72
NG	88.97	0.6773
DFO	281.41	0.7723
TM2500	Average = 170.12	0.67
NG	81.73	0.6222
DFO	258.52	0.7094
Supercritical		
COAL	63.14	236.1731

Table 11
Prices of fuel for power generation.

TYPE OF FUEL	Natural Gas (Ghana Gas)	Light Crude Oil (LCO)	Distillate Fuel Oil (DFO)	Bituminous Coal (SA)
PRICE(US$/MMBTU)	8.84	9.36	27.96	2.89

(Source: [7])
(Source: [9])

Table 12
Capital, fixed and variable operating and maintenance cost.

TECHNOLOGY	Capital Cost 1000$/MW	Fixed OM Cost 1000$/MWyr	Variable OM Cost $/MWh	Heat Rate kJ/kWh	Capital Recovery Factor, %/yr
GE Frame 9E.3 (110MW)	1,270	79.5	52.7	10,960	20
GE Frame 9E.4 (126MW)	1,520	75.2	11.5	10,650	18
Orenda OGT 25,000 (25MW)	635	23	6.2	9,480	16
SGT-300 (7.9MW)	603	12.5	4.3	11,773	17
SGT-400 (12.9MW)	610	11.1	5.1	10,355	15
Alstom GT11N2 (115MW)	1,828	58.2	20.9	10,619	17
TM2500 (25MW)	812	12.8	8.3	9,755	15
Supercritical (350MW)	1,438	28.81	23.6	23,027	14

(Source: [9])

Table 13
Results for the various technologies are given below.

Technology	Capital Cost, 1000$/MW	Fixed OM Cost, 1000$/MWy	Capital Recovery Factor, %/yr	Availability Eff., %	Capacity factor, %	Fixed Cost, $/MWh
GE Frame 9E.3 (110MW)	1,270	79.5	0.2	0.95	1	**40.07**
GE Frame 9E.4 (126MW)	1,520	75.2	0.18	0.95	1	**41.91**
Orenda OGT 25,000 (25MW)	635	23	0.16	0.95	1	**14.97**
SGT-300 (7.9MW)	603	12.5	0.17	0.95	1	**13.82**
SGT-400 (12.9MW)	610	11.1	0.15	0.95	1	**12.33**
Alstom GT11N2 (115MW)	1,428	58.2	0.17	0.95	1	**36.16**
TM2500 (25MW)	812	12.8	0.15	0.95	1	**16.17**
Supercritical (350MW)	1,438	28.81	0.14	0.95	1	**27.65**

Table 14
Summary of energy economics results.

TECHNOLOGY	Fixed Cost ($/MW/h)	Variable Cost ($/MWh)	Variable Cost w/CO2 Tax ($/MWh)	Total Cost of Electricity ($/MWh)	Total Cost of Electricity w/CO2 Tax ($/MWh)
GE Frame 9E.3	**40.07**	**221.34**		**261.41**	
NG	40.07	149.59		189.66	
LCO	40.07	155.29		195.36	
DFO	40.07	359.14		399.21	
GE Frame 9E.4	**41.91**	**175.37**		**217.28**	
NG	41.91	105.65		147.56	
LCO	41.91	111.18		153.09	
DFO	41.91	309.27		351.18	
Orenda OGT 25,000	**14.97**	**152.06**		**167.03**	
NG	14.97	90		104.97	
LCO	14.97	94.93		109.9	
DFO	14.97	271.26		286.23	
SGT-300	**13.82**	**220.92**		**234.74**	
NG	13.82	108.37		122.19	
DFO	13.82	333.47		347.29	
SGT-400	**12.33**	**195.635**		**207.965**	
NG	12.33	96.64		108.97	
DFO	12.33	294.63		306.96	
Alstom GT11N2	**36.16**	**216.29**		**252.45**	
NG	36.16	114.77		150.93	
DFO	36.16	317.81		353.97	
TM2500	**16.17**	**187.79**		**203.96**	
NG	16.17	94.53		110.7	
DFO	16.17	281.05		297.22	
Supercritical					
COAL	**27.65**	**90.15**		**117.8**	

Table 15
Average fixed cost and variable cost.

Technology	Fixed Cost, $/MWh	Variable Cost, $/MWh
GE Frame 9E.3 (110 MW)	40.07	221.34
GE Frame 9E.4 (126 MW)	41.91	175.37
Orenda OGT 25,000 (25 MW)	14.97	152.06
SGT-300 (7.9 MW)	13.82	220.92
SGT-400 (12.9 MW)	12.33	195.635
Alstom GT11N2 (115 MW)	36.16	216.29
TM2500 (25 MW)	16.17	187.79
Supercritical (350 MW)	27.65	90.15

Table 16
For GE Frame 9E.3.

CF	FC	VC	$TC = FC + (VC^{*}CF)$
0	40.07	221.34	40.07
0.1	40.07	221.34	62.204
0.2	40.07	221.34	84.338
0.3	40.07	221.34	106.472
0.4	40.07	221.34	128.606
0.5	40.07	221.34	150.74
0.6	40.07	221.34	172.874
0.7	40.07	221.34	195.008
0.8	40.07	221.34	217.142
0.9	40.07	221.34	239.276
1	40.07	221.34	261.41

Natural gas analysis recommendation

In general, considering all the various thermal plant technologies that uses natural gas as its fuel. Comparatively, the Orenda OGT25000 is the most efficient technology which consumes less fuel to generate a MWh of electric energy. It also emits less carbon dioxide into the environment.

Table 17
Total cost required for the various thermal power plants are show below.

CF	GE Frame 9E.3	GE Frame 9E.4	Orenda OGT 25,000	SGT-300	SGT-400	Alstom	TM2500	Coal
0	40.1	41.9	15.0	13.8	12.3	36.2	16.2	27.7
0.1	62.2	59.4	30.2	35.9	31.9	57.8	34.9	36.7
0.2	84.3	77.0	45.4	58.0	51.5	79.4	53.7	45.7
0.3	106.5	94.5	60.6	80.1	71.0	101.0	72.5	54.7
0.4	128.6	112.1	75.8	102.2	90.6	122.7	91.3	63.7
0.5	150.7	129.6	91.0	124.3	110.1	144.3	110.1	72.7
0.6	172.9	147.1	106.2	146.4	129.7	165.9	128.8	81.7
0.7	195.0	164.7	121.4	168.5	149.3	187.6	147.6	90.8
0.8	217.1	182.2	136.6	190.6	168.8	209.2	166.4	99.8
0.9	239.3	199.7	151.8	212.6	188.4	230.8	185.2	108.8
1	261.4	217.3	167.0	234.7	208.0	252.5	204.0	117.8

Table 18
Below is the maximum and base load demand for a period of one year in hours.

Time (Hrs)	Load demand (MW)
0	2200
1000	2100
2000	2000
3000	1900
4000	1800
5000	1700
6000	1600
7000	1500
8000	1400
8760	1300
8760	1200
8760	1100
8760	1000
8760	900
8760	800
8760	700
8760	600
8760	500
8760	400
8760	300
8760	200
8760	100
8760	0

Table 19
Summary of generation mix.

	Units	Coal	Orenda OGT25000	SGT400
Capacity factor	%	86.4	10	3.6
Fixed cost	$/MWh	27.65	14.97	12.33
Variable cost	$/MWh	90.15	152.06	195.64
Rated power	MW	1,900	220	80
Levelised cost	$/MWh	117.8	167.03	207.97

Light crude oil recommendation

From Table 7, the three technologies currently in use in the country can also use light crude oil (LCO) to generate electric power. It shows that the most efficient technology is the Orenda OGT25000 which consumes 0.224 kg of LCO to produce 1 kWh of electric energy. As compared to the other two technologies that is GE frame 9E.3 and 9E.4 both consuming 0.2589 kg/kWh and 0.2516 kg/kWh respectively. With the highest and lowest fuel rate compared, the Orenda OGT25000 uses about 7.2% less LCO to generate the same 1 kWh of energy. Again, about the same percentage of fuel cost is reduced to produce 1 MWh and less carbon dioxide emitted into the atmosphere. From the analysis, Orenda OGT25000 is the most economical technology as compared to GE frame 9E.3 and 9E.4 in the country to produce electricity using LCO as its fuel. It has the lowest fuel consumption rate and fuel cost to produce energy. This will reduce its operation cost of generation, therefore reducing the cost of electricity to improve the economy of the country.

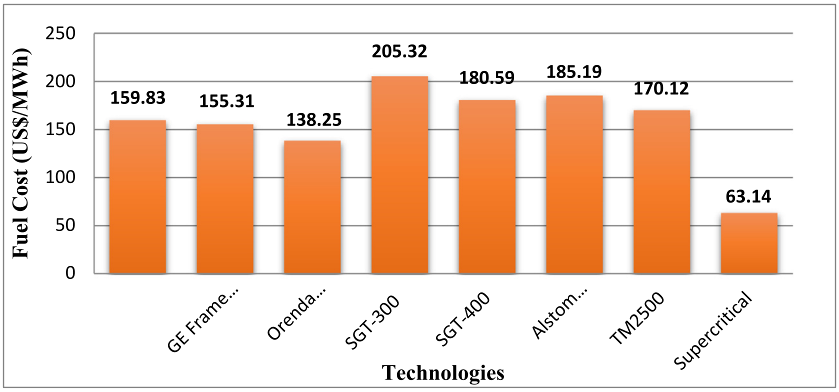

Fig. 1. Cost of fuel to generate a MWh of electric energy by the various power plants.

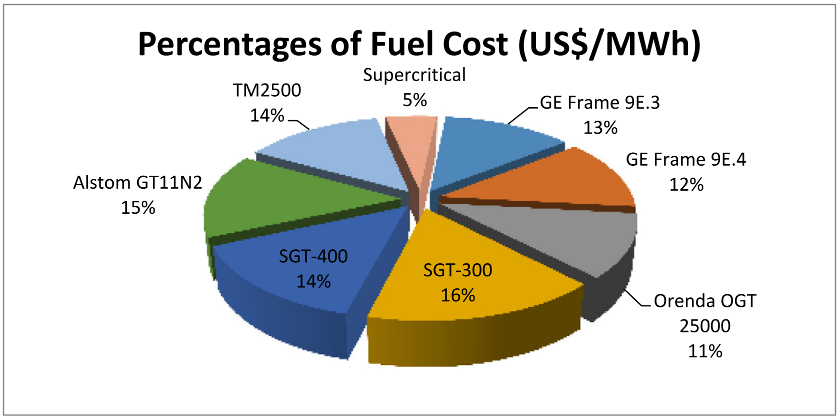

Fig. 2. Percentages of the fuel cost for the various thermal power plants.

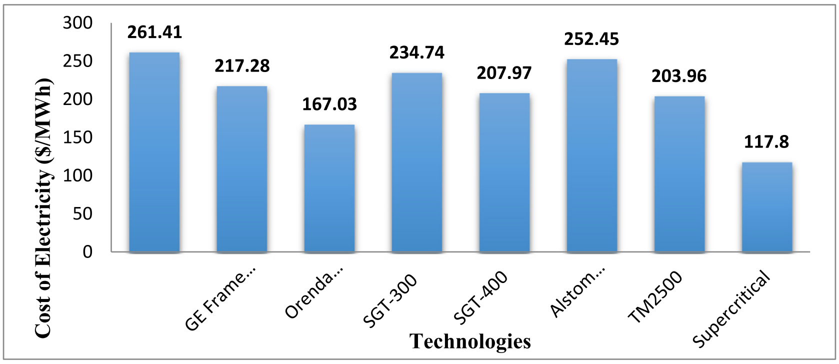

Fig. 3. Levelized cost of electricity for the various thermal plants.

Distillate fuel oil recommendation

In general, the more efficient of the two Siemens technology to use DFO as its fuel for generation at a low fuel cost, low fuel consumption and less carbon dioxide emission is the SGT-400. This will save the country some amount of money and generate at an affordable cost leading to less price of electricity charges.

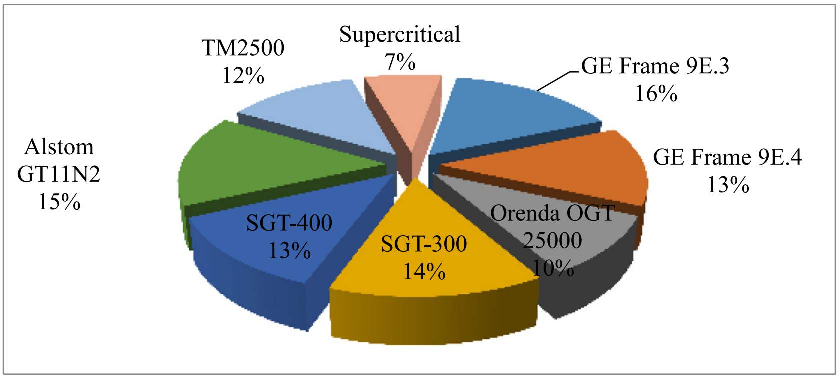

Fig. 4. Percentages of the Levelized Cost of Electricity for the various thermal power plants.

Screening Curves

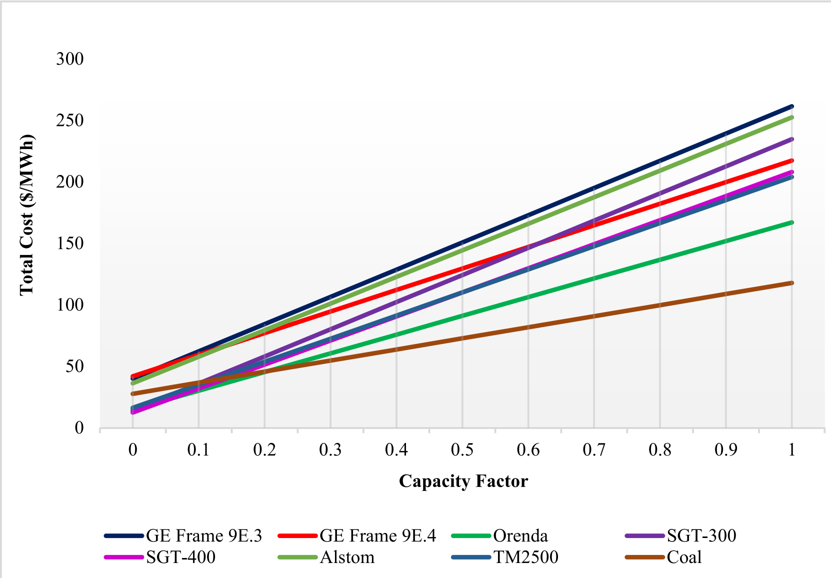

Fig. 5. A graph of the total cost for the various thermal power plants.

Load-Duration Curve

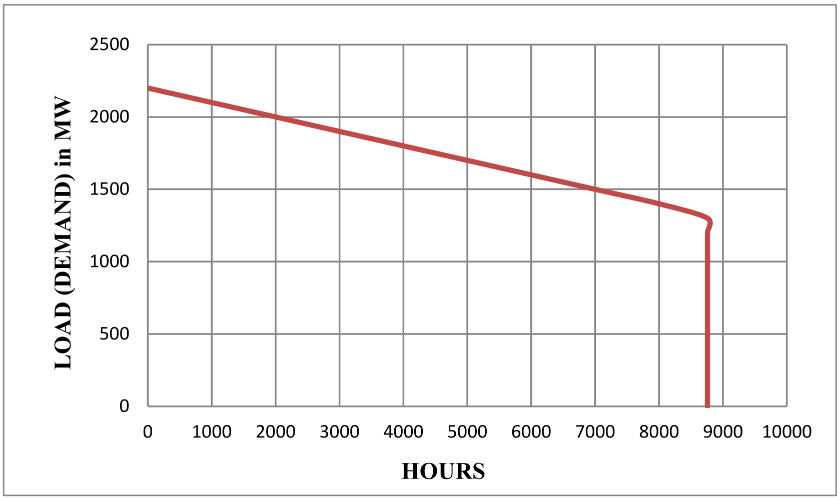

Fig. 6. A curve of the maximum and base load demand for a period of one year in hours.

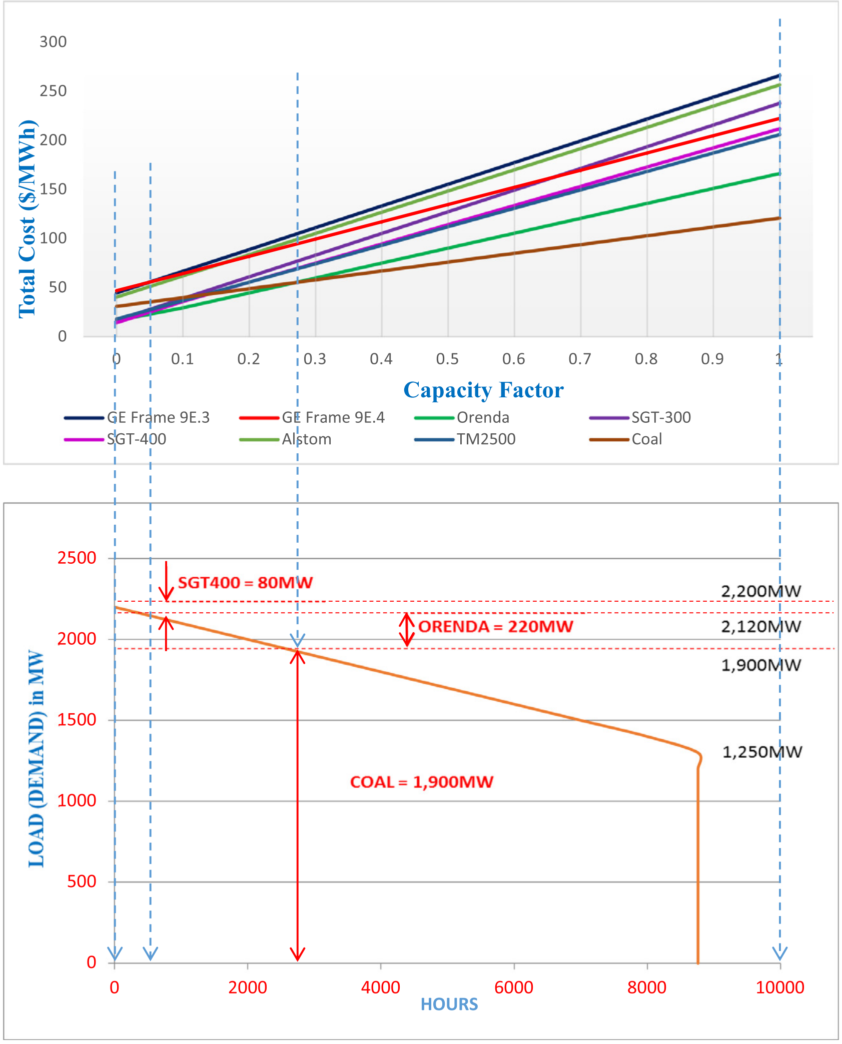

Fig. 7. A plot of screening and load-duration curves to determine optimum generation mix.

Conclusion

Power plants technology analysis

From an observation of the above Tables 6, 7 and 8, comparing the various fuel, DFO has the highest fuel cost and CO_2 emissions when used as a fuel for all the technologies. This is due to its high market price and high heating value. It has the lowest fuel rate also because to its heating value per kilogram. DFO as a fuel, increases the cost of generating electricity thus increasing the price of electric energy. Due to its high price, it is mostly not preferred in the power generating sector but sometimes used as a preservative fuel for starting up and shutting down of most thermal plant which runs on LCO. LCO figures from the Tables 6, 7 and, has moderate values in fuel rate, fuel cost and CO_2 emissions. For the cost of fuel, the price of LCO has dropped significantly on the world market for this year as compared to previous years. This has made generation cost of electricity on LCO very moderate and close to natural gas. LCO is the second preferred fuel for most power plants due to its heating value close to DFO but lower price than DFO. Although it requires more quantity to generate power and having high values of CO_2 emissions, natural gas is the most preferred fuel for almost all thermal plants basically due to its lowest price per million BTU on the world market. It reduces the frequency of maintenance on the thermal plant therefore reducing maintenance cost, increasing availability, reducing generation cost and maximizing profit. Finally, natural gas is approximately 3–4% cheaper than LCO and 52% more cheaply than DFO in fuel cost for thermal power generation.

Economic analysis of power plants (Optimum generation mix)

Based on the Screening curves in Fig. 5 of the various technologies and Load-Duration curve in Fig. 6 for the load demand, it is concluded that:

1. SGT-400 technology of 80 MW Rated Capacity with a contribution of 3.6% to the country's current load demand should be used as Peaking Power Plant.
2. Orenda OGT25000 technology of 220 MW Rated Capacity with a contribution of 10% to the country's current load demand should be used for Mid-load generation.
3. Coal Supercritical technology of 1900 MW Rated Capacity with a contribution of 86.4% to the country's current load demand should be used as Base-load Power Plant.
4. The other technologies (i.e. GE Frame 9E.3, GE Frame 9E.4, SGT-300, Alstom GT11N2 and TM 2500) are not economical, in this case, and hence it is advisable not to be used in power generation.

Conflict of interest

The Authors declare no competing financial interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2018.e00015.

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