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Evaluation of the Potential for Hybridization of Gas Turbine Power Plants with Renewable Energy in South Africa

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Abstract—Domestic energy supply to rural area is a task facing many governments. In efforts to meet this target, electricity generating companies have tried to exploit available resources of energy, including the combustion of fossil fuels even though they have been recognized to cause environmental problems such as climate change and acid rain. Moreover, these resources occur in limited quantities and therefore pose energy insecurity. It is believed that the addition of renewable energy (RE) resources in the general energy mix can assist in mitigating climate change and in augmenting energy security. This paper investigates the possible renewable energy that can be exploited in hybrid gas turbines (GTs) in South Africa (SA). In this study, data was collected through a desktop approach. It is found that there is potential for use of biodiesel, biogas, and concentrated solar power in GTs. Results also show that about 2.00 x10^6 MWh, 12.09 x10^6 MWh and 105.0 x10^6 MWh of electricity can be annually generated from biodiesel, biogas and concentrating solar collectors respectively through the gas turbine technology in SA. It is concluded that there is great potential for exploiting solar and biogas resources to drive gas turbine power plants in the country.

Index Terms—Distributed energy, Electricity generation, Gas turbines, Hybridization, Renewable energy

1 INTRODUCTION

Combustion of fossil fuels for heat and power production has been associated with environmental degradation, such as the emission of greenhouse gas (GHG) and the formation of acid rain. Apparently, the energy sector is a major contributor to the GHG emission in South Africa (SA). It has been shown that if the economy of SA grows without constraint in the near future, the country’s GHG emission will escalate [1]. In addition to environmental concerns, there is gradual depletion of the conventional energy resources (such as coal, oil and gas) which is leading to energy insecurity. One of the possible solutions in this regard is the exploitation of renewable energy (RE) resources in power plants, including gas turbines.

The gas turbine technology (GTT) has experienced tremendous transformation since the world’s first industrial gas turbine was built in 1939 [2]. It has evolved from the directly-fired coal combustion system characterized by low efficiency and heavy carbon emission to a more sophisticated, efficient, combined system with less emissions than the former. This latter version is an integrated system based on RE) resources (such as biomass, solar radiation and hydro power) which are proven to contain the menace of pollutant emissions.

Biomass based renewable energy resources in SA include canola, sunflower, soybean for biodiesel, sugarcane and sugar beet for ethanol production [3, 4]. The government’s policy of blending 2% of biofuel with the liquid conventional fuels [4] can promote the development of the biofuel market in the country. In addition, the strategy to develop the biofuel industry through the previously disadvantaged homelands areas [5-7] is commendable. However, this can be jeopardized if the host communities, where such biofuel projects would be located, do not adequately participate in the decision making process [3]. Other RE resources available are: solar radiation, biogas, hydro (water) etc. This paper focuses on the potential of RE resources that can be hybridized to drive gas turbine (GT) power plants in SA.

1.1 Fundamental operation of a gas turbine

The basic GT operation is schematically shown in Fig. 1, and thermodynamically presented in Fig. 2. Air enters an axial compressor at point 1, assuming the ISO conditions of 288 K, 101.3 MPa, and 60% relative humidity [8]. The air is then compressed to higher pressure and temperature at the exit of the compressor and enters the combustion chamber at point 2 where fuel is injected and combustion takes place (heat input) at a constant pressure. At point 3, the flue gas enters the turbine at the same pressure but higher temperature. The gas mixture is expanded in the nozzle section [8, 9] releasing its thermal energy with a portion being converted to kinetic energy in the gases to turn the turbine blades. This energy is partly converted to work to drive the compressor shaft while some portion of the remaining is converted to useful work to drive the electric generator. Some of the thermal energy in the gases exit the turbine as exhaust gas at point 4, at a temperature of about 400 – 600°C [9]. Points 1 – 4, in Fig. 1 constitute a complete thermodynamic cycle (Brayton cycle).

1 Data was converted to SI units by authors.

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Figure 1. The simple cycle gas turbine.

Figure 2. GT cycle diagram: P=pressure, and V=volume.

1.2 Types of gas turbines

GTs can be classified as being open cycle or closed cycle.

i. In an open cycle gas turbine (OCGT), the exhaust gas is discharged into the atmosphere while fresh and cool air is admitted into the compressor on a continuous basis. In this cycle, some of the heat in the exhaust gas can be recuperated for some other thermal applications. Open cycle gas turbine engines contribute a great deal of heat to the atmosphere which could have been harnessed to improve the turbine power output. A typical simple cycle (open cycle) GT converts 30–40% of heat from fuel input to shaft work leaving all but 1–2% of the remainder to waste heat in the exhaust [8]. This could be harmful to the environment through atmospheric heating especially when heat accumulation is taken into consideration.

ii. In the closed cycle gas turbines, a heat recovery system is included between points 4 and point 1. In this configuration, the system works as a combined heat and power (CHP) system. Closed cycle GTs use air, nitrogen, inert gases (argon and helium) as working fluid which are heated either by a combustor or high temperature heat exchanger before entering into turbine. The fluid is recovered after passing through a low temperature heat exchanger. The cooled fluid is thus compressed to continue the process. To maximize the power output of the fuel, two or more gas turbines can be combined in tandem with one another to form a combined cycle gas turbine (CCGT).

iii. A combined cycle is generally defined as one or more gas turbines with a 0 heat recovery steam engine at the exhaust of the first turbine producing steam for the second turbine. The principle is that after completing its cycle in turbine 1, the working fluid of the first heat engine, now at lower entropy becomes the source of energy for the second turbine. The combination of multiple streams of work on a single mechanical shaft turning an electric generator increases the overall net efficiency of the system by well over 50%. This is possible because, no single heat engine uses up to 50% of the energy in its fuel [10]. Combined cycle engines use the exhaust heat to increase the power plant output and boost the overall efficiency of the system by more than 50% of the simple cycle gas turbines [11, 12].

GTs can also be classified according to the type of firing/combustion of the fuels. Thus, we have:

i) Directly fired gas turbines

Directly fired gas turbines (DFGTs) are designed to accept thermal energy directly from flue gases after combustion. The fuel used in this system must be clean to avoid fouling problems at the turbine blades [13, 14]. A major advantage of DFGTs lies in the fact that a high turbine inlet temperature (TIT) is ensured which is an important factor in achieving high power output.

ii) Externally fired gas turbines

In externally fired gas turbines (EFGTs), hot gases obtained from the combustion of fuels are not in direct contact with the turbine blades [15]. In these GTs, heat is transferred to the working fluid (air) through a high temperature heat exchanger (HTHE). This technology holds several merits over other designs such as its flexibility in operating in both closed and open cycles, flexibility in fuel type (solid, liquid or gas). In open cycle EFGTs, coal or other fuels can be comfortably combusted in the combustion chamber which is aligned with the HTHE. Fuel cleaners, injectors and compressors are not required in admitting fuel in EFGTs compared to DFGTs. The major drawback of this configuration is the HTHE component and the fouling problem on the exhaust side [16, 17]. A closed cycle EFGT requires an additional gas cooler to reduce the temperature of exhaust gas so that it is close or equal to ambient temperature before it can be admitted to the compressor.

1.3 Gas turbine fuels

Among several factors that affect turbine performance and efficiency is the energy source to drive the turbine. Fuel type, source and composition are very important in the selection of the gas turbine combustion fuel. Heavy duty gas turbines have a special feature of wide fuel flexibility [18]. Thus, Jones et al [19] suggested that classification of gas turbine fuels should be between gaseous and liquid fuels, and within the gaseous fuels, and according to calorific values (Table 1).
Table 1: Classification of Gas Turbine fuels by type (Source: [9]).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Typical composition</th>
<th>LHV* (kJ/Nm³)</th>
<th>Typical specific fuel characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra/Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHV gaseous</td>
<td>CH₄ &lt; 10%</td>
<td>&lt;11,200</td>
<td>Blast furnace gas, Air blown IGCC, biomass gasification</td>
</tr>
<tr>
<td>fuels</td>
<td>N₂+CO &gt; 40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High hydrogen</td>
<td></td>
<td>5,500 - 11,200</td>
<td>Refinery gas, petrochemical gas hydrogen power</td>
</tr>
<tr>
<td>gaseous fuels</td>
<td>C₃H₈ = 0-40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>CH₄ &lt; 60%</td>
<td>30,000</td>
<td>Weak natural gas, landfill gas, coke oven gas, corex gas</td>
</tr>
<tr>
<td>LHV gaseous</td>
<td>N₂+CO₂ = 30-50%</td>
<td>11,000</td>
<td></td>
</tr>
<tr>
<td>fuels</td>
<td>H₂ = 10 - 50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>CH₄ = 90%</td>
<td>45,000</td>
<td>Natural gas, liquefied natural gas (LNG)</td>
</tr>
<tr>
<td></td>
<td>C₃H₈ = 5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inerts = 5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High LHV</td>
<td>CH₄ and higher</td>
<td>100,000</td>
<td>Liquid petroleum gas (butane, propane), refinery off-gas</td>
</tr>
<tr>
<td>gaseous fuels</td>
<td>hydrocarbons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid fuels</td>
<td>C₇H₁₈ with x &gt; 6</td>
<td>32,000</td>
<td>Diesel oil, naphtha, crude oils, residual oils, bio-liquids</td>
</tr>
</tbody>
</table>

* LHV = lower heating value.

It has been shown that nearly 10,000 units of General Electric (GE) gas turbines run on NG while close to 20 run on other gases [19]. Similarly, a little above 100 run on light distillate oil (LDO) while about 50 run on other liquid fuels. However, the global power sector is currently being driven by a complex combination of customer economics, environmental concerns and global political uncertainties to look at cost-effective gas and liquid fuel alternatives without sacrificing plant efficiency and emission characteristics [20].

1.4 Progress in alternative fuel application in GTs

One good special feature of heavy duty GTs is that they are flexible combustion tools for a wide variety of gaseous and liquid fuels ranging from natural gas to heavy oils, synthesis gas (syngas), liquefied petroleum gas (LPG), petrochemicals (propene, butane, propane), hydrogen-rich refinery by-products such as naphtha, ethanol, biodiesel, aromatic gasoline and gasoil [21]. Gaseous fuels from biomass conversion technologies, leading to bioenergy production, such as fast pyrolysis, gasification and pyrolysis oil gasification are generally known as synthesis gas. Nevertheless, the application of these alternative fuels in small-size energy systems, such as those used for distributed micro-cogeneration, has not yet reached a level of technological maturity that could allow a large market diffusion [22].

Several tests need to be carried out to find the best option among alternatives. Cadonin et al [22] analysed the performance of a 100-kW micro gas turbine combustor driven by natural gas and biomass-derived synthesis gas. The results of the tests performed under different operating conditions show that the fuel distribution did not affect the fluid dynamic behaviour. Also the synthesis gas reduced NOx concentration. Following this quest, characterization of alternative fuels within the operating conditions of the combustion chambers of gas turbines such as specific pressure, temperature and equivalence ratio have been carried out. A numerical analysis of this is presented by Glaude et al [21] using some alternative fuels and two natural gases of different compositions. Oxygenated compounds: methanol, ethanol, and dimethyl ether (DME) as the alternatives and ethane and a process gas with a high content of butane as natural gases were used for the analysis. The simulation results showed that the behaviour of the alternative fuels was remarkably different from that of conventional ones. Using biofuels as alternatives to NG may require engine modifications to accommodate differences in fuel qualities. However, Nikpey et al [23] has shown that a mixture of biogas and natural gas can be burned in a commercial 100kW micro gas turbine (MGT) without engine modification. The result of the experimental analysis showed that electrical efficiency was almost unchanged and no significant changes in operating parameters were observed. Also combustion of a mixture of natural gas and biogas contributes to a significant reduction in CO₂ emissions from the plant compared to the sole combustion of NG.

Synthesis gas can be obtained from coal gasification. However, it has been shown that the combustion of this gas has adverse effect on the turbine blades due to the presence of inherent chemicals in the gas despite its cleaning before firing. The problem is that coal-derived syngases may contain alkali metal impurities that combine with the sulphur and chlorine elements from coal to form salts that are deposited on the turbine blades, causing corrosion [24]. A model developed by Young et al [24] for predicting dew point temperatures and deposition rates of sodium and potassium salts on turbine blades showed that when chlorine is present the alkali species in the mainstream gas flow are the chlorides; but when chlorine is absent, the superoxides dominate. On the contrary, synthesis gases from biomass conversion do not contain alkali metals, hence their combustion has no significant effect on the turbine blades.

1.5 Gas turbine hybridization

Solar energy is one of the most promising sustainable options to partially replace fossil fuelled power plants. However, the cost of generating electricity solely from solar thermal plants is high [25]. Moreover, solar radiation is intermittent, therefore it cannot supply a base load unless a storage system is included which also tends to augment the cost of energy production. In this vein, hybridization of two or more energy sources can assist in providing a solution. For instance, biofuel or conventional fuel can be hybridized with solar energy to supply a base load using gas/steam turbine systems to reduce the carbon emission without compromising the reliability of the plant. Hybridization can be performed by retrofitting an
existing fossil-fuelled power plant or designing a completely new hybrid power plant [26]. It should be mentioned that there is more flexibility in designing a new hybrid power plant than hybridizing an existing conventional plant. In each case, design challenges have to be properly handled. It is necessary to simulate the hybrid system, taking into account techno-economic parameters, in order to establish its performance before implementing any retrofitting or prototyping a brand new hybrid system.

Basic schemes for hybridization are serial or parallel. In a serial scheme, compressed air is pre-heated by solar energy before it enters the combustion chamber. Air pre-heating reduces the amount of fuel required to attain the desired outlet temperature from the combustion chamber (Fig. 3).

For parallel connection, the air from a compressor is divided into two streams: one stream is heated by the solar subsystem while the other stream is heated by the combustion chamber, and the two streams are mixed before impinging on the turbine (Fig. 4). It is easier to isolate the solar and combustion subsystems in a parallel hybridization scheme for various tasks such as retrofitting, operation and maintenance. However, the solar subsystem may not be able to heat the air to the same level as the combustion subsystem. Thus, mixing the two streams would reduce the temperature of the mixture sent to the turbine. Thus, the series scheme is thermodynamically more advantageous. In both hybridization schemes, renewable energy (RE) can be combined with conventional fuel (CF) or RE with RE (such as solar with biofuel).

Fuel consumption is drastically reduced when the air from the compressor is pre-heated by using solar collectors before entry into the combustion chamber. This has been demonstrated in Spain as shown in Fig. 5.

To boost the combustion processes, hydrogen gas can be injected into the combustion chamber. This gas can be produced by using electrolysis or other well established methods.

1.6 Energy production and consumption issues in South Africa

South Africa (SA) is the topmost African country in the generation of electricity. The evolution of the electricity industry in SA since 1882 is reported by Amusa et al [28] with Eskom as the chief producer and distributor of the commodity amidst other independent players in the industry. Currently, Eskom generates over 96% of electricity used in SA with private generators and municipal authorities accounting for 3.2% and 0.8% respectively [28]. Due to the political scenario and the policies [29] that characterized the socio-economic life of the country before early 1990s, a greater percentage of the population had no access to electricity. Electrification of SA has nevertheless witnessed a tremendous transformation and unprecedented growth since the 1990s. It is reported that within 5 years (1994–1999), about 2.8 million households were connected to the national grid [28, 30] with a target of reaching 11.4 million households by 2025. The residential consumption is relatively low compared to other sectors as shown in Fig. 6, [31].
It is interesting to note that electricity production in SA is, to a greater extent, fossil-fuel based (Fig. 7), with coal and oil accounting for about 94% as at the end of 2013. The high fossil fuel share of the total energy mix in SA is causing environmental concern. Currently, SA is the 12th largest emitter of carbon dioxide (CO₂) in the world and is responsible for nearly half of the CO₂ emissions for the entire continent of Africa [32, 33].

CO₂ accounts for more than 80% of the total greenhouse gas (GHG) emissions in SA since the last decade. With electricity generation in SA constituting greater coal consumption index more than other sectors of the economy, and CO₂ emission from the electricity generation industry ranks highest in the category of sectoral CO₂ emission. Table 2 shows that 13 out of the 27 power stations from the major player in the industry are coal-fired while 4 stations are gas turbine based and the rest being RE based.

It is understood that the quest to achieve a high turbine output efficiency is the driving force to burn more fossil fuel in order to attain a high turbine inlet temperature (TIT). To promote sustainable energy provision, it is necessary to look for possible options that can lead reduce CO₂. In this connection, hybridization of gas/steam turbines with RE sources cannot only cut down the CO₂ emission but also improve the energy security of the country. That is, if part or all of the heat supplied to the gas turbine can be drawn from a low-carbon source made of a hybrid gas turbine system in which the coal or natural gas combustion is supplemented or substituted with a low-carbon heat source, then the overall emission from the unit can be reduced or eliminated [26]. Currently, gas turbines in SA are driven by diesel, kerosene fuel or natural gas, and are operated in open cycle mode and none is hybridized gas turbines [35, 36]. The objective of this study was therefore to evaluate the potential for hybridization of GTs with renewable energy.

Table 2: Eskom’s power stations by plant mix [31].

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of stations</th>
<th>Total nominal capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal-fired</td>
<td>13</td>
<td>35726</td>
</tr>
<tr>
<td>Gas/liquid fuel turbine</td>
<td>4</td>
<td>2409</td>
</tr>
<tr>
<td>Hydroelectricity</td>
<td>6</td>
<td>600</td>
</tr>
<tr>
<td>Pumped storage</td>
<td>2</td>
<td>1400</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
<td>1880</td>
</tr>
<tr>
<td>Wind energy</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>41995</td>
</tr>
</tbody>
</table>

2 METHODOLOGY

2.1 Data collection

In the present work, a desktop method was used to assess the potential for possible hybridization of renewable energy (RE) resources to drive gas turbines in the energy sector of SA. Data were collected (from reports, journal articles and other published work in electronic and printed forms) on the available RE resources and existing capacity of GTs in the electricity generation chain. Eskom is the sole electricity distributor of SA. It purchases and distributes energy produced by small groups of private power producers under the Independent Power Producer (IPP) programme.

2.2 Data Analysis

An energy balance approach was used to estimate energy conversion from an energy resource to electrical power. The output energy (Eₜ) was computed from the annual available energy to the plant (Eᵢ):

\[ Eₜ = \eta f Eᵢ \] (1)

where \( \eta \) is system efficiency, and \( f \) is capacity factor.

For biofuels, the input energy \( Eᵢₜ₉ \) was calculated as follows:

\[ Eᵢₜ₉ = DᵢCᵢ \] (2)

\[ Eᵢₜ₉ = \eta f DᵢCᵢ \] (3)

where \( Dᵢ \) is average energy density of a specific biofuel (MJ m⁻³), and \( Cᵢ \) is fuel production (m⁻³/year).

The average values of \( Dᵢ \) for diesel (3398 MJ m⁻³), bioethanol (23 496 MJ m⁻³) and biogas (24.57 MJ m⁻³) were computed from previous work [38-40], and capacity factor \( f = 50\% \).

Annual thermal energy produced by a concentrating solar field was estimated from:

\[ Eᵢₜ₉ = \eta f DᵢCᵢ \] (3)
where \( n \) is number of hours in a year (8760), \( \eta_s \) is the thermal efficiency of the solar collector field (assumed 20%), \( f_\text{c} \) is capacity factor of the plant (assumed 30%) and \( P_s \) is solar resource potential (MW).

For a solar-biofuel hybrid system, a serial hybridization system was adopted due to its thermodynamic benefits. So, the solar concentrating collector field converted the input solar energy (\( E_{\text{solar}} \)) to heat. The output energy from the collector field is added to that from the combustion processes in the combustor to yield electrical energy (\( E_{\text{elec}} \)) from the GT. Therefore, \( E_{\text{elec}} \) was estimated from:

\[
E_{\text{elec}} = \eta_{\text{GT}} (E_{\text{th}} + E_{\text{sb}})
\]

where \( \eta_{\text{GT}} \) is efficiency of gas turbine.

Hybridization was considered with a combined cycle gas turbine (CCGT) due to its higher efficiency. A summary of efficiency of data on gas turbines is presented in Table 3.

Table 3: Data on efficiency and capacity factor of open cycle gas turbine (OCGT) and combined cycle gas turbine (CCGT). (source: 35).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency (%)</th>
<th>Capacity factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCGT</td>
<td>34</td>
<td>10</td>
</tr>
<tr>
<td>CCGT</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

3 FINDINGS AND DISCUSSION

3.1 Resource potential

3.1.1 Biodiesel

SA has great potential for biodiesel and bioethanol production. Liquid biofuels can be produced from a number of biomass materials proven to contain oil and sugar which include soybeans, maize, jatropha, rapeseed, castor oil, plain vegetable oils (canola, sunflower), used vegetable oils, sugar beet, sugarcane, sorghum and sugarcane bagasse. The threat on food security of biofuel production from edible food crops is a global issue and SA is no exception. The country has come up with a national biofuel strategic policy of 2% integration into the national liquid fuel mix [4]. Even though some of the policies are yet to be implemented due to some socio-economic reasons [3], the country is endowed with abundant feedstock to produce biofuel [5, 41, 42]. According to Nasterlack et al [41], the proposed biofuel project at Cradok has the potential to launch a biofuel industry in SA with social and environmental benefits that outweigh the potential drawbacks.

Although biodiesel production from biomass resources is still at its infancy [5, 43], about 200 companies and organizations are already producing biodiesel from waste vegetable oils [44]. Table 4 shows the biofuel production capacity by some organizations in 2013.

Table 4: Biofuel production by company and capacity [45].

<table>
<thead>
<tr>
<th>Organization</th>
<th>Product (Feedstock)</th>
<th>( C_b ) (x10^3 m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exol Oil Refinery</td>
<td>Biodiesel (WVO)</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 5: Estimation of animal and human waste potential of SA [52 - 56].

<table>
<thead>
<tr>
<th>Animal</th>
<th>Average Population (199)yr</th>
<th>Average waste (kg/person/day)</th>
<th>Total waste (kg/yr)</th>
<th>Biogas yield (m³/kg)</th>
<th>Total biogas (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coffee</td>
<td>13.00x²</td>
<td>10.00</td>
<td>5.00x10²</td>
<td>0.50</td>
<td>20.48x10³</td>
</tr>
<tr>
<td>Sheep</td>
<td>0.027x³</td>
<td>2.00</td>
<td>18.00x10²</td>
<td>0.05</td>
<td>0.0030</td>
</tr>
<tr>
<td>Goat</td>
<td>0.0021x⁴</td>
<td>2.00</td>
<td>1.93x10³</td>
<td>0.06</td>
<td>0.0076</td>
</tr>
<tr>
<td>Piggery</td>
<td>0.0016x⁵</td>
<td>1.20</td>
<td>0.70x10³</td>
<td>0.07</td>
<td>0.0049</td>
</tr>
<tr>
<td>Poultry</td>
<td>9.00x⁶</td>
<td>0.10</td>
<td>6.40x10²</td>
<td>0.06</td>
<td>2.16x10³</td>
</tr>
<tr>
<td>Human</td>
<td>5.00x⁷</td>
<td>1.20</td>
<td>2.31x10³</td>
<td>0.07</td>
<td>1.69x10⁴</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7006.083</td>
</tr>
</tbody>
</table>

Note: * computed from a = [52], b = [53], c = [54], d = [55], e = [56].

It is reported that SA generates about 4.2x10⁷ m³ of MSW annually translating to 0.7 kg per capita per day [57, 58]. This implies that with the estimated population of 53 million inhabitants of SA, the present MSW may be put at 37100 tons per day. The organic component of MSW comprises the rapidly decomposable materials (food wastes, newspaper, office paper, cardboard and yard wastes) and slowly decomposable materials. If the estimated 9.04 million tonnes of food waste generated every year in South Africa [59] is harnessed, MSW will generate enormous biogas. Analysis by Pitchel, [60] has shown that biological decomposition of 1 ton (1000 kg) of MSW produces 442 m³ of landfill gas containing 55% CH₄ and a heat value of 19730 kJ/m³. It is estimated that biogas potential of SA is capable of generating about 2.5 Gigawatts (GW) of electricity [61]. Similarly, 450 x10⁶ m³/day, approx. 4.5 MWe can be generated from waste water treatment per day [62].

3.1.3 Hydrogen gas

Hydrogen is a fuel with very high energy density. It is regarded as the fuel with the highest energy content per unit mass as its higher heating value (HHV) is about 3.54 kWh/Nm³ (39.42 kWh/kg), that is, 2.5 and around three times more energetic than methane and gasoline, respectively [63,64]. In SA the Department of Science and Technology (DST) has established a national hydrogen production programme (HySA). A state of the art hydrogen storage laboratory is being established at the CSIR [65] which will enable the synthesis, characterization and testing hydrogen storage systems. Combined heat and power (CHP) is part of the HySA programme [66] geared towards utilizing hydrogen gas for power production. Hydrogen can also be produced by water splitting, using solar power as the primary heat source [65]. Combustion of hydrogen in gas turbines has no hazardous emission like CO₂, SOₓ, CO, HC but NOₓ has been reported [46]. However, this does not create a problem if oxygen rich fuels (such as ethanol, biodiesel) are burned in gas turbines along with hydrogen. Through this, the oxygen oxidizes the NOₓ. Gas Turbine engines designed for liquid fuels can be modified to run on hydrogen, attaining temperatures of up to 2300K [46].

3.1.4 Solar radiation

Solar radiation is the most influential environmental factor on the performance of concentrated solar power (CSP). Heller et al [27] reported that using the CSP, air from the compressor can be heated to 290-1000°C. South Africa's location on the globe is favourable because its latitude and climate are generally well suited for the utilization of solar energy [67]. The country is endowed with a large area of solar radiation amounting to approximately 194 000 km² [68], including the Northern Cape, one of the best solar resource areas in the world [69]. Using geographic information systems (GIS), Fluri [70] has shown that a total of 547.6 GW of electricity can be generated throughout SA using CSP plants. Currently, the kaXu Solar One (in Northern Cape) is SA’s first solar thermal electricity plant (STEP). It is based on parabolic trough concentrators and is capable of generating 100 MW, equivalent to 320 GW of electricity a year, to the national grid using steam turbines.

However, it is suggested that if only 1% of the total land area of high solar radiation in SA, is used, 64 GW [68] can be generated. This will translate to 400 GW solar radiation resource (for 16% solar to electricity efficiency). For a solar to thermal efficiency of 20%, then we have 80 GW thermal energy from solar.

It is also shown that only areas with average direct normal irradiation (DNI) above 7.0 kWh/m²/day (2555.0 kWh/m²/yr) are suitable for the project. This is greater than the minimum requirement of 1000 kWh/m²/yr suggested by Spelling, [26]. SA’s total installed electricity capacity of approximately 40 GW [68,70] from other sources makes it reasonable to devise means of utilizing the solar potential.

3.2 Potential for RE-based electricity generation using GT

3.2.1 Single source of energy

The potential electricity production using single sources of RE is presented in Table 6. This table shows that if all the biodiesel produced in 2013 was used to drive GTs for electricity generation, then the annual energy output would be 0.27 x10⁶ MWh and 2.00 x10⁶ MWh for the OCGT and CCGT technologies respectively. Clearly, the CCGT option is more efficient for the same input energy. However, for both options the biodiesel resource cannot sustain the existing gas turbines rated at a nominal capacity of 2409 MW equivalent to 2.11 x10⁶ MWh and 10.55x10⁶ MWh respectively in the two technologies. Moreover, there are competing demands for biodiesel, especially from the transport sector.
For biogas, the biogas-driven CCGT technology has the potential to generate about 12.09 x 10^6 MWh per year, which is enough to displace the existing fossil-driven GT capacity. It is observed that the OCGT still falls short of the existing GT capacity. 

A total of 105 x 10^6 MWh electrical energy can be generated from CSP if 1% of available solar land area (SLA) is used for solar-driven CCGT in SA. This solar potential can sustain the existing GTs while brand new hybrid solar gas turbines (SGTs) can be added. Even though the SGTs power plants look attractive in many ways, its limitations are on initial capital cost and seasonal variation of solar irradiance. In view of the later, thermal energy storage (TES) is usually added in the installation analysis which jacks up the cost of installation. In the absence of TES, biofuels can be exploited to drive hybrid solar-biofuel GT power plants.

### 3.2.2 Hybrid sources of energy

It has been shown in Section 3.2.1 that biogas and solar energy have great potential to drive a CCGT plant in SA. However, solar energy is intermittent while biogas can supply a base load. Thus, hybridization of solar and biogas appears to have a reasonable potential. Currently, the existing energy output from fossil-driven GTs in SA is about 2.11 x 10^6 MWh. This can predominately be supplied by the solar subsystem (without storage), with the biogas component taking over at night or during periods of low insolation.

### 4 CONCLUSION

The potential for exploiting renewable energy (RE) resources to drive a gas turbine (GT) power plant has been evaluated. The open cycle gas turbine (OCGT) and combined cycle gas turbine were used to study the available potential.

iv. At the current biofuels production capacity, about 2.00 x 10^6 MWh of electricity per year can be generated in SA from biodiesel by using a CCGT power plant.

v. Biogas integration into gas turbine power production is an established technology. About 12.09 x 10^6 MWh can be obtained from CCGT, which is higher than the current share of the fossil-driven GT technology.

vi. Harnessing solar radiation in South Africa for GT power generation is a promising with a potential of up to 105.0 x 10^6 MWh being generated from the solar resource.

vii. It is concluded that there is enormous potential to combine solar and biogas resources to drive gas turbine power plants.

viii. There is need for further investigation into the optimization of a hybrid solar-biogas power plant under the South African meteorological conditions to assess the economic performance of the system.

### REFERENCES


**AUTHORS BIOS AND PHOTOGRAPHS**

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