# Gas power plant fuel requirements and uncertainty considering increasing renewables penetration

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## Nomenclature

**CCGT** Closed-Cycle Gas Turbine
**GTP** Gas-To-Power
**HFO** Heavy Fuel Oil
**LDC** Load Duration Curve
**LNG** Liquefied Natural Gas
**LP** Linear Programming
**MDT** Minimum Down Time
**MIP** Mixed Integer Programming
**MSL** Minimum Stable Level
**MT** Medium-Term
**MTTR** Mean Time To Repair
**MUT** Minimum Up Time
**OCGT** Open-Cycle Gas Turbine
**PASA** Projected Assessment of System Adequacy
**PV** Photovoltaic
**QP** Quadratic Programming
**RE** Renewable Energy
**SRMC** Short-Run Marginal Cost
**ST** Short-Term
**VO&M** Variable Operation & Maintenance

## I. Introduction

With recent discoveries of large proven gas reserves off the coasts of Mozambique and Tanzania coupled with the already flourishing gas industries in West and North Africa [1], there is little doubt that gas-fired power plants have a major role to play in the African energy mix across the continent. The proven gas reserves across the continent as of 2015 are shown in Figure 1. This gas is not merely limited to the countries with local access to these reserves but could be used across the entire African continent with existing natural gas pipelines and Liquefied Natural Gas (LNG) terminals across West and North Africa [2, 3] as well as developments planned for East Africa [2, 4] and Southern Africa [5].

Despite the nascent status of many African power systems, the rise of renewable generation has gathered momentum from wind in Darling (South Africa) to Zarafana (Egypt) and solar Photovoltaic (PV) in De Aar (South Africa) to Tangier (Morocco). Considering this, as a renewable plant may be considerable in size relative to the power system of the country, especially in smaller systems, the penetration level

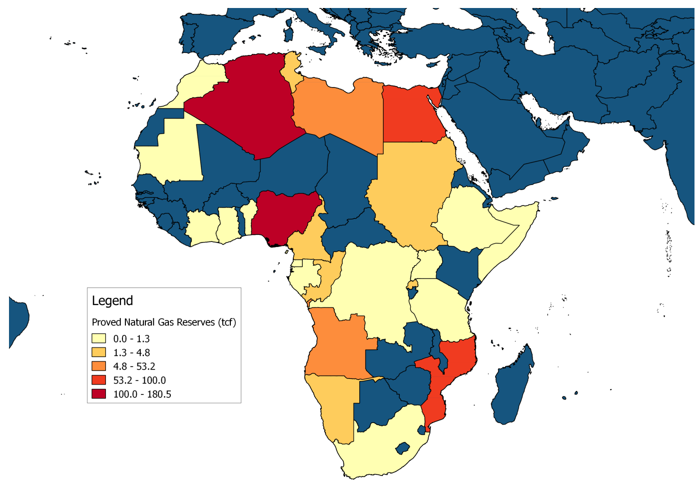


Figure 1. Map showing the proven gas reserves in Africa as of 2015 (except for South Africa which is based on information from 2012) [6]

attained from even a handful of projects may be significant. As African countries start to realise their Renewable Energy (RE) potential, the increase in intermittent renewable generation will impact on the dispatch of conventional fossil fuel-based generation as well as hydro resources where available.

In order to evaluate the effects of this increase in renewable energy penetration, a representative model has been developed in PLEXOS® Integrated Energy Model [7] to gauge the effect that an increasing intermittent renewable energy mix has on a power system reliant on a conventional mix of coal, gas and hydropower and primarily how it affects the medium-term gas requirements for the portfolio.

## II. Representative model in PLEXOS

### A. Model overview

The developed model in PLEXOS® consists of a representative gas-electric hybrid system as shown in Figure 2. From Figure 2 one can see the different components that have been modelled in the system which include:

- Electrical:
  - Generators
  - Fuels
  - Nodes

  - Lines
- Gas:
  - Gas fields
  - Gas nodes
  - Gas pipelines
  - Gas storage

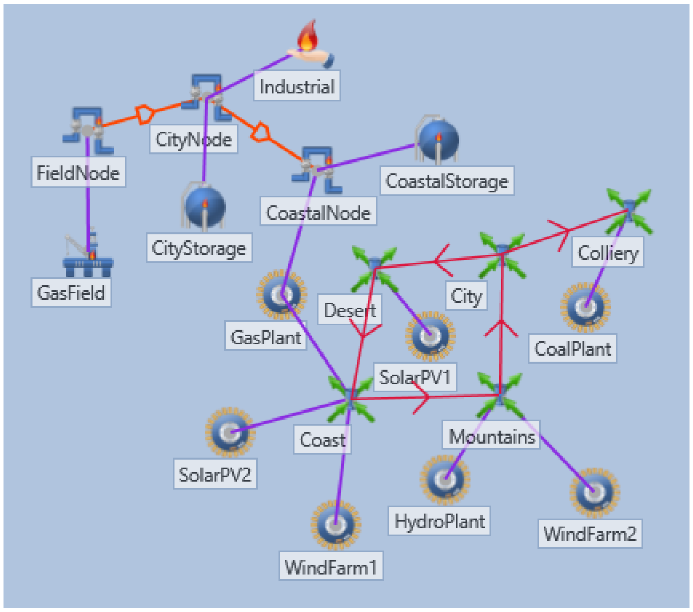


Figure 2. Overview of the gas-electric representative model in PLEXOS® Integrated Energy Model

The simulation horizon is over a single year with an hourly load and seasonality profile assumed, with these profiles presented in Figure 3 and Figure 4 respectively. The maximum demand of the system is 2 500 MW, occuring in the southern winter as exemplified by Figure 4. The model includes an installed capacity of conventional generation (coal, gas and hydro) to match this demand and to provide a 40% capacity reserve margin when fully available.

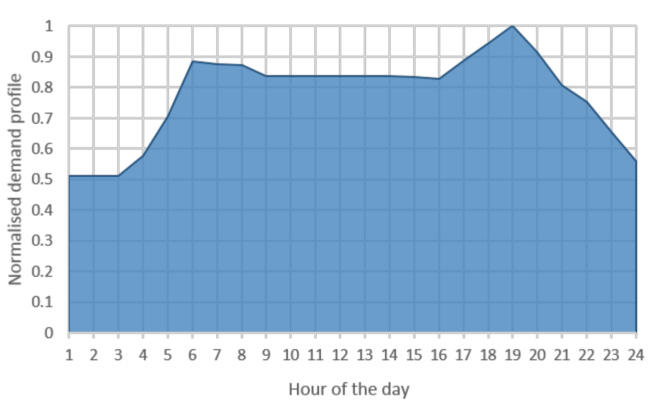


Figure 3. Hourly demand profile

The split of conventional generation capacity is as follows:

- Coal-fired generation: 20%
- Hydroelectric generation: 30%

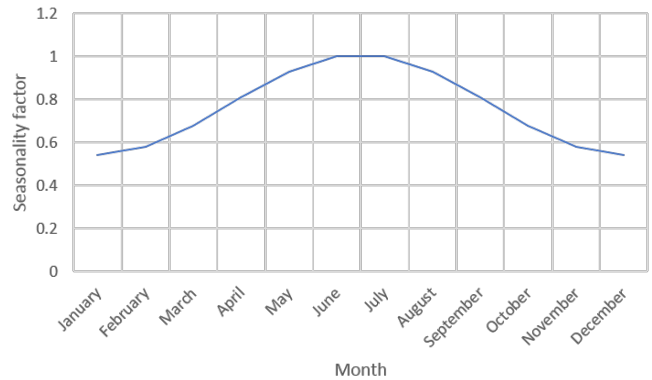


Figure 4. Annual seasonality of demand profile

Table I
TECHNO-FINANCIAL PARAMETERS OF THE GENERATORS

| Property | Coal | Gas | Hydro |
|---|---|---|---|
| Unit size (MW) | 100 | 35 | 105 |
| Number of units | 7 | 50 | 10 |
| Minimum Stable Level (MSL) (% unit size) | 40 | 33 | 50 |
| Minimum Up Time (MUT) (hrs) | 12 | 2 | - |
| Minimum Down Time (MDT) (hrs) | 12 | 1 | - |
| Ramp rate (% unit size/min) | 40 | 30 | 50 |
| Heat rate (GJ/MWh) | 10 | 12 | - |
| Fuel price ($/GJ) | 3 | 7[a] | - |
| VO&M Charge ($/MWh) | 4 | 30 | 6 |
| Capacity factor (%) | - | 50 | - |

[a] The price for natural gas as a fuel is calculated from the Production Cost ($3/GJ) at the gas field and the Flow Charge for the Field - City ($1/GJ) and City - Coast ($2/GJ) pipelines

- Gas-fired generation (Open-Cycle Gas Turbines (OCGTs)): 50%

The techno-financial parameters of the aforementioned generators are presented in Table I. These values are assumed from typical parameters encountered in existing systems.

Based on the Variable Operation & Maintenance (VO&M) charges, heat-rates and fuel prices presented in Table I, the Short-Run Marginal Cost (SRMC) of each generation type can be determined along with the expected merit order, as shown in Table II.

Although lines are modelled to connect the different nodes and areas of the system, these are assumed to have zero impedance and a maximum flow constraint that is not binding (as this is not the focus of the study). The gas and electric systems are linked via the gas offtake for the gas-fired plant (see Figure 2).

In addition to the aforementioned generator parameters, both forced and unforced outage rates are also modelled, each with their respective Mean Time To Repair (MTTR) with the values

Table II
SRMC OF DIFFERENT PLANTS IN THE SYSTEM

| Ranking | Plant | SRMC ($/MWh) |
|---|---|---|
| 1 | Wind/Solar | 0 |
| 2 | Hydro | 6 |
| 3 | Coal | 34 |
| 4 | Gas | 114 |

Table III
OUTAGE PROPERTIES OF THE GENERATORS

| Outage | | Coal | Gas | Hydro |
|---|---|---|---|---|
| Forced outages | Rate (%) | 4.9 | 2.4 | 2.7 |
| | MTTR (hrs) | 45 | 68 | 117.3 |
| Planned outages | Rate (%) | 7.6 | 3.5 | 8.9 |
| | MTTR (hrs) | 504 | 240 | 295.4 |
| Maintenance | Rate (%) | 2.5 | 1.5 | 1.8 |
| | MTTR(hrs) | 82 | 60 | 63.1 |

based on those from [8] and presented in Table III. With these parameters included, PLEXOS® optimises the placement of unforced outages in periods of low demand while forced outages occur randomly.

### B. Renewable model

The intermittent renewable generation is assessed with the consideration of solar PV and wind power technologies. Annual hourly data of solar and wind resources are based on data for four separate sites (two solar sites [9] and two wind sites [10]) in South Africa. This resource data is used as an input for the associated generation profiles. A fixed annual energy yield is explicitly defined using the hourly data previously mentioned with a 20% and 30% capacity factor assumed for solar PV and wind plants respectively. Three different compositions of renewable generation are assessed, namely:

1) Equal wind and solar mix
2) Wind only
3) Solar only

These three different renewable compositions are then assessed for four different penetration levels (by installed capacity):

- 10% penetration (Low)
- 20% penetration (Medium)
- 30% penetration (High)
- 40% penetration (Very High)

The penetration level is calculated as shown in Equation 1 below,

$$p = \frac{P_{ren}}{P_{coal} + P_{gas} + P_{hydro} + P_{ren}} \tag{1}$$

where:
$p$ = penetration level
$P_{coal}$ = installed coal-fired power capacity
$P_{gas}$ = installed gas-fired power capacity
$P_{hydro}$ = installed hydropower capacity, and
$P_{ren}$ = installed RE capacity

### C. Simulation options

For the running of the model, PLEXOS® includes the following three simulation phases, with a running order as presented:

1) Projected Assessment of System Adequacy (PASA)
2) Medium-Term (MT) Schedule
3) Short-Term (ST) Schedule

Initially, the PASA phase optimally places unforced outage events (maintenance and planned outages) in periods of low demand for the subsequent MT and ST Schedule phases. Following this, the MT Schedule phase runs, which allows the optimisation of medium to long-term decisions (in our model, the optimal use of the hydro considering an annual energy constraint) at the same time as considering short-term decisions. In order to do this, it reduces the chronology of the problem using a Load Duration Curve (LDC) and solves for the optimal use of the hydro considering the annual energy constraint in a reduced problem. This annual constraint is then decomposed into a number of constraints for each step of the ST Schedule phase. A step size of one week over one year (i.e. ˜52 weeks) was used for the ST Schedule phase. Additionally, the simulation uses a Mixed Integer Programming (MIP) solver in order to allow integer unit commitment decisions to be made.

## III. RESULTS

### A. Results with hydro

The change in the annual energy production per generation type for all the different renewable scenarios is presented in Figure 5. The results show that as the renewable generation increases from zero to very high penetration, it mostly displaces the more expensive gas-fired generation while a small amount of coal-fired generation is also displaced. The hydro generation, stays approximately constant with the maximum annual energy being fully utilised due to its position in the merit order (see Table II). With the gas-fired generation right at the bottom of the merit order, it should be the first to be displaced with the advent of renewable generation, however there is still some gas generation which is not displaced. This non-displaced gas generation is a result of its favourable inter-temporal characteristics which allow it to balance supply and demand in the presence of increasing renewable penetration. Therefore, the amount of non-displaced gas generation is monitored as a means of assessing the impact of the renewable generation in terms of the system's requirements from flexible generation in response to intermittent generation.

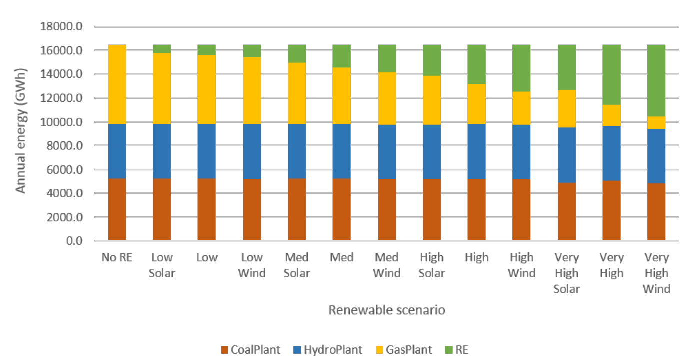


Figure 5. Annual generation profile of each generation type for different renewable scenarios

To get a clearer idea of the amount of non-displaced gas-fired generation in relation to renewable generation added to the mix, the amount of non-displaced gas generation is

Table IV
RATIO OF HYDROPOWER CAPACITY TO RE CAPACITY FOR DIFFERENT PENETRATION SCENARIOS

| Penetration level | Ratio | |
|---|---|---|
| | Hydro | RE |
| Low (10%) | 9 | 2 |
| Medium (20%) | 2 | 1 |
| High (30%) | 7 | 6 |
| Very High (40%) | 3 | 4 |

presented as a percentage of the generation added from RE resources in Figure 6. This reveals that up until a certain level of penetration, the percentage of non-displaced gas generation remains fairly constant around 1-3 %. However at a certain level (very high penetration scenario), the ability of the system to respond to the intermittent nature of the renewable generation becomes binding and the displacement of generation in the system becomes reliant on parameters which are not purely economical, and thus out of merit order dispatch occurs.

From Figure 6, there does not seem to be any real trend in the use of gas as the flexible resource for the lower renewable penetration levels, and this is due to the significant role being played by the hydro generation and its very favourable inter-temporal characteristics. The role of the hydro is important when analysing the results as it is at the top of the merit order as well as offering the most flexibility. It is clear though that after a certain threshold, the system will need to use another flexible resource. The sharp rise in the non-displaced gas generation occurs as the capacity of the RE approaches that of the hydro. In fact, in the very high penetration scenario it is the first scenario where the renewable generation capacity overtakes that of the hydro generation (as shown in Table IV), which suggests that this may be the reason for the greater reliance on gas generation in this scenario.

Therefore, there is evidence to suggest that the necessity for gas-fired generation as a flexible resource is based on the capacity of other similar flexible resources in the system and the existing merit order. The small amount of non-displaced gas generation for the low to high penetration levels can be attributed to a a number of factors, namely outages of hydro units, the role of hydro as baseload generation and the fact that when annual hydro energy constraints are decomposed to weekly constraints, there is a degree of error and sub-optimal use of the hydro due to detail lost with the use of an LDC in the MT Schedule phase. Additionally, the less flexible inter-temporal characteristics of the gas units in comparison to the hydro, especially that of MUT and MSL, will lead to gas-fired generation remaining in use despite the availability of more economical generation. This can result in over-compensation from the gas generation and may explain the slightly higher percentage of non-displaced gas-fired generation in the low penetration scenarios.

### *B. Results without hydro generation*

Although the previous results give an idea of the effects that intermittent RE generation places on a power system, the complexity of the role of hydro does not allow the effect to be

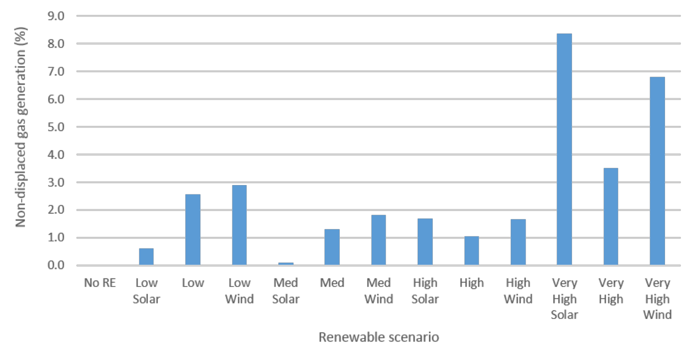


Figure 6. Non-displaced gas-fired generation for different RE penetration scenarios

fully quantified. In addition, the fact that hydro resources are affected by uncontrollable circumstances (monsoon, drought), the removal of the energy from the hydro resource would allow a more in-depth analysis of the impact of RE on gas requirements.

In order to demonstrate the effect of the intermittent RE generation on the system, and how it necessitates flexible generation against the existing merit order, an additional scenario is analysed in which the conventional energy mix is now limited to coal and gas-fired generation only. In this scenario, the split of gas and coal-fired generation is 70% and 30% respectively, with a minor change in the coal unit sizes (coal unit is 105 MW as opposed to 100 MW). The change in the annual generation profile for all of the renewable scenarios is presented in Figure 7. Figure 8 presents the non-displaced gas generation for the different renewable scenarios. The results show that as the renewable generation increases from zero to very high penetration, it again mostly displaces the more expensive gas-fired generation. However, there is a more defined trend than previously where hydro was included, where the amount of non-displaced gas generation steadily increases as the penetration level increases. This is from approximately 0% in the low penetration scenarios up to 17.6% in the very high penetration, solar-only scenario. It is also evident that with the mixed composition of renewable generation, the amount of non-displaced gas generation drops, depicting less flexibility required.

### *C. Analysis of the dispatch of generation*

The results in Section III show that the introduction of intermittent generation, either solar PV, wind or both, places additional requirements on the power system requiring generation with flexible inter-temporal characteristics. This can result in out of merit order dispatch of generation. To obtain a glimpse into the trend in the daily dispatch on the system, the average normalised output of each generation type at each hour of the day across the year is computed. The normalised output from each generation type with no intermittent RE penetration is presented for both the full (coal, gas and hydro) and limited (only coal and gas) energy mix scenarios in Figure 9 and Figure 10 respectively.

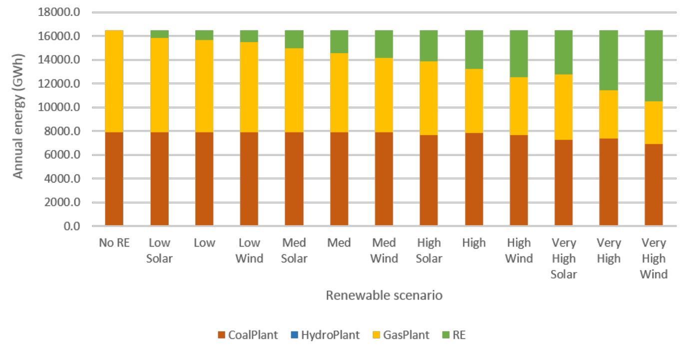


Figure 7. Annual generation profile of each generation type for different renewable scenarios

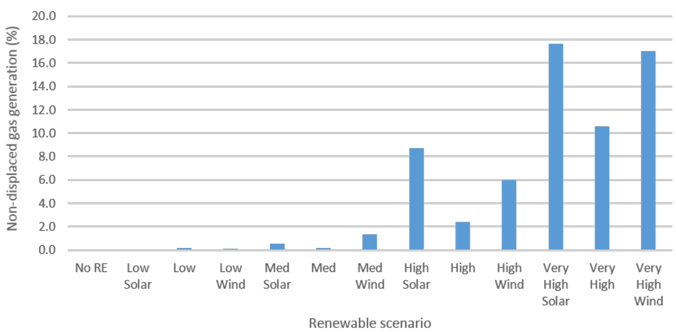


Figure 8. Non-displaced gas-fired generation for different RE penetration scenarios

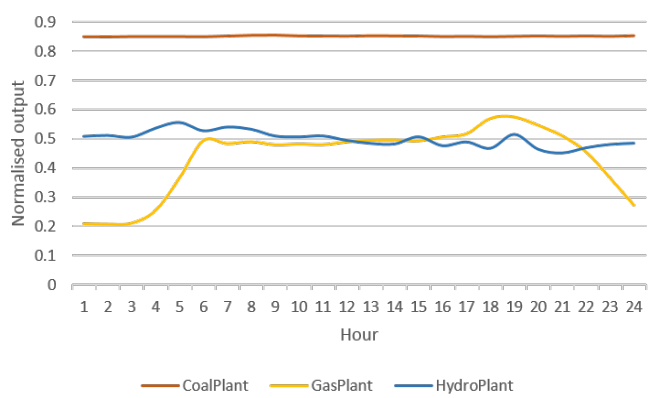


Figure 9. Normalised average hourly load profile for no RE penetration scenario with a full energy mix (coal, gas, hydro)

From Figure 9, it is clear that the hydro along with the coal are providing baseload generation, with the OCGTs acting as a mid-merit generator providing a portion of the baseload but also operating as a peaking plant at peak times of the day. A similar scenario is present in the limited energy mix in Figure 10, albeit without the baseload hydro. The presence of the baseload hydro in the full energy mix scenario and the fact that it is acting as the flexible resource in response to the RE penetration level means that it is advantageous to assess the impact on the daily dispatch of the hydro resource due to the advent of renewable generation.

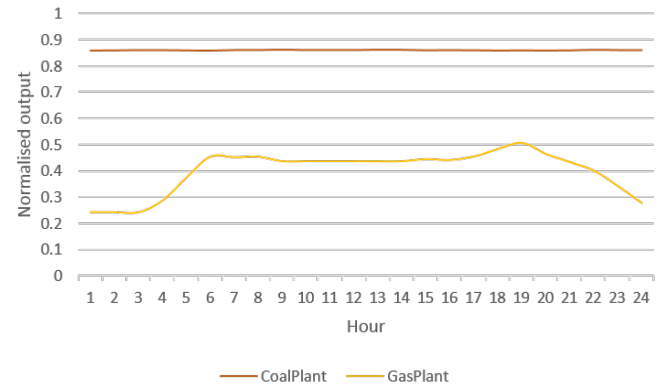


Figure 10. Normalised average hourly load profile for no RE penetration scenario with a limited energy mix (coal, gas)

As the generation profile from solar PV is more predictable than that of wind (a peak defined around midday), the renewable scenarios with only solar penetration can provide a unique insight into the dispatch of generation in response to the presence of intermittent generation. Figure 11 to Figure 14 present the aforementioned normalised hourly generation profiles for all solar-only scenarios.

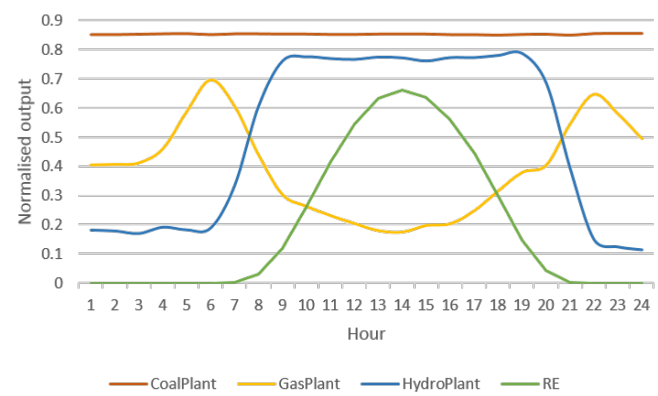


Figure 11. Normalised average hourly load profile for 10% penetration scenario with solar only and a full energy mix (coal, gas, hydro)

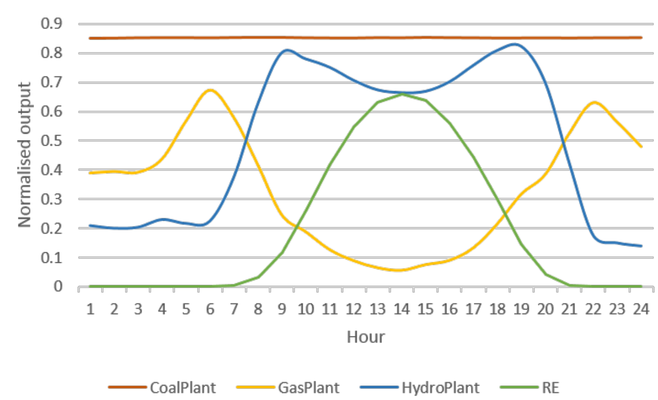


Figure 12. Normalised average hourly load profile for 20% penetration scenario with solar only and a full energy mix (coal, gas, hydro)

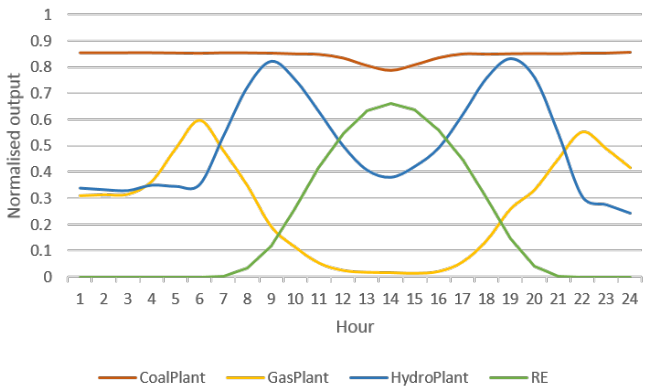


Figure 13. Normalised average hourly load profile for 30% penetration scenario with solar only and a full energy mix (coal, gas, hydro)

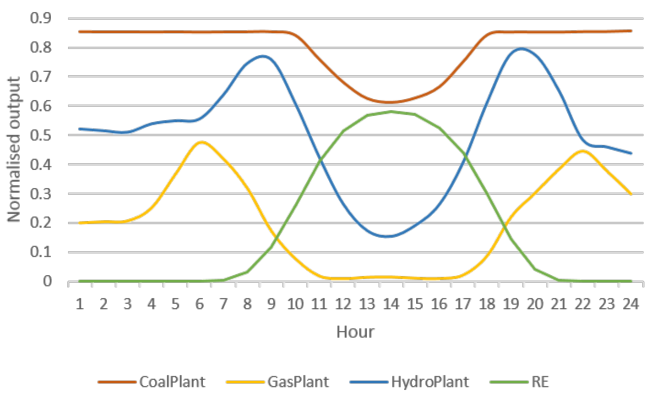


Figure 14. Normalised average hourly load profile for 40% penetration scenario with solar only and a full energy mix (coal, gas, hydro)

Figure 11 shows that there is a shift in the dispatch times of the hydro, with a small amount still operating as baseload generation, but the majority of the hydro generation dispatched during daylight hours in order to match the solar generation. As the penetration increases, the displacement of the gas-fired generation is also evident.

In the very high penetration scenario (Figure 14), it becomes apparent that there is significant displacement of baseload coal-fired generation, showing the system's shift to dependency on the flexible generation required from the gas-fired generation due to the increased capacity of renewable generation and the inability of the hydro to solely provide this flexible resource.

As the hydro capacity is providing the majority of the flexible resource in the full energy mix scenario, this analysis gives an indication of the change in the dispatch of flexible generation due to the necessity to balance supply and demand in the presence of intermittent generation. A similar analysis with the limited energy mix scenario does not provide this insight due to its mixed role (baseload and peaking) in the scenario with no renewable penetration.

## IV. Conclusion

With many power systems in Africa fighting to keep the lights on, growth of the generation capacity across the continent is paramount. The nascent status of these power systems coupled with the growth and drive in the renewable energy sector may result in high penetration levels achieved with a relatively small amount of projects. This coupled with the gas developments across the continent means that both the Gas-To-Power (GTP) and renewable sectors will be significant in Africa going forward. In order to model the interaction of the two and more specifically the impact of RE on natural gas requirements, a representative model was developed in PLEXOS® with an energy mix of coal, gas, hydro, solar PV and wind resources.

The results show that the advent of renewable generation necessitates flexible generation to respond to the intermittent supply from the RE resources in order to balance supply and demand. In general, gas plants employing OCGT technology have a higher SRMC than many other technologies (i.e. coal, hydro, geothermal, Closed-Cycle Gas Turbine (CCGT) and nuclear). However, its favourable inter-temporal characteristics make it a prime candidate for the response to the intermittency of renewable generation like solar PV and wind. The amount of gas generation dispatched out of merit order can be significant, especially in a system without reliable hydro (which also has favourable inter-temporal characteristics). However, hydro generation is hindered by energy constraints based on the natural inflow of water into reservoirs and cascaded hydro networks.

It was shown that the the required capacity of the aforementioned flexible resource is closely related to that of the renewable generation. However, a mixed composition of renewables will aid in reducing the intermittency of RE output. Nevertheless, there is still a requirement of flexible generation on the power system of the future and the fact that gas-fired generation has both favourable inter-temporal characteristics and is not hindered by energy constraints like hydro resources will mean that the development of gas-fired generation capacity and additional gas requirements may be necessary for power systems in Africa that wish to pursue ambitious RE programmes.

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