Transition to new fuels:
Optimized power generation solutions for the transition in the Caribbean

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The energy generation portfolio in the Caribbean consists mainly of aged engines which are running on heavy fuel oil.

Dependence on heavy fuel oil or similar fuels does not only hurt the Caribbean's valuable environment but also makes its economies more prone to the harmful consequences of oil price shocks. The volatility of oil prices has a long history of dragging Caribbean countries into debt, unemployment and economic recessions. Hence the Caribbean countries would profit immensely from a rapid energy transition.

The first and most economically rewarding step into a more ecologically and economically friendly future is the transition from HFO and diesel to alternative fuels like natural gas or propane gas.

Newly available fuels, new technologies and ambitious renewable goals are presenting a disruptive change for the utilities in the Caribbean. It opens the way to a sustainable, reliable, resilient and affordable energy future, but also brings more complexity to the planning process.

This presentation will focus on main criteria like project size, efficiency, flexibility, stability, reliability, availability and emissions, which need to be evaluated to decide which technology and fuel to use. It will especially discuss where reciprocating engines and where gas turbine technology have their advantages and how to make sure that newly built power plants will complement the renewable growth story of the region.

As Siemens' Portfolio contains every Technology mentioned, the authors are in no way pressured to advertise one specific Technology. Therefore, it should be clear that this paper enables unprecedented objective and factual insights on the topic.

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Abbreviations

LCOE	Levelized Cost of Electricity
RICE	Reciprocating Internal Combustion Engine
HFO	Heavy Fuel Oil
MW	Megawatt
WACC	Weighted Average Cost of Capital
SC	Simple Cycle
CC	Combined Cycle
OEM	Original Equipment Manufacturer
FFR	Firm Frequency Response
Hz	Hertz
CO	Carbon Monoxide
CO2	Carbon Dioxide
SOx	Sulfur Oxides
NOx	Nitrogen Oxides
g	Gram
kWh	Kilowatt hour
CCGT	Combined Cycle Gas Turbine
GT	Gas Turbine
dB	Decibel
ISO	International Organization for Standardization
N+2	Plants with at least 2 backup units

1. Best technology fit depends on Project size and specific needs

For high temperature cogeneration applications gas turbines will always be the best option.

Otherwise technology needs to be analyzed project by project. Projects with smaller capacities of up to 20 MW are usually best equipped with Reciprocating Internal Combustion Engines (RICE). Projects with larger capacities over 130 MW are best suited for gas turbines, mainly because of their higher efficiencies and lower maintenance which lead to the lowest cost of electricity (see Figure 1).

For plant capacities between 20 MW and 130 MW the preferred technology depends highly on project specifics. Factors analyzed in order to decide for a technology are: Levelized Cost of Electricity (LCOE), Efficiency, Flexibility, Stability and Reliability requirements, Ambient Temperature, Noise and Emission restrictions, Availability Needs and Maintenance Tolerance.

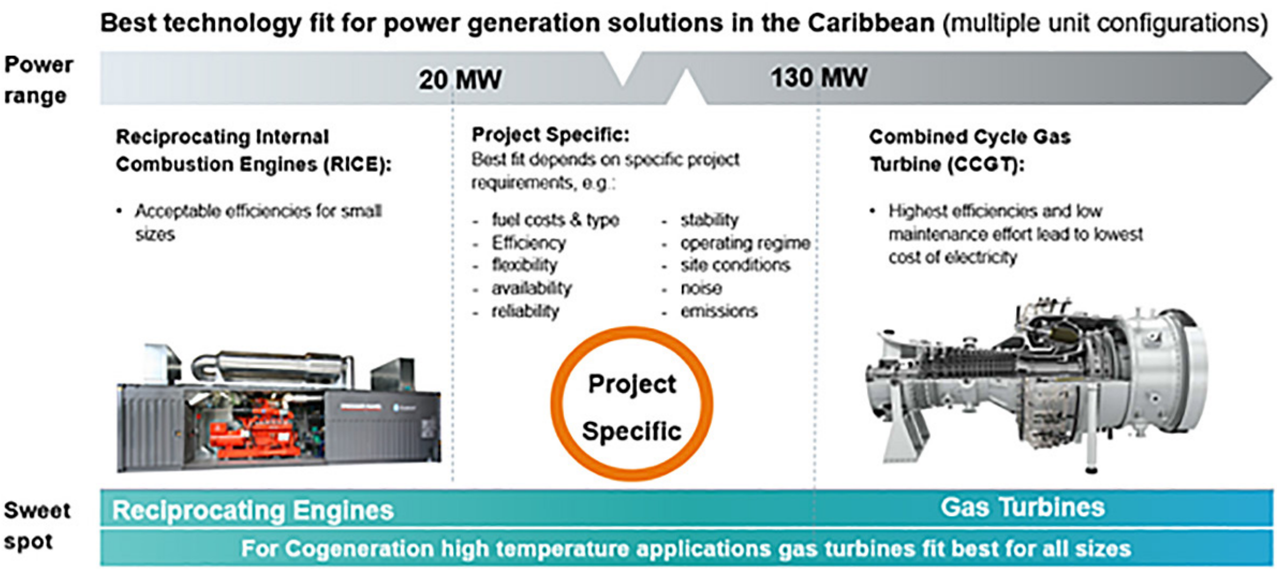

Figure 1, Best technology fit for power generation solutions in the Caribbean, Source: Authors' research

2. Levelized cost of Electricity (LCOE)

Levelized Cost of Electricity (LCOE) is calculated by the sum of all costs divided by energy simplified calculation is

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t=	*Investment expenditures in year t (including financing)*
M_t=	*Operations and maintenance expenditures in year t*
F_t=	*Fuel expenditures in year t*
E_t=	*Electricity generation in year t*
r=	*Discount rate*
n=	*Life of the system*

LCOE is the most important economic indicator to evaluate power generation projects. Most important factors which influence the LCOE are operating conditions, Capital Expenditure (CAPEX), fuel price, efficiency, evaluation time and financing conditions.

The higher the fuel price and the higher the operating hours, the more will efficiency be the dominating factor in the comparison of different configurations.

For projects with a capacity of 50 MW the LCOE of industrial gas turbines is the lowest for base load plants in every case. For intermediate load, either RICE or gas turbines offer the lowest LCOE depending on fuel costs. RICE reaches the lowest LCOE for peak load plants. (Figure 2, 50 MW)

For projects with a capacity of 100 MW gas turbines offer the lowest LCOE for base load, intermediate load and even peak load (aeroderivative gas turbines) if the fuel prices are not too high. (Figure 2, 100 MW)

For projects with a capacity of 150 MW the LCOE for gas turbines is the lowest in every case. Aeroderivative gas turbines are used over common industrial gas turbines for peak loads and lower fuel prices. (Figure 2, 150 MW)

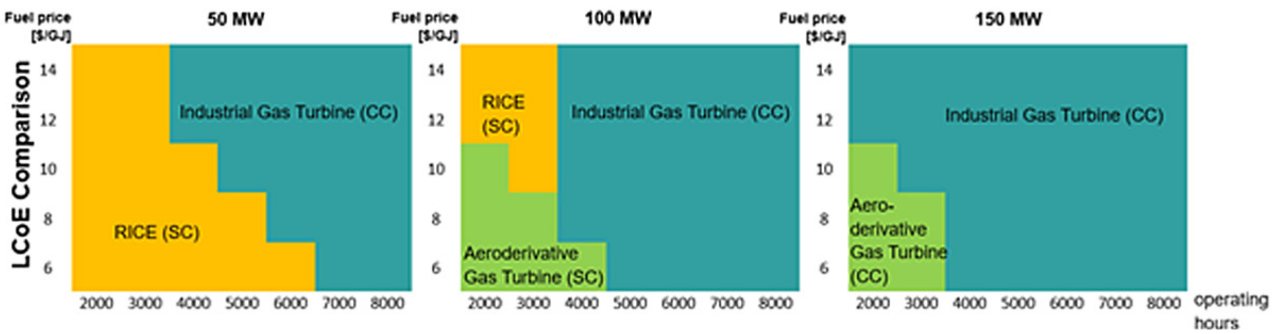

Figure 2, LCOE Comparison of RICE to GT, Source: Authors' research, Siemens Configuration Tool

This analysis is based on a Siemens Configuration Tool (CAPEX/OPEX comparison of a wide range of turbines and engines). The assumptions are: 20 years of lifetime, weighted average cost of capital (WACC) of 12% and equity of 30%. Also, only multiple unit configurations were included. But else all reasonable configurations (#units, SC, CC) were considered. (Sources: GTW handbook, Thermoflow, Diesel and Gas Turbine, OEM publications, Siemens data and competitive intelligence)

3. Efficiency

3.1 The importance of Efficiency in power generation

In the context of power generation, efficiency relates output of electricity to energy contained in the fuel used. In simplified terms, the more efficient a plant is, the less fuel it consumes to create the same amount of electricity.

Considering that gas prices in the Caribbean are comparatively high, efficiency is going to be the most important factor in any life cycle business model (e.g. LCOE evaluation). Because plants with high efficiencies have the lowest LCOE, they will directly lead to cheaper electricity prices. Difference in fuel costs on a typical 200 MW plant ~16 million USD/year. Furthermore, higher efficiency plants also cause less harmful emissions like CO2.

Due to high exhaust temperatures, combined cycle gas turbine solutions offer the highest efficiency of any energy generation solution. Multiple unit concepts guarantee high efficiency over a broad power range.

For example, a ~ 200 MW 3x1 SGT-800 combined cycle gas turbine solution would provide efficiencies of up to or even above 55%, while a comparable reciprocating engine would be around 46% (in simple cycle) or ~49% (in combined cycle). The efficiency difference directly translates into equivalent fuel savings and CO2 emission reduction.

Figure 3 shows Electrical Net Efficiency for 1, 2 or 3 gas turbines depending on capacity need and the load. Here we can see that efficiency is at lower levels when the load is not on its maximum. For one gas turbine at about 40 MW and 50% load, efficiency is at 47% and for 3 gas turbines with combined 140 MW and 65% load, efficiency is at 50.9%.

With rising load and higher capacity needs, efficiency increases sharply. At 100% load the efficiency is the highest respectively. For one gas turbine and about 70 MW, efficiency is at 53.9%. For three gas turbines and over 200 MW, efficiency is at 54.5%.

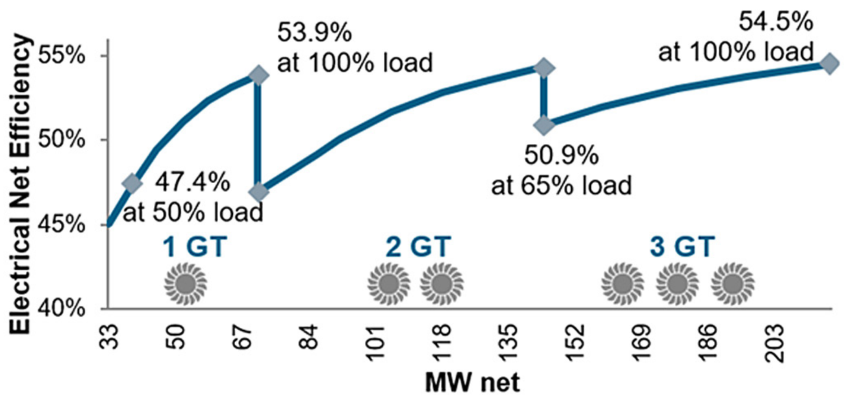

Figure 3, Efficiency for a gas turbine solution for different loads, Source: 'Advantages of a gas turbine combined cycle solution for the Port-au-Prince area', Siemens 201?

3.2 The different requirements for output and efficiency declarations for RICE and GT

While manufacturers of gas turbines are required to state accurate values for electricity, the same is not true for RICE. ISO 3046 13.3 "Declaration of specific fuel consumption" allows reciprocating internal combustion engines to state a 5% smaller fuel consumption than it actually is.

4. Flexibility

A systems' capability to react to dynamic and changing conditions is called flexibility. It refers primarily to rapid supply and demand changes lasting a few hours but can also mean long term changes like deploying new generation and transmission resources over period of multiple years.

Instead of traditional base load plants, fossil power plants will need to provide high operational flexibility and high efficiency over broad power range.

Gas turbine plants are designed as base load plants to decrease the average energy generation cost of the country. Nevertheless, they have the ability to load follow which will provide benefits even when the net demand is lower during night hours.

This flexibility also allows countries' generation mixes to change dramatically with for example much higher contribution from renewable energy resources.

In the Caribbean high operational flexibility becomes increasingly important in order to follow load and complement intermittent renewable generation.

Figure 4 shows how multiple gas turbine configurations offer high flexibility while maintaining high efficiency. For a net power demand below 150 MW, two gas turbines are in use and operate at an efficiency of 53.8%. For a slightly higher power demand, an additional gas turbine would be started, and the efficiency would decrease. But the efficiency would only get as low as 52.2%. A further increase would then increase the efficiency up to 54.4% until another gas turbine needed to get connected.

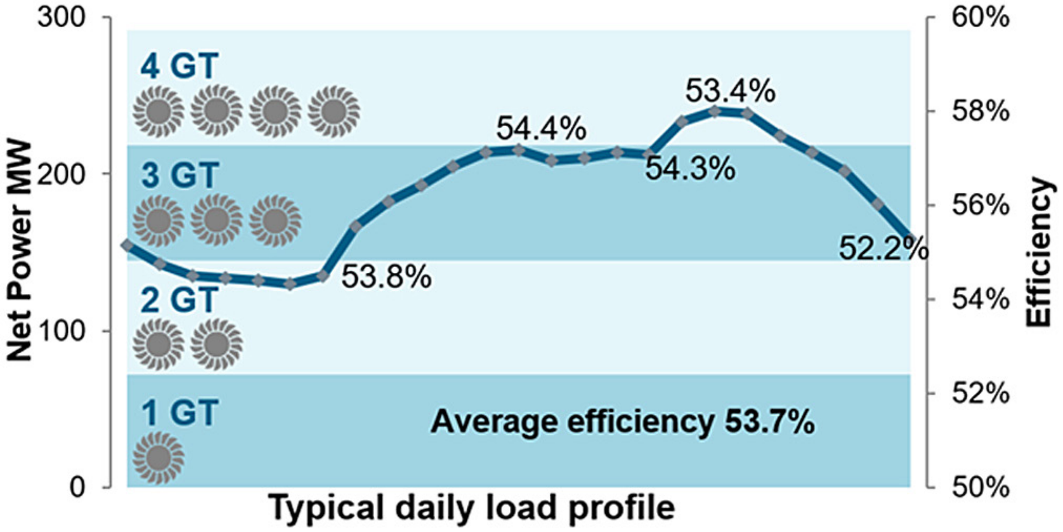

Figure 4, Daily load profile and efficiencies of GT, Source: 'Advantages of a gas turbine combined cycle solution for the Port-au-Prince area', Siemens 201?

5. Stability

The stability refers to the ability of a system to return to its steady state when subjected to a disturbance. Since networks in the Caribbean are not covering large geographic areas, a main concern is frequency stability.

During networks losses, remaining generating units need to damp the frequency deviation and react quickly to bring the frequency back to normal as fast as possible. In the case of failure to provide the needed stability, additional power plant trips and subsequently a complete black out can follow.

Concerning system stability (industrial) gas turbines have one significant technical advantage over comparable RICE solutions. The rotating mass of the gas turbine, steam turbine and generator rotors provide a high amount of mechanical inertia. After sudden changes of load in the network, this mechanical inertia is going to decrease the change in frequency, allowing the control system of the power plant to react and bring the frequency back to normal.

Figure 5 shows as an example of a frequency response to an immediate loss, comparing a power plant with low inertia with a power plant with high inertia. It can be seen how the frequency change is limited by the inertia to about 0.7 Hz, before the control system of the plant brings the frequency back to normal. In contrast to that a low inertia power plant will experience a frequency deviation of almost 1 Hz. The stability of both power plants can be increased by adding a firm frequency response battery, but it will affect power plants with high inertia more effectively.

Congruent results will be found for many other network incidents, including more severe losses or increases in load. In a case of large load increase, for example in the event of another generator tripping, the response is even more powerful. Up to 70% load increase can be achieved in 10 seconds.

Load rejections means that there is a sudden loss in load. Even in an extreme case of complete load rejection, for example a 3x1 SGT-800 configuration would stabilize itself without tripping.

Especially for small grid sizes, the growing share of renewables' unsteadiness make frequency stability a major and increasing concern for many islands. Hence the stability capabilities of gas turbine solutions will also support a significant increase of renewable power.

Solar power, for example, can introduce quite steep ramps as clouds cover or un-cover the panels. For this gas turbines offer the perfect solution, as they exhibit stability, they can provide the necessary balancing.

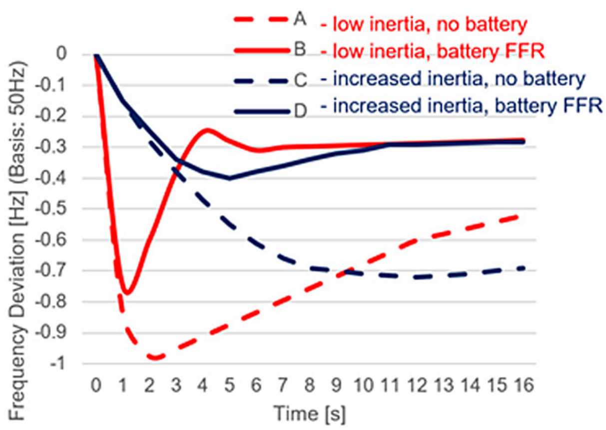

Figure 5, Frequency Deviation in case of a loss for different amounts of inertia, Source: Anna Joswig, Matthias Baca

6. Reliability

Power system reliability describes the overall ability of the power system to perform its function. IGRE

Reliability of power generation is of upmost concern, especially essential for small networks, because often already one power plant is responsible for a crucial share of power generation in the network and its failure would have far-reaching consequences.

The SGT-800 industrial gas turbine for example, was introduced in 1999 and agglomerated over 7 million operating hours, exhibiting 99.8% fleet reliability. RICE usually do not even reach a reliability of 98%.

Figure 6 shows how the different reliabilities of gas turbines and RICE make up the probability for a unit to fail. Gas turbines possess significant higher unit-reliability compared to RICE. Because RICE are 5 times more unreliable (2% compared to 0.4%) than a gas turbine and have 4 times more units in use to achieve the same capacity, RICE hold a 20 times higher chance to lose one unit of a plant. Hence the N+2 requirements to RICE plants due to lower unit reliability and availability are not applicable for gas turbine plants but are critical for RICE-plants.

Figure 6, Consequences of Unreliability, Source:

7. Temperature

The warmer the ambient temperature gets, the lower gets the oxygen concentration in the air. Hence thermal power plants, which rely on oxygen to burn their fuel mix, operate differently at different ambient temperatures.

In the Caribbean, gas turbines often operate with a derating compared to ISO power and efficiencies (see Figure 6a). Anyhow, quotations and examples (including this paper) are always already corrected for site conditions (most of the times 25°C or 30°C). RICE, however, using ISO (15550:2002, clause 5) standard reference conditions most of the time. This poses especially in the Caribbean a big problem, because this will lead for example to higher fuel consumption than what customers expect.

In case of lower temperature there are significant upsides for gas turbines in power output and efficiency compared to guaranteed values. In contrast to RICE, gas turbines have the capability for more power generation and even higher efficiency in colder ambient conditions. Figure 6 shows that gas turbines operate at higher efficiencies when ambient temperatures become lower, while RICE would not gain any advantages. Both Technologies get a derating at higher temperatures, gas turbines slightly faster than RICE.

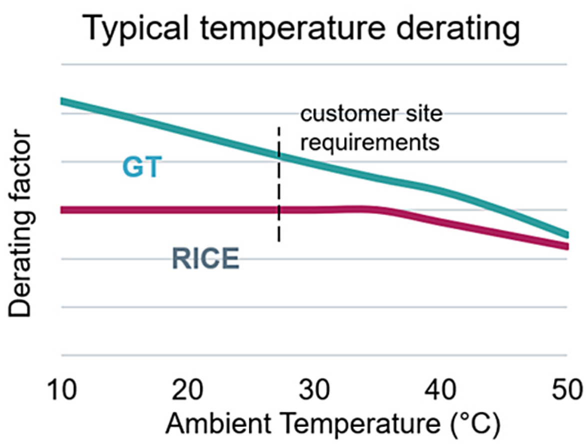

Figure 6a, Typical temperature derating, Source:

8. Noise

A low frequency sound is about 500 Hz and lower. A high frequency sound is about 2000 Hz and higher. Recent research of the University of Gothenburg has shown that low frequency noise bears health risk for workers and residents. High protection (equipment) and long distances for workers and residents are required.

Noise from a gas turbine consists mainly of high frequencies (e.g. 4400 Hz. Is a usual output of a gas turbine) which is easily damped down. For comparison, a usual conversation is held at 60-70 dB. Near field (at 1m distance from the enclosure) noise is below 85 dB and far field noise can be damped to any requirement (for example from World Bank) to minimize disturbance to nearby residential areas. The gas turbine enclosure is suited for outdoor installation without any other noise measures than a stack damper.

Contrary to that, reciprocating engines emit low frequency noise (e.g. 90-120 Hz., near field >113 dB) and vibrations which are difficult to damp. Normally indoor installations in heavy buildings are required and long distances to residential areas are preferred. Therefore, RICE could endanger both the health of nearby populations and plant personnel if special precautions are not taken.

9. Emissions

Global Emissions

CO_2 emissions from power generation depend on efficiency and fuel type. Natural Gas has the lowest CO_2 emissions of all fossil fuels (propane is close behind).

Different technologies play a major role when determining the emissions impact of a given power plant. Depending on the plant layout, the methane emissions can have a significantly negative impact on the CO_2 position. Power plant operators need to be aware that a wholistic approach towards emissions is needed to gain a picture of the impact of their power plant and its technology used.

Methane is a 30 times more potent greenhouse gas than CO_2. 'Methane slip' describes the process of unburned fuel ending up in the atmosphere. For RICE, the Methane slip is 3 g/kWh and only 0.15 g/kWh for gas turbines. Hence it is negligible small on Gas Turbines but significant on RICE (20 times higher). Therefore, CO_2 equivalent is almost as high as running engines on HFO or Diesel.

Gas Turbines save 28% of CO_2 emissions compared to RICE when both use natural gas (see Figure 7).

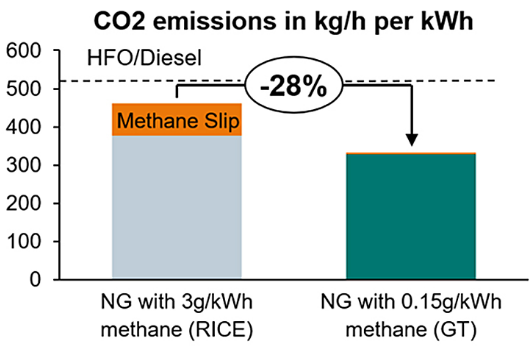

Figure 7, CO_2 equivalent of the methane slip, Source: Michael Welch

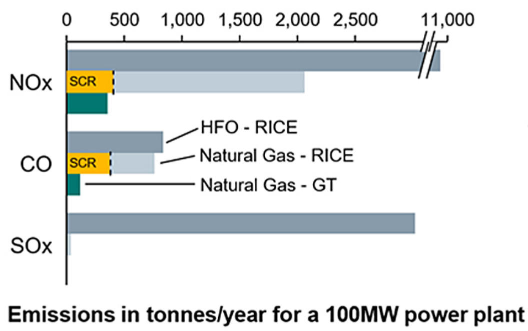

Figure 8, Local emissions for different technologies, Source: Michael Welch

Local Emissions

Switching from HFO/diesel to natural gas or propane gas brings huge reduction in unhealthy and potentially toxic local emissions. But even in local emissions there are still significant differences between gas turbines and RICE.

Unabated, RICE are often non-compliant with local or e.g. world bank guidelines. Additional CAPEX/OPEX is needed for scrubbers and catalysts (SCR). Furthermore, operational complexity increases with scrubbers and catalysts. Abatements impact reliability, safety, start-up time and suitability for cycling. This can potentially change the evaluation of the project completely.

Figure 8 shows the local emissions for different technologies and fuels for a 100 MW plant. RICE running on HFO produce with 11,000 tons/year by far the most NOx, RICE running on natural gas follow with about 2,000 tons/year and GT on natural gas with only about 350 tons/year. CO emissions of engines are for both HFO and natural gas at about 700 tons/year relatively high. CO emissions for gas turbines are almost negligible small, because gas turbines operate at significantly higher temperatures. For HFO on RICE engines the values for SOx reach as high as 3,000 tons/year. As SOx will not be emitted if only natural gas is used. However, RICE burn small amounts lube oil which results in minimal emissions.

10. Availability and Maintenance

RICE require constant monitoring and numerous regular short time interval maintenance like lubrication oil replacements, valve or filter change.

In contrary, gas turbines are easy to operate and require mostly only non-invasive day-to-day maintenance. They can even run remotely controlled for periods without local supervision.

Also, OEM service effort is significantly different. Gas turbines maintenance could be as low as 40 days in 20 years with spare core. This reduced maintenance effort leads to significant savings and higher availability from using gas turbines. The difference in O&M costs on a typical 200 MW plant is more than 10 million USD/year.

Figure 9 shows the two different maintenance schedules for reciprocating engines and gas turbines. RICE need almost daily small maintenance services and about every 5,000 operating hours medium services. Every 10,000 operating hours or less, larger maintenance is required.

For gas turbines, small services will only become relevant after about 12,000 operating hours and then will only be needed about every 5,500 hours. For a 6-year observation period, only one medium maintenance service after about 28,000 hours and one larger maintenance service after about 48,000 hours is common.

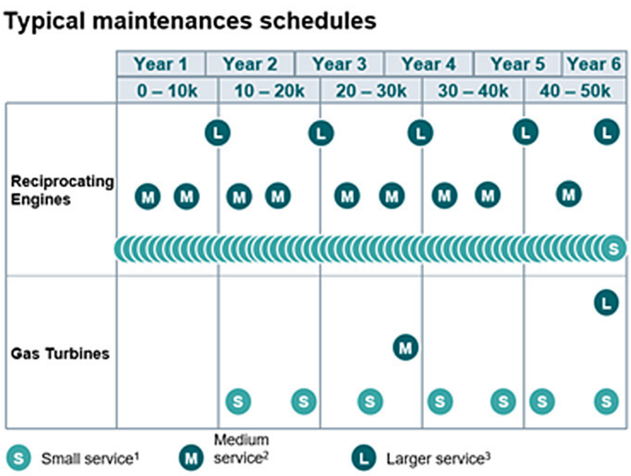

Figure 9, Typical maintenance schedules for RICE and GT, Source: Authors' research

11. Tailored Solutions for the Caribbean:

11.1 CCPP – Regasification Integration

Regasification Integration offers thermal energy transfer between LNG regasification and a combined cycle power plant. Lowering the gas turbine inlet air temperature will increase the energy output significantly and thus counter the aforementioned temperature derating.

This will lower the costs per kW due to higher installed capacity.

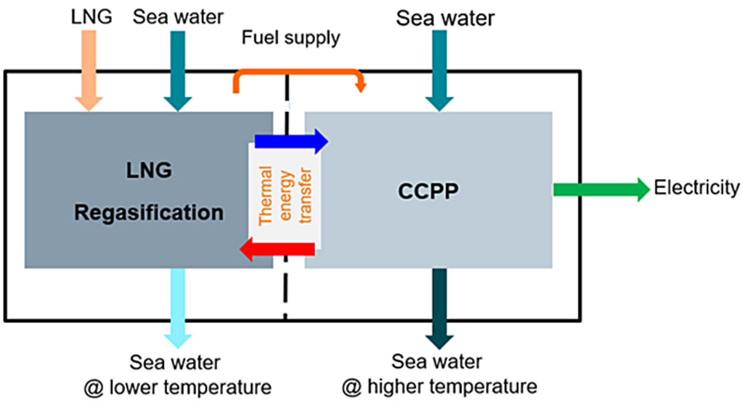

Figure 10, Regasification Integration, Source:

11.2 Organic Rankine Cycle (ORC)

Since water is an increasingly scarce commodity (especially in the Caribbean), Instead of water-steam, the ORC system vaporizes an organic, high molecular mass fluid in the bottoming cycle. Even low-temperature heat can be converted into useful work, that can itself be converted into electricity.

ORC offers a water-free combined cycle solution at comparable 'steam' combined cycle resulting in CAPEX and OPEX advantages.

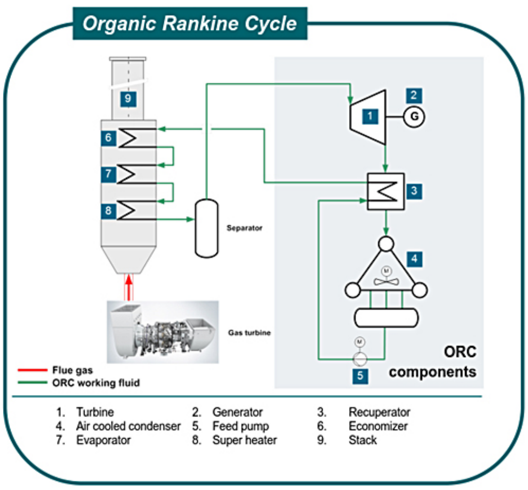

Figure 11, Organic Rankine Cycle, Source: Siemens Organic Rankine Cycle Waste Heat Recovery with ORC

11.3 Offshore power plants

Offshore power plants (SeaFloat Power Plants) include benefits like, short project duration and less project risk, highest quality with low CAPEX, smallest footprint of a world class combined cycle power plant and easy installations and maintenance due to pre-designed solutions with plug & play concept.

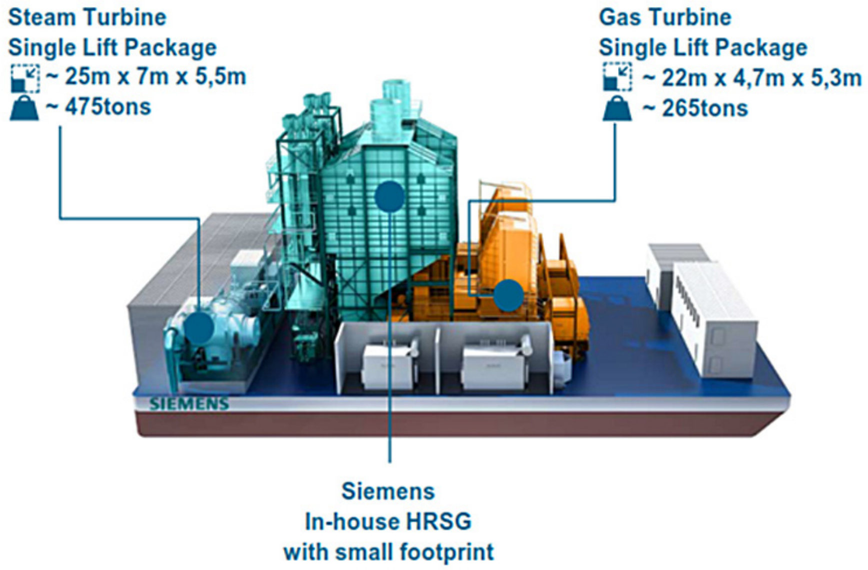

Figure 12, Typical plant layout of SSC-800 4x1, Source: Typical plant layout SSC-800 4x1 (sequential layout: ~78x29m), SeaFloat SCC-800 Technical Solution Information

11.4 Hybrid solutions

Combination of gas turbines with battery storage is the ideal complement for renewables, because the high inertia of combined cycles already supports high share of renewables in networks. A Combination with battery (initially or at later stage) provides additional synthetic inertia and ensures readiness for the future. Additional benefits for networks include frequency control, immediate startup and grid restoration.

Figure 13, Hybrid solution, Source:

12. Conclusions

Availability of new fuels, competitive renewables and new efficient generation technology radically changes the power generation sector in the Caribbean. Decisions between gas turbines and RICE are mainly driven by size, fuel price and operation conditions. But many other factors like stability, emissions, noise and reliability need to be considered.

RICE have a sweet spot for installed capacities below 20 MW, while efficiency and low maintenance costs immensely favor combined cycle gas turbines with installed capacities above 130 MW. Between those capacity-needs, it depends on project specifics.

Highly efficient, flexible combined cycle technology is an ideal complement for the renewable growth while ensuring a reliable network. Recent successes of gas turbines across the Caribbean show that transition to new fuels also drives a new generation of technology.

References

1. Levelized Cost of Electricity, United States Department of Energy, Office of Indian Energy, August 2015
2. Advantages of a gas turbine combined cycle solution for the Port-au-Prince area, Siemens AG, Month Year
3. Overview of Power System Reliability Assessment Techniques, T. K. Vrana, E. Johansson, Norwegian University of Science and Technology, Norway, CIGRE, 2011
4. Electric Power Systems Flexibility Challenges and Opportunities, Power System Transformation, Electric Power Research Institute, February 2016
5. Decarbonizing Power Generation through the Fuel Flexibility of Gas Turbines, M. Welch, N. Prasad, June 2018, Vienna, Austria, Siemens AG