GE AERODERIVATIVE GAS TURBINES FOR GRID FIRMING AND HYBRID APPLICATIONS in regions with high renewables penetration

By: Ihab Chaaban
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ABSTRACT

The GE aero derivative gas turbine product is an energy solution to balance the intermittency of renewable sources and provide reserve capacity, frequency and voltage regulation especially in those grids with high renewable penetration that exhibit criteria mandating adaptation and changes to help maintain a reliable and stable operation. The product has continuously evolved, moving from the conventional peaker application, to adapt to the new grid codes with capabilities to operate in hybrid mode with renewable and energy storage technologies. The integration of the GE Aero product with the renewable sources generation mix, improves the operational performance by eliminating curtailment, reducing emissions, fuel consumption and variable cost. Selecting the right technology in a grid firming application is key to a stable and economical operation while remaining in compliance with regulatory and environmental constraints. The integration of the GE’s aeroderivative technology with the renewable sources and energy storage technologies is the bridge for grids aiming towards a higher renewable portfolio standard (RPS). This white paper addresses the implications that occur in grids with high renewables penetration and shows the GE aeroderivative benefits and value proposition that enable those grids to maintain a stable and cost-effective operation within their targeted Renewable Portfolio Standard (RPS).
INTRODUCTION
Utilities are continuously improving their operations and diversifying their generation mix to have an efficient and stable operation ($P_{\text{generated}} = P_{\text{load}} + P_{\text{TL}}$) (4) to consumers while reducing GHG emissions and caring for the environment. The lowering costs of non-conventional renewable sources such as solar and wind have allowed adding those sources to the grid on a global scale. While some grids are aiming for an aggressive Renewable Portfolio Standard (RPS) in the next decades, there is always the underlying concern of whether their targets are achievable or not bearing in mind the stability and reliability of tomorrow’s grid.

Whether the generators are operating in regulated or deregulated environment, the common factor is always to get remunerated in a lucrative way to sustain their operations. Whether the mechanism is via an auction or a bilateral agreement or any other sort of settlement, the qualified sources that are bidding to generate power will be required to qualify for a capacity, energy or ancillary services. In the bidding environment, the merit order governs the selection of the most efficient sources that will be accumulated to get to the clearing price.

In some regions, the non-conventional renewable sources have started to displace some of the coal fired plants and perhaps other fossil fuel-based sources from the merit order standpoint and the relevant LCOE (Levelized Cost of Energy). Per Lazard’s levelized cost of energy (15), the renewable energy sources have reached comparatively lower levels (29 to 56 $/MWhr for onshore wind and 36 to 44 $/MWhr for Solar PV utility scale) than conventional sources.

While utilities often go through an integrated resource planning studies to understand the impact of the new generation mix on their respective grid, the natural question that imposes itself is: What is the optimum point of renewables penetration where a sustainable and reliable operation could be maintained. The classification of low, medium or high penetration could vary by grid to determine how high is high and how low is low. In a simplistic form, a grid that starts to see the renewable sources displacing the conventional ones on the merit order chart would imply that this grid is starting to get in the high range of renewables penetration and must consider all the impact associated with such change. Under such scheme, there is an implication to a possible shut down of some of the fossil fuel plants such as the combined cycle gas turbines (CCGT) ones if they’re unable to operate at an efficient load point. This circumstance opens the door for other technologies such as the GE aeroderivative gas turbines or batteries, subject to the application, to balance the deficit in a rapid and flexible way and yet fully integrate with the renewables’ sources.
Another indication signaling the high renewables penetration is the net demand curve. The famous CAISO duck curve is one of those as an example. Going farther to the east, and taking India as another example, there is a massive injection of Wind and Solar plants on the grid in specific zones, the net demand curve even looks steeper and tending to be more like a giraffe than a duck. Both implies an imminent need for a rapid and flexible sources, such as the GE Aeroderivatives, to ramp up in the peak hours when the renewables are turned down or completely off line.

Since the Solar and Wind sources are connected to the grid via inverters (Power Electronics) and have an intermittent generation profile, there are several challenges that will be summarized in the next section demonstrating the measures that should be considered to overcome those challenges.

**THE INTEGRATION OF RENEWABLE ENERGY SOURCES**

**THE RISING NECESSITIES WITH THE HIGH RENEWABLE ENERGY SOURCES PENETRATION**

The declining cost of renewables enabled the addition of a substantial amount of renewable assets on certain grids. Several regions have already exceeded 30 % of renewables installed capacity (2) on the grid such as California as well as many European countries while others are aiming at aggressive targets by 2050 to even get to 100% RPS independent of fossil fuel such as Denmark (3). While those figures signal the depth of the renewables’ penetration, it should be noted that for some regions like ERCOT in Texas, in some occurrences, the instantaneous wind generation recorded even a higher value (48.3%) (3) of the electricity demand on March 23, 2016. Those grids are up to several challenges to integrate all these renewables energy sources (RES) into the grid, among those challenges:

1. The steep curves showing the transition between normal and peak hours drive an imminent need for flexible technologies with fast ramps
2. A need for Spinning reserve sources to firm the capacity and balance the demand to counteract the variability of wind and solar
3. Lack of rotational/synchronous inertia back to grid leading to frequency deviations and hindering the system to recover rapidly from contingencies
4. The power electronics tends to Weaken the grid with a low Short Circuit Ratio, SCR, (SCR at the point of interconnect (poi) = Short circuit 3LG MVA poi / MW rating of the inverter) (10) as they enlarge the equivalent AC grid impedance (9).
5. The ancillary services that include Frequency and Voltage Regulation to support the grid stability become a necessity
6. Voltage ride through contingencies
7. A need for the integration with the existing generation mix with the associated turn down ratio
8. An efficient Turndown requirement with minimal emissions impact
9. TL (new build or curtailment) – negative prices - to the extent of considering a distributed structure and avoid any transmission lines constraints.
10. Flexibility to balance rapidly the load variation – incentivize flexible sources Production Tax Credit (PTC) or subsidies
11. Losing the synchronous inertia to consider a compensation with ancillary services, mainly Reserves and PFR – Procurement of Inertia (MW s). The following curve shows how the lack of inertia drives up the need for primary frequency response in ERCOT(3).
12. RoCoF if not overcome may cause tripping and blackouts

![Figure B RoCoF curve – Source : GE](image-url)
THE BALANCING AUTHORITIES

In the USA, the Balancing Authorities (BA’s) play a big role to regulate and stabilize the system frequency. The high renewables penetration added challenges to the BA’s to meet NERC’s reliability requirements and FERC’s ancillary services mandates.

In order to address the renewables intermittency and further integrate those sources, the BA’s share operational data regarding local frequency and area control error and hence share load and generation variability which allows the potential for lower region level reserve requirements.

The interconnection between balancing areas provides significant benefit to both regions as excess generation (in the form of hydro or wind) can be exported to the other (11).

It must be noted that the transmission lines (TL) access and cost have to be considered within this balancing process and compare those to more cost-effective measures serving the same purpose. Additionally, some regions differ from others in terms of the TL capacity and the adequacy to construct interconnections in case of asynchronous grids with different frequencies and different grid codes. In some instances, the ramping requirements may not be fulfilled at all times via the available interconnects and hence the immediate distributed flexible sources won’t be adequately substituted by BA’s for balancing the frequency in a certain region when needed.

OTHER ELEMENTS TO CONSIDER

1. Forecasting for wind and solar is key to an optimized operation. It’s almost inevitable to have a zero margin of error in those forecasts which drive the need for other means to firm the capacity, such as Batteries or Aeroderivative gas turbines, each selected based on the application and the system requirements.

2. The production tax credit is an important element that allowed for a rapid deployment of renewables. This credit is declining mainly due to the reduced cost of renewables sources which imply another financial impact on the proforma and open the door for a diversified portfolio that meets the capacity requirements.

3. Some grids located in geographical regions are enabled to hybridize co-located wind and solar sources. Obviously, not too many spots on the planet would have this cooperating wind and solar profiles and should consider hybridizing the renewables with thermal sources to optimize the cost and meet the load profile at the point of interconnection.

ENERGY STORAGE IS AN ENABLING FACTOR FOR RENEWABLES PENETRATION

OVERVIEW

The intermittency of the renewable sources requires means to firm the capacity. The evolution of several energy storage technologies enabled the expansion of renewables. Specifically, Li-Ion Batteries have become a feasible solution to store the energy generated by renewables for peak shifting and eliminating curtailment. While the cost of storage of the Li-ion batteries have been declining substantially to levels below 300$/KWhr, nevertheless, there’s still more work to be done to reduce the cost below 150$/KWhr (5) to enable further expansion of this technology. The GE Renewables team continues to develop its Reservoir (Li-Ion batteries) solution that is currently improving the battery life, its safety features and reducing the construction time to support generation, transmission and distribution projects on the grid. The BESS (battery energy storage system) sizing along with managing its state of charge is significant for a successful operation. The Peak demand time can increase the width of the net demand period beyond the storage capacity and hence a longer storage duration may be needed than the offered duration capacity, which could reduce the peak demand credit. Conventionally, for longer durations of storage, the BESS needs to charge during the previous day and hence the ability to forecast the net demand over extended periods is essential for a lucrative operation. Under certain circumstances, utilizing a hybrid solution with the GE aeroderivative gas turbines could prevent revenue loss for these applications as will be shown in the coming articles.

Furthermore, several grid operators and regulators, globally, are still in the process of enabling grid scale batteries to participate in the wholesale marketplace while ensuring a stable operation within the generation mix. Due to the nature of this relatively new technology, Independent System Operators (ISOs) are paying close attention to the storage duration capability...
as well as the dual profile of the batteries being a generation source when discharging and a load while charging. Batteries when deployed are complete with inverters (DC/AC), battery management systems and balance of plant and hence referred to herein as Battery Energy Storage System (BESS). Despite the status-quo for Batteries, it is still finding spots on the grid where it serves economically several purposes such as arbitrage, deferring transmission lines investments in addition to other applications that will be addressed in this paper.

THE BESS LIFE CYCLE CONSIDERATIONS

There are several elements to consider when selecting the Li-ion battery technology, among those (5):

1. **Round trip efficiency**
   Li-ion batteries go through degradation within the life cycle of the project due to the charge/discharge cycles that they go through. The here below graph displays several profiles as an example that GE would consider when sizing the Reservoir BESS for a specific project. The beginning of life (BOL) sizing tends to be more utilized on thermal hybrids, specifically when operating with gas turbines such as the GE EGT* that is mainly an Aeroderivative gas turbine operating in hybrid mode with a BESS that both assets support ancillary services (spinning reserve, frequency and voltage regulation) on the grid, while the others are utilized for other

2. **Depth of discharge**
   This element refers to the battery capacity that can safely be discharged without damaging the battery and hence it is a limitation to consider when sizing the battery

3. **Parasitic loss factor**
   This constitutes the plant parasitic loads that could be within 1% of the BESS capacity to feed those loads
4. Thermal management:
Each BESS includes a thermal management system to withstand the site conditions, that includes heat ventilation and air conditioning systems.

5. Recycling cost
One of the concerns that is associated with batteries is the recycling cost which contributes to the life cycle cost of this technology. A company from Canada has founded a new process (6) to recycle materials in Li-ion batteries at a rate of 80% to 100%, which is above other processes that reaches 30%-40% only. The operation includes a 2-phase process to mechanically reduce the size of the batteries and then shredding them and removing plastics and metals. Meanwhile Australia has been leading the re-use and recycle efforts to tackle its 3300 tons of Li-ion battery waste. This waste is growing by 20% a year and could exceed 100,000 tons by 2036. (7)
THE GE AERODERIVATIVE GAS TURBINE FIT IN THE RENEWABLES GENERATION MIX

SO WHY CHOSE A GE AERO

To support renewables operation in those grids with high RES penetration:

1. The Aeroderivative gas turbines have a rapid start ranging from 5 to 10 minutes that is well suited in those applications where a fast start is required and participate in sub-hourly segment

2. The product has high ramp rates that goes up to 50MW/min which serves the frequency regulation where the transition from RES to conventional ones occur in a short duration (recall the giraffe curve)

3. The GE aeroderivative gas turbines are multi-shaft machines that are capable of handling large frequency and voltage excursions to provide Frequency regulation and spinning reserve

4. The GE Aero package has an optional Synch Condenser either via clutch or in those models configured with a free power turbine could accommodate a clutch-less solution to control MVARs on the grid and hence support voltage regulation.

5. The GE Aero packages provide a relatively shorter project cycle & hence a lower CAPEX solution

6. The Flexibility of this product based on its aviation inheritance could achieve ~300 daily start/stops without maintenance penalties and affecting the OPEX

7. High turn down ratio capability

8. Adaptation to operate in Hybrid mode with renewables and batteries via a single control platform. This concept could be applied to any model or configuration of the aeroderivative gas turbines.

The EGT or thermal hybrid could be implemented for any configuration

Customized to the application and smaller BESS for lower CAPEX projects

Figure G: thermal hybrids with different Aero models – Source: GE

Figure H: Hybrid architecture – Source: GE
THE GE AEROS VALUE PROPOSITION

The different scenarios where the GE aeroderivative gas turbines when operating with RES or BESS, they exhibit different criteria that lead to a value proposition in each case:

A. GE Aeros + wind or solar plant:
- Firming the RES capacity
- Reduce curtailment of Renewables that could result in up to 10% of value of the annual energy production or more
- Lesser emissions and gaining carbon credits
- Improve matching of production and consumption and avoid lost revenue in PPAs
- Increase revenue through increased participation in multiple ancillary services segments
- Lower variable cost

B. GE Aeros + Power BESS (EGT*) base benefits:
- GT and power BESS fully integrated allowing lesser fuel burnt that leads to Millions of dollars of annual cost savings
- Reduced emissions gaining carbon credits
- Being online in less than 250 ms and ability to ramp up to 50MW/min for certain models
- Support Black Start capability and participate in that segment when applicable
- Less thermal stress on the aero gas turbine translated to reduced variable O&M cost
- AGC and load following to provide quality power to Industrials and eliminate losses

C. EGT* base benefits in addition to an ancillary services segment: All the base benefits in addition to the following:
- Generate a revenue stream due to higher asset utilization and participation in ancillary services
  - Spinning Reserve
  - Frequency Reg.
  - Voltage Regulation
  - Synthetic inertia
- Reduce the clearing price and hence reduce the load serving cost
- Reduce Production cost by allowing larger CC capacity to be shut down if not operating at an efficient point

In previous sections of this paper it was shown that the BESS capacity duration is essential to determine whether the BESS is adequate for capacity firming solution. For those cases that the storage duration extends to unreasonable duration, it was observed that by dissecting the large peaks and selecting a thermal hybrid solution instead of a BESS only could reduce both CAPEX in the short term as well as OPEX on the long run.

THE HYBRIDS OPERATIONAL IMPROVEMENT

Improving the conventional and renewable assets operating in hybrid mode is essential to enhance the assets utilization and create operational and grid benefits.

As an additional scope, the GE Distributed Energy Management System (DEMS) platform is a multi-layer control system supporting supervisory optimization, monitoring & controls enabled by messaging & communication technologies which will maintain the electrical output of each hybrid generating sources based on input from their own internal device settings with respect to the real-time load scenarios.

The GE DEMS determines the set points for the individual Distributed Energy Resource (DER) controllers based on the power load balancing objectives to help maintain safe, reliable and economic microgrid operation, which may be amended from time to time. Set points determined by the GE DEMS are communicated to the individual asset controllers. (12)
MODELING HYBRID OPERATION

GE developed modeling techniques to uncover the feasibility of implementing hybrid solutions. It is vital to analyze all the operation of the hybrid assets by considering all the project financials, fixed and variable cost as well as the anticipated revenue (energy, capacity or ancillary services) to compute the NPV, IRR and LCOE of the hybrid asset. The analysis conducted via the so-called hybrid architect configurator (13) allows the enhancement of the assets’ utilization, based on the load profile, site conditions and solar or wind regional characteristics, to improve the financial parameters.

The following chart shows an example of hybridizing aeroderivative gas turbines with a Solar PV plant in an island mode operation. In such example, the regional fuel and operational costs of the thermal asset are taken into consideration to optimize the said financial parameters by allowing the renewable asset to operate in durations characterized by high revenues and lesser cost when compared to the conventional asset.

In a similar fashion, the configurator can model the hybrid operation of the Aeroderivative gas turbine with the Power BESS as an EGT* to demonstrate the value proposition shown in the previous sections of this white paper.

Several other modelling computations could be performed to analyze other examples showing the improve performance of other hybrid assets to provide a preliminary feasibility assessment of a hybrid operation.
IS 100% RPS THE RIGHT APPROACH?

An intriguing question that has become embedded in the mind of any grid operator, that is, to have a cost-effective operation with lesser GHG emissions, at which point the RES penetration could achieve such target? The following exercise was conducted by Min (Martin) Yan GE’s Global Research Center principal engineer where he considered several cases of hybridization between thermal, renewable and batteries assets to compute the LCOE. The here below example results, show that 100% RPS is not necessarily the right answer for every grid.

Where is the sweet spot on the Renewable % line?

![Diagram showing different hybridization scenarios](image)

Solution KPI Comparison

<table>
<thead>
<tr>
<th>Solution Configuration (optimized for min LCOE)</th>
<th>100% GT</th>
<th>Hybrid w/o BESS</th>
<th>Hybrid w/ BESS</th>
<th>100% Renewable</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% GT</td>
<td>4x</td>
<td>4x</td>
<td>2x</td>
<td>0x</td>
</tr>
<tr>
<td>Hybrid w/o BESS</td>
<td>—</td>
<td>98 MW</td>
<td>124 MW</td>
<td>224 MW</td>
</tr>
<tr>
<td>Hybrid w/ BESS</td>
<td>—</td>
<td>—</td>
<td>577 MWh*</td>
<td>259 MWh*</td>
</tr>
<tr>
<td>Renewable %</td>
<td>0%</td>
<td>32%</td>
<td>43%</td>
<td>100%</td>
</tr>
<tr>
<td>Total Year 1 GT on hours</td>
<td>17,913 hrs</td>
<td>12,791 hrs</td>
<td>11,990 hrs</td>
<td>0 hrs</td>
</tr>
<tr>
<td>CAPEX</td>
<td>$2,12 M</td>
<td>$300 M</td>
<td>$366 M</td>
<td>$3,000 M</td>
</tr>
<tr>
<td>LCOE</td>
<td>$98.1/MWh</td>
<td>$94.7/MWh</td>
<td>$92.4/MWh</td>
<td>$386/MWh</td>
</tr>
</tbody>
</table>

* DCBOL battery capacity
** Year 1 Renewable Generation / Annual Energy Produced

Figure M: LCOE Analysis - Source: GE
AERODERIVATIVES AND THE HYDROGEN PLATFORM

One of the GE Aeroderivative gas turbines attributes is the capability of burning various types of fuels. Among those fuels, that would contribute to a high RPS, are bio-diesel, bio-gas and hydrogen mixtures. Hydrogen has been drawing a lot of attention lately to become an alternative fuel for various applications, among those: Power Generation. Hydrogen production though has low round trip efficiency hindering its application as a competitive fuel. The CO2 tax levels must also go to higher levels compared to where they currently are, as an enabler for the hydrogen usage in such application. There are several means for hydrogen production. Steam methane reforming (SMR) is the most mature and that would still use natural gas as the most common feedstock. Electrolysis of water is an alternative process which can be used to produce high quality hydrogen (=100%) through electrochemical conversion of water to hydrogen and oxygen. SMR has higher Global Warming Potential (GWP) and water footprint than water electrolysis (14). The following graph from Stanford University (5) compares the different means of hydrogen production with Solar PV along with the associated cost and benchmarking the SMR methodology on the graph against the other processes.

![Solar H₂ Technoeconomic Analysis (TEA)](image)


**Figure N:** Solar H₂ Technoeconomic analysis – Source: Stanford University
While the purpose of this paper is not to go into the technoeconomic analysis of such fuel, nevertheless, the growing interest in hydrogen as well leveraging the excess energy generated by RES located in highly penetrated grids with renewables, could promote this platform in the future.

The artificial leaf was an interesting innovation in the Stanford analysis (5), nevertheless, yet the economic viability of the hydrogen fuel production will remain as a challenge in the coming years.

The Aeroderivative gas turbines with its diverse fuel capabilities will remain a viable option to burn hydrogen in power generation applications where the hydrogen mixture could go up to 85% or above (subject to GE consultation) in some models.

**CONCLUSION**

This paper showed the impact of the high renewable penetration and some of the challenges that are normally encountered within the process of integrating those RES into the grid. It also demonstrated how integrating RES with the GE aeroderivative gas turbines could address some of those challenges to ensure a stable operation. Hybrid operation has become a viable solution within the integration process of RES. The value proposition that is introduced by the Aeroderivative gas turbines enables a more seamless generation mix and provide a practical option for grid operators that seek the cost effectiveness as well as the reliability of their grid. The modeling of hybrid assets encompasses a macro view of all the elements that contribute to the plant proforma and indicate to developers the feasibility of the hybrid plant in focus. The paper also addressed the high RPS targets and showed through some examples that 100% RPS may not be the optimum solution for certain grids based on LCOE analysis for different scenarios. The Aeroderivative gas turbines with its diverse fuel capabilities provide a workable solution to burn a mixture of hydrogen fuel in anticipation of such fuel becoming competitive for a large-scale implementation. The GE Aeroderivative gas turbine product has evolved from simple cycle peakers into a grid firming and hybrid operation solutions to support today’s modern grid transformations.
ABOUT THE AUTHOR

Ihab Chaaban is a global technical and commercial development leader with over 27 years of experience in the Power Generation and Systems industry, 10 of which with GE, with deep domain expertise in the Energy, Utility and Electrical Power Businesses. Chaaban started his career as an Electrical Engineer and held several roles in Engineering, Sales and Services in the Caterpillar and Solar Turbines organizations via global assignments in the Middle East, Africa, Brazil, Canada and the USA.

Chaaban started his career with GE as an Application Engineering Lead for the aeroderivative global division followed by other roles in commercial operations leadership and proposal management for aeroderivative, Distributed Power and Industrial Frames Gas Turbines. Chaaban assumed the role of GE aeroderivatives global commercial development director to support the grid firming segment including the Gas Turbines Hybrid Operations with renewables assets and Batteries. Chaaban is a Licensed Professional Engineer in Ontario Canada, holds a B.Sc. in Electrical Engineering from Alexandria University, an MBA from Lansbridge University and speaks five languages (English, French, Arabic, Portuguese proficiently with a good command of Spanish).

ACKNOWLEDGMENT:

The development of this white paper benefited from the input provided by GE’s outstanding group of Technical & Industry Experts. I would like to give special thanks to each of them for sharing their time and expertise with us. While the white paper has benefited greatly from their input, the views it contains are solely those of the author and may not necessarily reflect the views of our experts.

Special thanks to:
• Martin Yan – Principal Engineer – GE Corporate Global research
• Adnan Zafar - Senior Engineer – Controls Engineering, GE Renewable Energy

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