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NAVIGATING THE JOURNEY TO DECARBONIZATION & GRID STABILITY

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1.0 Introduction

The Energy Transition and decarbonization* have been front and center in every forum relevant to the environment and global warming, which concurrently makes most of us wonder what the grid of tomorrow will look like with such transition. Energy transition means relying on new sources of energy that have lesser to zero greenhouse gas emissions. The purpose of this paper is to go several layers deep to outline the implications and consequences associated with these initiatives. For example, how will the renewable assets such as wind turbine generators and solar PV connected to the grid via inverter-based resources impact the grid stability? How will green hydrogen, becoming an economically viable feedstock, serve the grid's inertia and could it be considered as an energy storage alternative? How will the grid code serve the diversity of existing and futuristic assets? Will there be a one-size-fits-all grid code? These are all elements of a multidimensional complexity that need to be considered while navigating the energy transition journey. At the end of the day, we must keep reliability in check while we're solving for sustainability and affordability. From the time of Edison and Tesla, we've been evolving and developing the grid infrastructure; however, as the saying goes, yesterday's solutions are today's problems.

* Decarbonization in this paper is intended to mean the reduction of carbon emissions on a kilogram per kilowatt hour basis

2.0 Renewables and Energy Storage

A straightforward approach has been adopted for over a decade, that is, increasing the renewable portfolio standard (RPS) for many grids to reduce the carbon footprint. It's conventional, from a decarbonization standpoint, to install grid scale wind turbines and solar PV that have no fuel cost and have no carbon emissions (excluding the production, transportation, disposal, and other relevant lifecycle carbon footprint). Nevertheless, there are many consequences associated with the deployment of those renewable assets, most importantly, the variability and intermittency that substantially impact capacity factors and resource adequacy. This is where the energy storage technologies come into play to cover the energy gaps during the day, month, or year. Lithium-ion batteries, with a relatively high-power density, can efficiently serve two- to six-hour durations to firm a renewable asset capacity.

It took some time to recognize the effectiveness of the batteries in grid scale applications such as Li-ion battery technology with its relatively high energy density, exceeding 200 WH/KG, to serve the grid and it took longer to create the marketplace conditions that compensate those assets owners, mainly serving frequency regulation and spinning reserve in short durations. Lithium-ion batteries reduced the curtailed energy from wind and solar PV to serve as arbitrage, they deferred transmission upgrades, shifted peaks, and provided ancillary services. In addition to Lithium-ion, there are other battery technologies serving in the same domain, such as NMC (Lithium Nickel Manganese Cobalt Oxide), LFP (Lithium Iron Phosphate), where both are derivatives of Li-ion technology, NA (Sodium) ion and Zn (Zinc) ion, where each chemistry is distinguished by one or more attribute from a list that includes: cost, safety (avoiding thermal runaway), aging (degradation), specific power, depth of discharge and specific energy (1). Fig. 1 shows an average hourly performance for a combination of 100 MW Solar PV, 100 MW Wind and 100 MW/400MWH (4 hours storage) LFP BESS (Battery Energy Storage System) in an arbitrary chosen location in New Mexico. The valleys on the diagram show the energy gaps that have to be covered to help meet the required capacity at those durations. Short term energy storage is a move in the right direction towards grid firming and providing ancillary services, however, there are 24 hours in the day, which means there is a need for long duration energy storage (LDES) technologies to support full decarbonization and close the gap towards a 95-100% capacity factor.

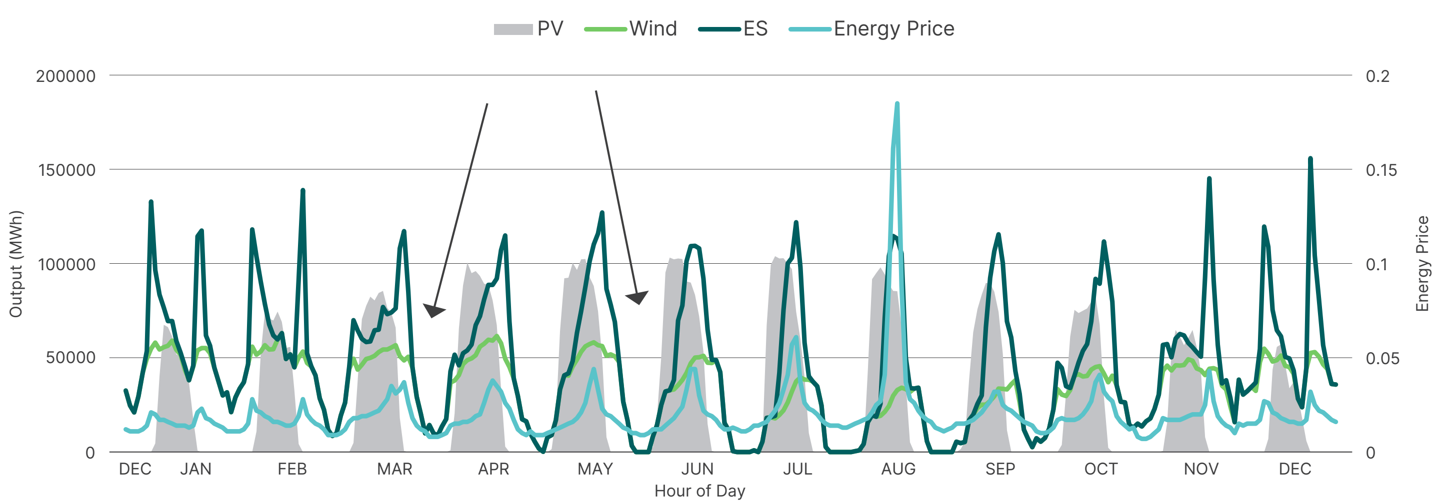


Fig. 1: 100MW Solar PV + 100 MW WTG + 100MW/400MWH BESS Hourly Energy Production showing the energy gaps

3.0 Other Energy Storage Technologies

There are several technologies that could serve this segment; among those Pumped Hydro Energy Storage (PHES) that is the most predominant has a long-life, however it is location dependent with some environmental impact and with a low energy density profile (2). Vanadium redox-flow batteries is another technology as well as others that rely on gravity and kinetic energy or a Zinc cathode technology that can all take us to 12 or even to 24 hours durations of storage and beyond. Nevertheless, there is still a need to create marketplace conditions that compensate LDES technologies to help ensure a grid wide deployment. Most importantly, from an operational standpoint, there's always the issue of how fast the energy can be extracted from those LDES technologies to support the grid. Additionally, according to Lazard.com, many long-duration storage technologies are large capital assets that are challenging to size in modular increments. They also have yet to become more affordable in terms of LCOS (levelized cost of storage).

In contrast, India has pioneered the RTC (Round the Clock) concept by relying on renewables (wind turbines plus solar PV) and short duration BESS, integrated in hybrid system, to achieve higher order of capacity factors to the extent of 85%-90% or even more, relying on oversizing the renewable and BESS assets as well as locating the plants in certain regions in the subcontinent where the wind profile and speed are higher during the night and the Global Horizontal Irradiance (GHI) necessary for the Solar PV is high during the day and the same reciprocity, to some extent, applies seasonally. This integration provided a reasonable blended LCOE (levelized cost of electricity) with substantial decarbonization, however, not too many regions in the planet are blessed with such phenomenon of wind and solar energy complementing each other and hence the concept can't be applied in every geography. So the question remains, how do we achieve a firm capacity with an affordable low carbon footprint and yet maintain grid stability.

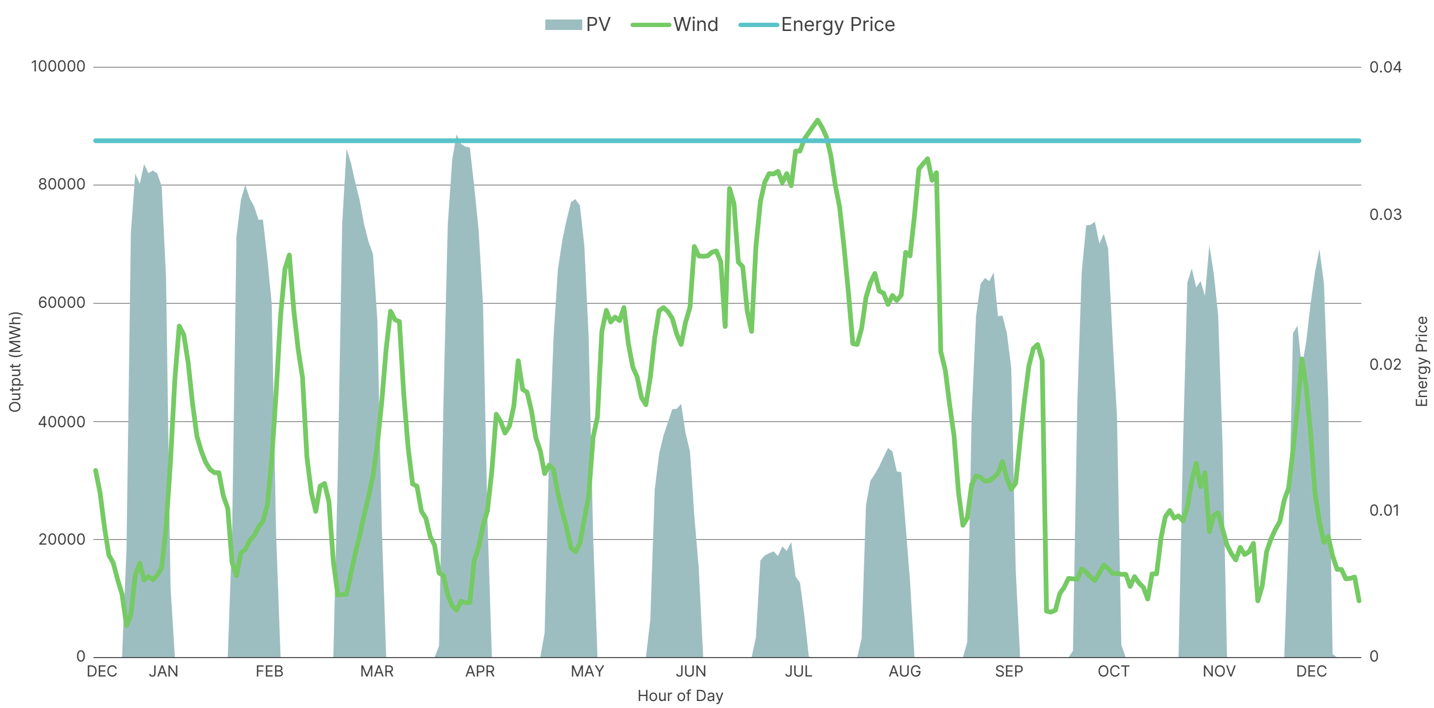


Fig. 2: Anantapur India Wind + Solar compensating each other on a year average

4.0 Green Hydrogen as an Alternative Energy Storage Solution

As shown in the previous section, short duration and promising long duration energy storage technologies are viable solutions to firm the intermittency and variability of solar and wind with some limitations, but looking at the bigger picture for 100% RPS, (Renewable Portfolio Standard) reliability and stability, we are up to MW days or months of storage rather than MW hours as well as operational techniques of dispatch and massive capex investments.

Green hydrogen (hydrogen created by water electrolysis using renewable power) has been considered as one of the branches of the decarbonization tree, albeit there are still many hurdles to overcome to make such feedstock economically viable.

Additionally, water scarcity and the required green power resources that need to be added to the grid (or collocated with the electrolyzer hydrogen island) are additional hurdles to overcome. Policy in certain regions is allocating funds to subsidize such commodity as ITC (Investment Tax Credit), with the associated applicable incrementality, deliverability and temporal correlation, to lower the LCOH (Levelized Cost of Hydrogen) ($/KG) and create a hydrogen economy (Fig. 3). There are other measures that could push the deployment of green hydrogen such as higher prices of CO_2 in $/metric Ton in the ETS (Emissions Trading System) in the range of 200-300 $/metric Ton and beyond.

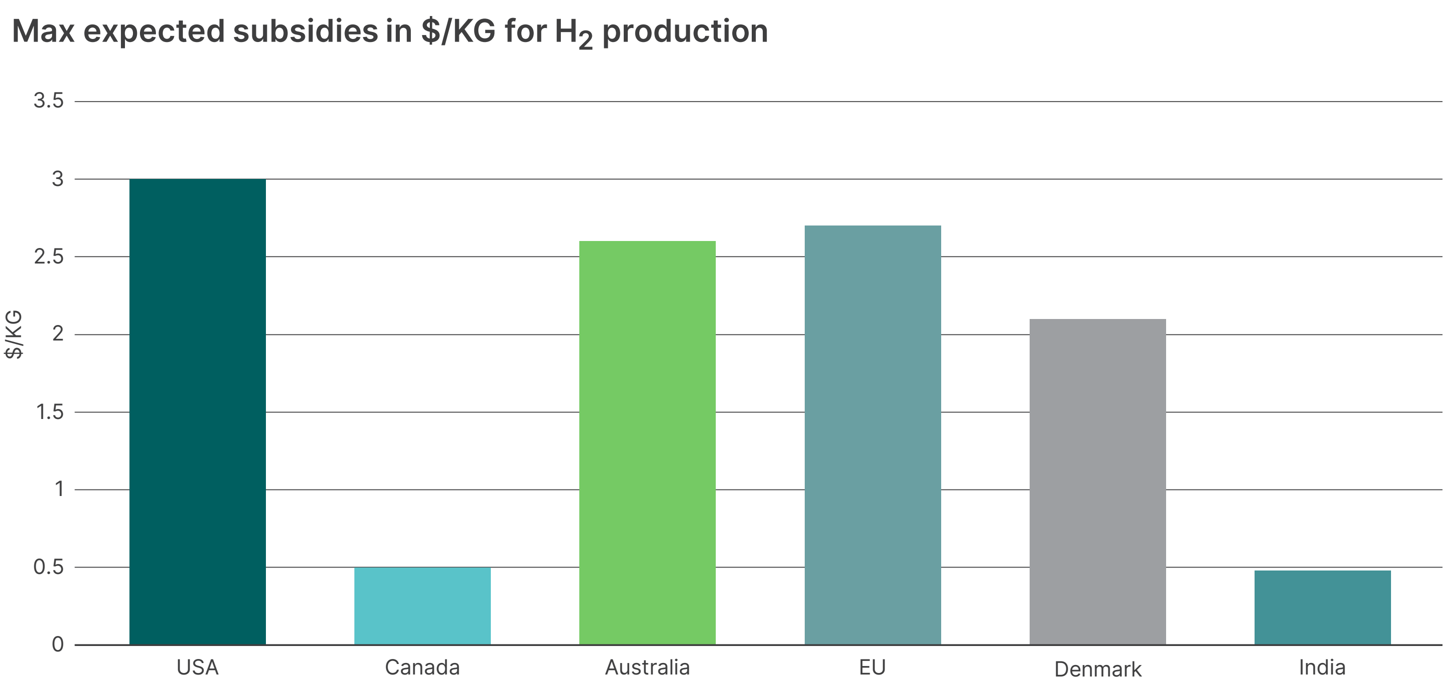
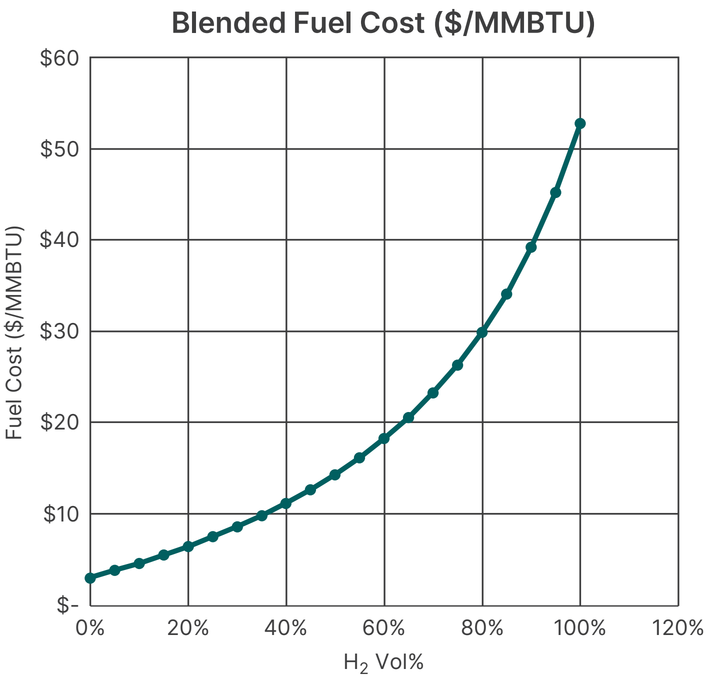


Fig. 3: Max expected subsidies in various regions as ITC subject to the carbon intensity in the hydrogen production and the applicable regulation - Source: US IRA, Canada Gov., Australian Gov., EU H_2GLOBAL, India-briefing.com

Natural gas (NG) is currently a prominent bridging fuel towards decarbonization and hence its price is a natural benchmark to those deploying a hydrogen production facility with an LCOH and offtake price in mind. The benchmarking against gas and the level and duration of subsidies will be directly proportional to the speed of implementation of a hydrogen economy. The affordability element of the energy transition can also be gradually achieved by blending NG (Natural Gas) with percent of Hydrogen by volume. The following diagrams show the equivalent fuel price for a blend of %H_2 by volume with NG. In this arbitrarily chosen case, the NG price is priced at 3$/MMBTU while the H_2 price is set at 6$/KG (equivalent to 52.75 $/MMBTU LHV) without any ITC subsidies. The equivalent blended fuel associated CO_2 emissions is also shown in Fig. 4 to better illustrate the achieved reduction in CO_2 emissions with such blend at relatively speaking affordable levels.



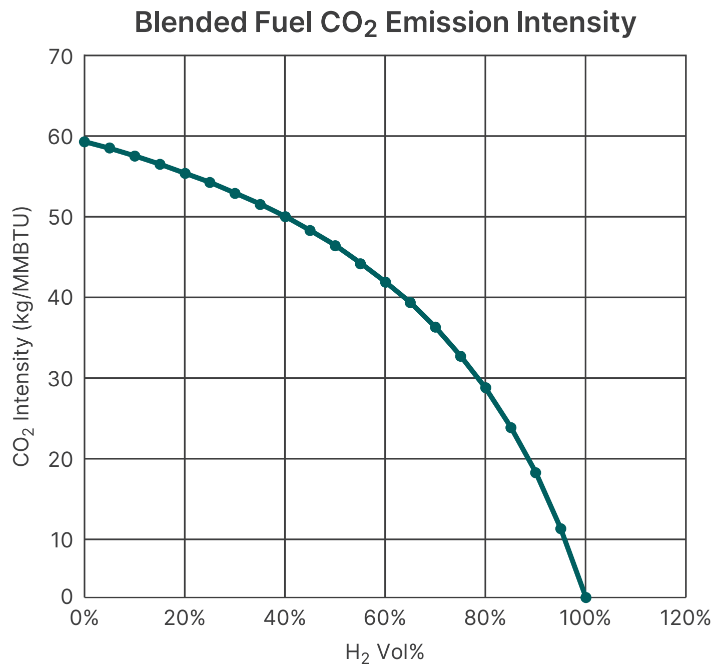


Fig. 4: NG and H_2 blend cost and CO_2 emissions intensity

5.0 The Continuum of Short to Long Energy Storage Duration

In the previous sections, various types of energy storage technologies and their fit on the renewable capacity firming spectrum were mentioned. The question is, what if there's a single technology that could cover the whole spectrum of storage duration, as a continuum, whether it is short, medium, or long. The hydrogen molecules hold the energy that could be stored in several forms, such as gaseous, liquid and even as a solid (metal hydride). Each form of storage will serve a different use case ranging from daily, weekly, monthly, or even seasonally.

The aeroderivative gas turbine (aero) technology has been known for decades in the power generation industry for peaking applications that need the fast starts and ramping MW/min, system inertia, load following and hybrid applications (with renewable energy and BESS). The aeros have been serving those segments running on a diverse set of fuels such as natural gas, diesel, bio diesel, ethanol, and hydrogen.

As we are witnessing a new era promoting the deployment of hydrogen as a carbon free fuel (when combusted), it would be a natural transformation for the aero turbines to add to its attributes the use case of a short (dispatchable capacity firming) to medium (load following) to long (seasonal) duration energy storage when running on hydrogen fuel. The aero technology offers the versatility of running on blends of natural gas and hydrogen including up to 100% H_2 by volume in some models. Nonetheless, considering the current challenges of the hydrogen economics, it would be prudent to maintain the cost effectiveness of the feedstock by gradually using blends of NG and H_2 in the near term and concurrently reduce the CO_2/kWh emissions as shown in the previous section. This capability enables the reduction of CO_2 emissions while maintaining grid stability as all the attributes of this technology, including synchronous inertia, fast starts, and fast ramping, would still be applicable.

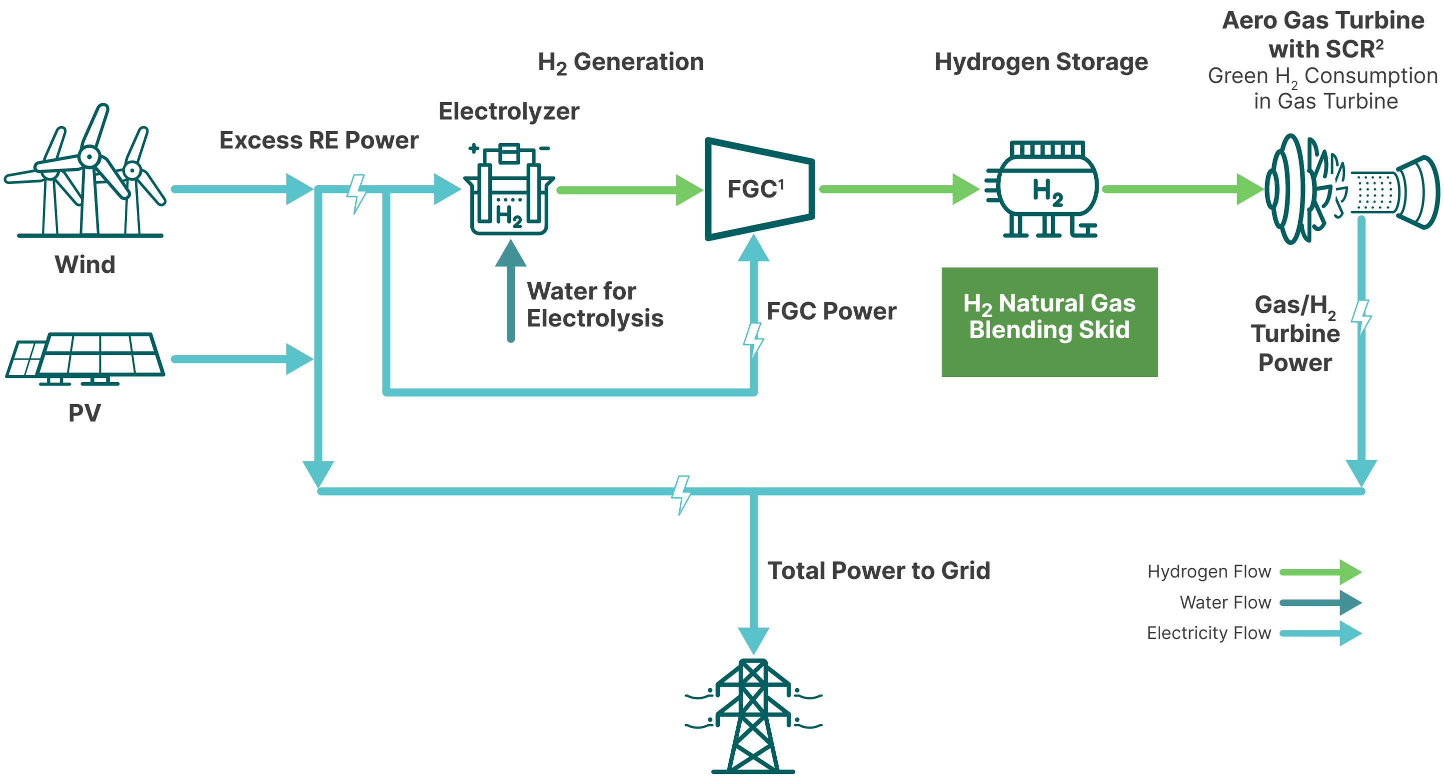


Fig. 5: A fully integrated system including the Renewable and Hydrogen islands along with a blending skid and Gas Turbine that could be deployed as a short to long term energy storage device.

1. FGC (Fuel Gas Compressor)
2. SCR (Selective Catalytic Reduction)

As an example, a hypothetical model considering an aero GE Vernova LM6000 PC Sprint* package (~50 MW) as a Peaker with an annual average 1656 hours (Fig.6), running on a blend of NG set at 3 $ / MMBTU and 35% H_2 by volume, considered at 1$/KG LCOH (with an IRA full production tax credit subsidy) led to a 135 US$/MWH LCOE. Monitoring the EIA USA Energy Information Administration across several ISOs (ISONE, NYISO, CAISO, ERCOT), it was found that the yearly average of wholesale electricity prices can easily go beyond 200 US$/MWH in most cases and reaching 1600 US$/KW in ERCOT (12). Thus, running an aero to firm the capacity in such short durations is an economically feasible option providing that there is sufficient supply of green hydrogen.

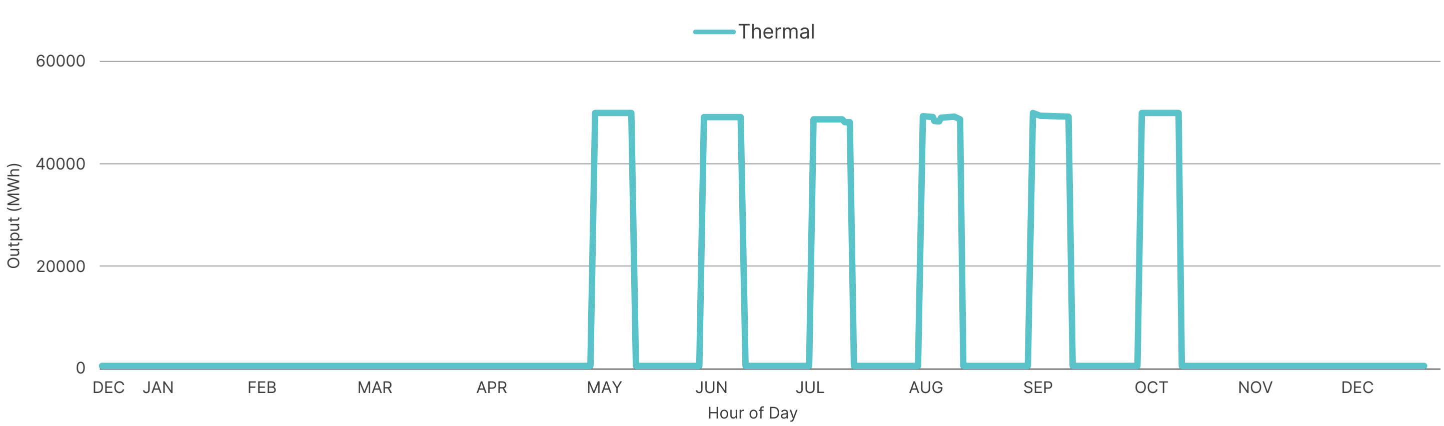


Fig. 6: Year 1 hourly output with energy price (averaged for the month)

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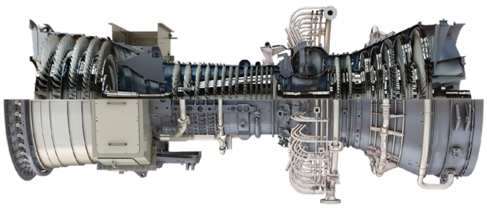
Primary Gas Turbine KPIs



LM6000 PC Sprint
with evaporative cooling

Year 1 Key Performance Indicators			
Hours ON	**1656 hrs.**	# Starts	**184**
% ON	**18.90 %**	# Cold Starts	**1**
Hours OFF	**7104 hrs.**	# Warm Starts	**183**
% OFF	**81.10 %**	# Hot Starts	**0**
Plant Load Factor	**18.44 %**	Avg. Shutdown duration before Cold Start	**2892.00 hrs.**
Load ON	**99.88 %**	Avg. Shutdown duration before Warm Start	**15.00 hrs.**
Efficiency ON	**38.95 %**	Avg. Shutdown duration before Hot Start	**0.00 hrs.**
Annual CO_2 Emission (mTon)	**36,552**		

Fig. 7: Thermal asset key performance indicators

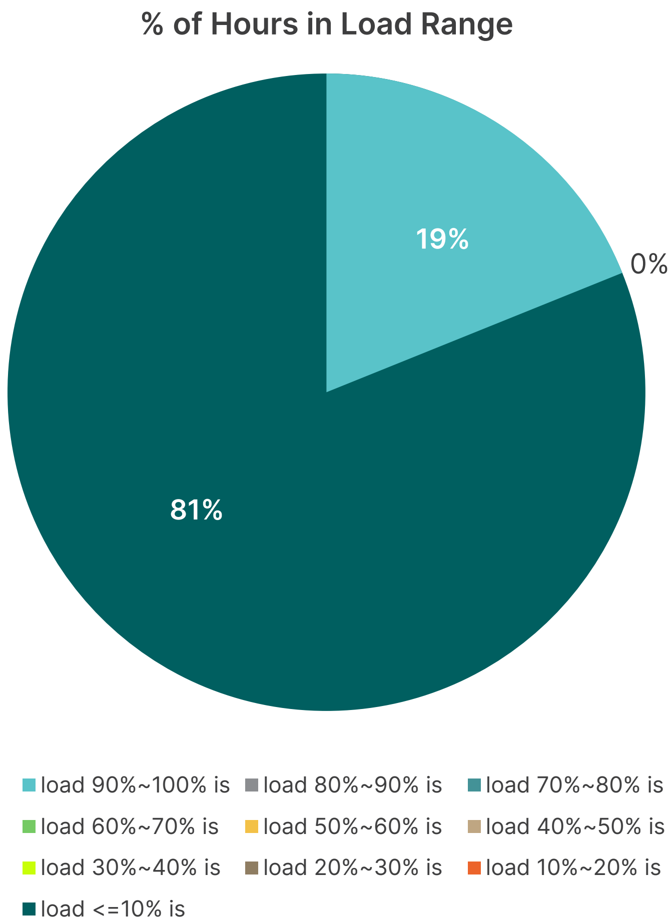


Fig. 8: Percent of hours in load range

6.0 The Operational Big Picture

6.1 Inverter Based Resources (IBRs) Performance

The high penetration of renewable resources and battery energy storage systems, with no doubt, will have an impact on the grid. Most of these assets are connected to the grid via inverters and hence are called Inverter Based Resources (IBRs) that behave differently from synchronous resources such as gas/hydrogen turbines. Additionally, more power electronic devices are seen today on the grid among Flexible AC Transmission Systems (FACTS) and High Voltage DC Transmission (HVDC). Today's grid, in most regions, will have a diverse set of resources that behave differently under load variation and fault conditions and therefore the mandatory grid codes that help ensure the system stability have a challenge to holistically review those codes considering today's grid assets. In summary, the question now becomes how to keep the grid stability considering the new assets' performance.

IBRs, under balanced conditions, would perform smoothly without significant implications, but we know that any flight will have bumps and turbulences, which translates into the grid language as load variations and fault conditions. For example, under faulted conditions, IBRs behave differently when compared to rotating machines, as the fault current properties of IBRs are different from those of rotating/synchronous machines. The impact of those differences could be higher in Distributed Generation and islanded Microgrids, which are also venues to overcome Transmission and Distribution congestions on the grid, and are becoming more common solutions in this era.

Inverters, with all their different types, are semiconductor switching devices that do not tolerate high overcurrent, and hence the IBRs are required to limit their fault current contributions to typically 1.1-1.5 per unit of the inverter's nominal current rating (5). IBRs do not produce the large fault currents typical of utility sources or synchronous generators that can instantaneously go to the 300% levels. Additionally, they do not go through the sub-transient, transient, and steady state phases of a fault in synchronous machines but rather act in a constant manner which confuses the relay coordination scheme. So, it may be difficult for an IBR protection system to distinguish the difference between a fault and an Inrush current or a sudden load variation (5).

Let's also recall that IBRs are static devices that synthesize the AC sinusoidal waves to match the AC grid, (with dominant AC generating synchronous machines) which normally would become non-sinusoidal with harmonics under fault conditions and hence the protection system must consider those harmonics to protect the assets as it should.

There are 2 main categories of inverters:

- Grid-following: Connected to a power system where voltage and frequency are controlled by other resources and where the inverter regulates the active and reactive power injection.
- Grid-forming: The inverter regulates the system voltage and frequency.

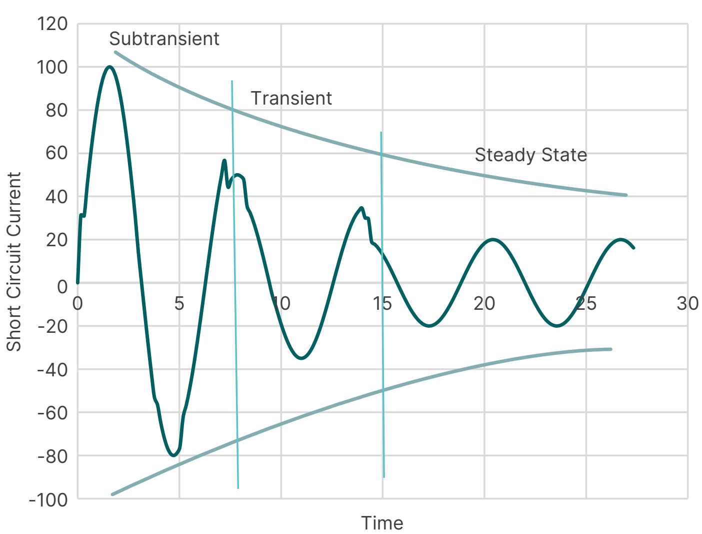


Fig. 9: Typical Short Circuit current in synchronous machines

As frequency droop is normally the followed control mechanism when there are multiple sources sharing the load on the grid, where the frequency is set according to the power output of the generators, grid forming inverters technology is a strong fit in this scheme with other resources for active power sharing as well as voltage droop functionality for reactive power sharing. Grid following inverters would be more on the following side to inject active and reactive power only.

Grid following and grid forming inverters, as differently configured as explained, will not even act in the same way during a fault or sudden changes in loads or generation, which is common in Wind and Solar PV assets. As Frequency is inversely proportional to load variation, this renders the highly penetrated IBR system fragile and susceptible to tripping and blackouts without the ability to ride through the change or fault unless certain measures are taken. Adaptive protection schemes and maintaining the synchronous inertia in the system can substantially reduce the risks of brown out or black out incidences due to the different behavior of IBRs in short circuit, loss or increase of loads situations, which could make zonal and nodal regions unstable, overall decreasing the reliability of the grid.

Droop function:

$$\Delta P = - K \cdot \Delta F$$

K: MW/Hz (Regulation Power), Droop (%): - (Δf/Δfn) / (ΔP/ΔPn) * 100

Pn: Nominal Power MW, Fn: Nominal Frequency Hz

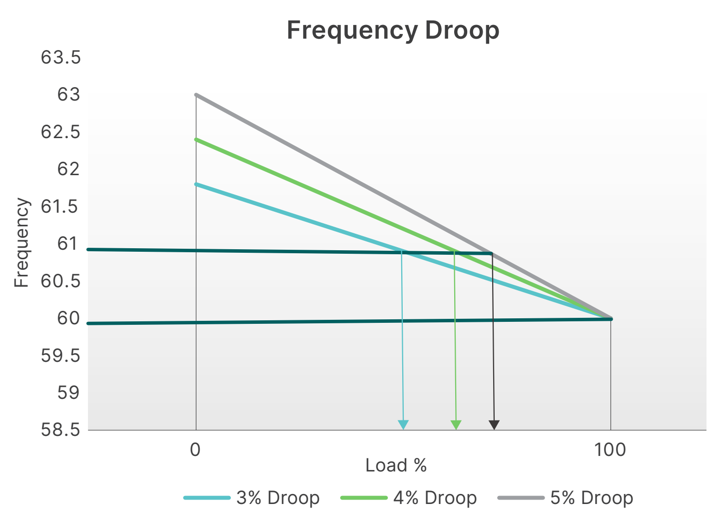


Fig. 10: A diagram showing various resources with different frequency droop levels against the load%

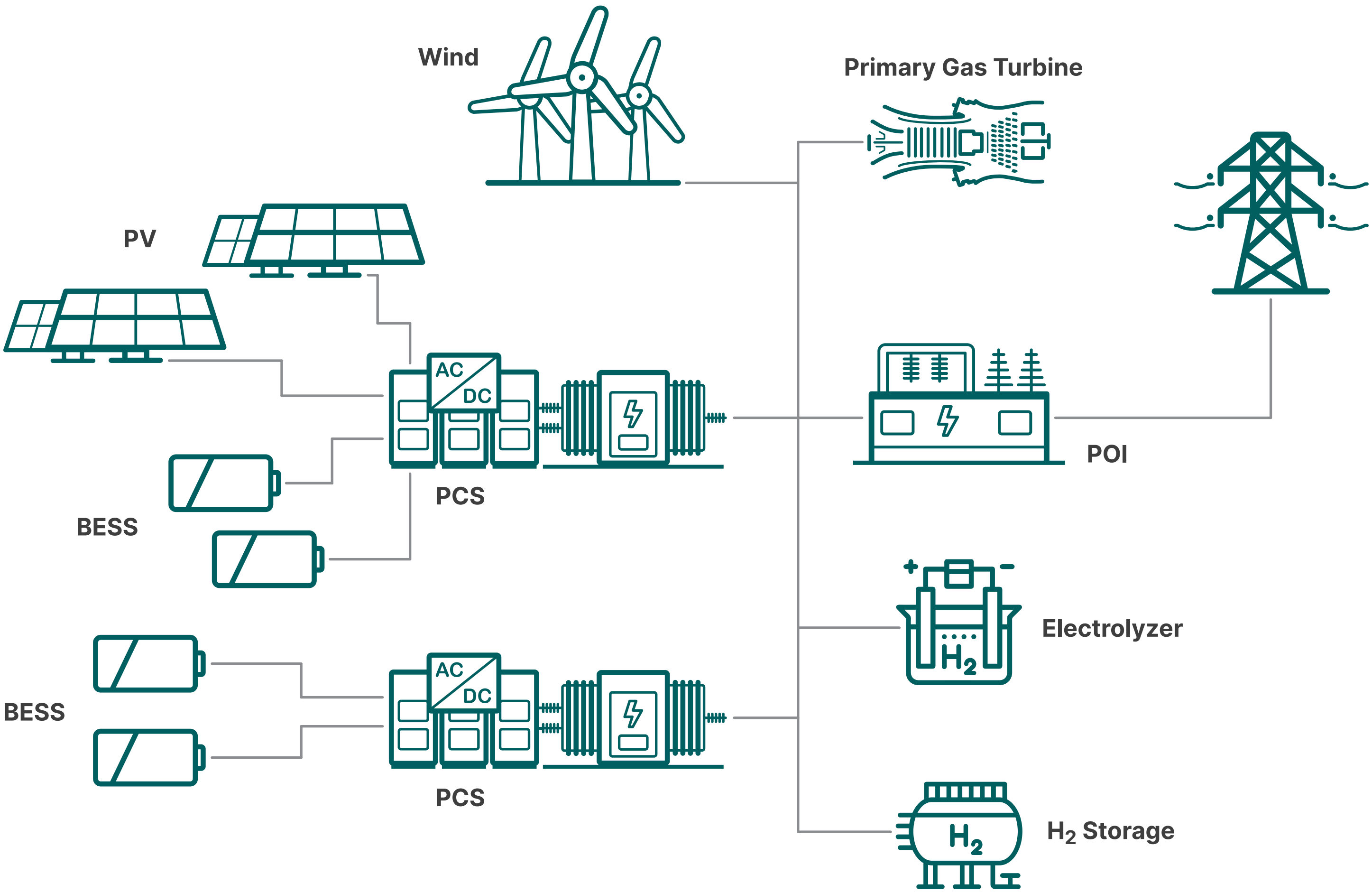


Fig. 11: A schematic showing the interconnect of IBRs into the integrated green hydrogen system

6.2 The Grid Code

Today's grid is going through massive changes in terms of retiring coal units, addition of gas turbine units, increasing penetration of wind, solar PV, and BESS as well as other technologies, reliance on demand response and distributed generation and load growth due to AI and ML (Artificial Intelligence and Machine Learning) in data centers, among other drivers. Yet, reliability and stability will remain paramount for any grid operator, albeit different methodologies will have to be implemented to maintain a stable grid. Among the parameters that grid code must define, subject to the geography and characteristics:

- Inertial response
- Frequency response
- Ramping capability
- Active power control
- Disturbance ride through tolerance
- Reactive power and voltage control

Among the most important elements of operational parameters is how a grid would detect and respond to faults and load changes to control the rate of change of frequency (RoCoF) in a timing that would enable the grid to ride through the disturbance safely, remain in stability, and avoid a blackout. Inertial response is a key characteristic that enables mitigating the RoCoF events and that would be followed by the frequency restoration in primary, secondary, and tertiary phases. For conventional grids where there's an abundance of rotating assets, such as gas turbines, the inherent synchronous inertia is currently the most proven method of mitigating high RoCoF events (8). Nevertheless, with the introduction of static assets such as Solar PV and BESS connected via IBRs, synthetic inertia Fast Frequency Response (FFR) type devices now have the potential to provide a power response to help prevent high RoCoF events. The concern is whether those devices will detect and engage in a time period sufficient to mitigate the risk of a RoCoF event. For synchronous technologies the response time is immediate, however for synthetic inertia devices, the response time to activation may be formulated:

$$T_{response} = T_{measurement} + T_{signal} + T_{activation} + T_{ramp} \quad (8)$$

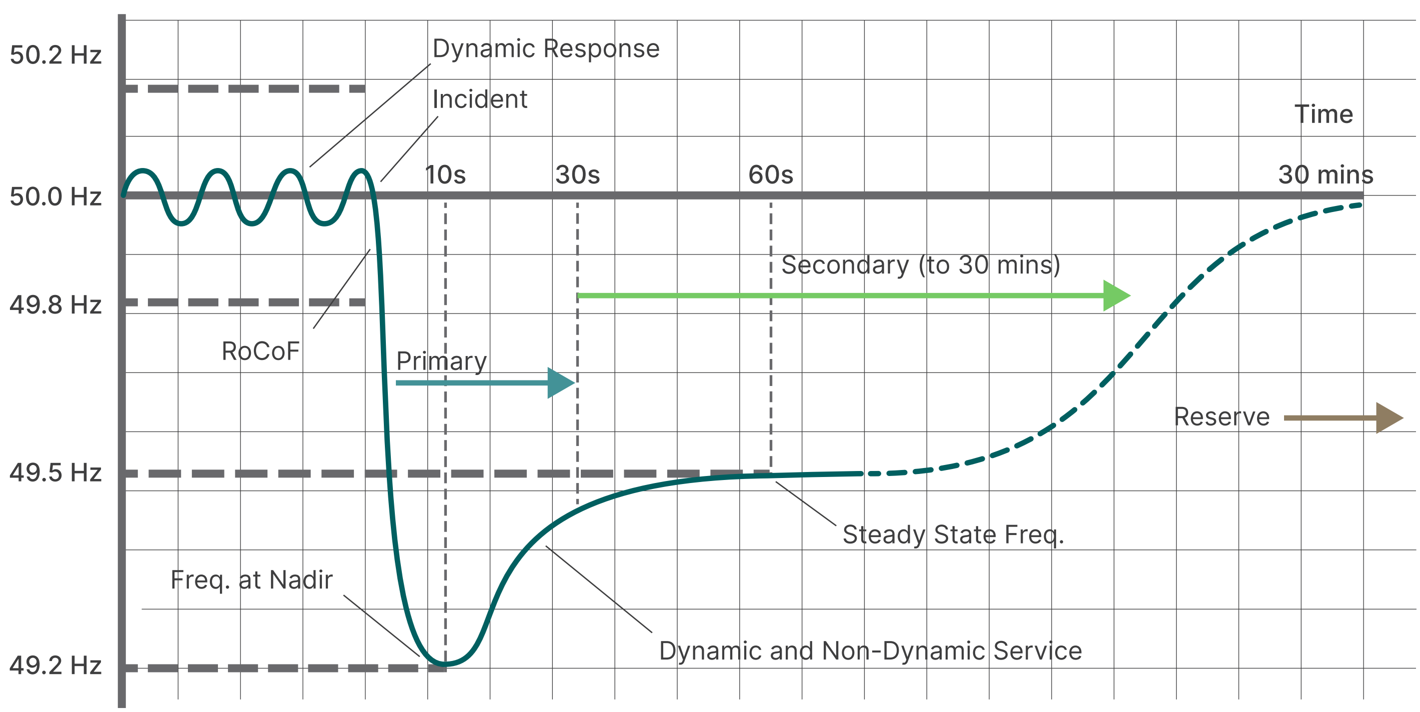


Fig.12: A typical chart showing the rate of change of frequency against time.

Based on the previous section, there are many countries and regions that are changing their grid codes to accommodate the diminishing synchronous inertia in their grid by mandating Hz/sec rates over modified durations in milliseconds to mitigate the risk of RoCoF events. For example, Eirgrid, with its current renewables penetration, has been considering a 0.5Hz/sec to 1Hz/sec RoCoF in a duration of 500 ms (milli seconds), subject to the MW connection in consideration, to help ensure that the grid assets will tolerate such event and remain in the stability region (9), compared to 2.5Hz/sec in Denmark and 2Hz/sec in Spain (10). Additional grid code parameters, such as Low Voltage Ride Through (LVRT), which is connected to the same stability issue, imposes further restrictions on the assets in interconnect studies. There's no one size grid code fits all, and this process will be a learning curve for all grid operators. The takeaway, from the Eirgrid example and other highly penetrated regions with renewables and IBRs, such as CAISO, is that the needle is pointing towards harsher codes when moving away from synchronous inertia, imposing capex, and operational challenges.

As shown in the previous sections, the aeroderivative technology can run on blends of hydrogen fuel (up to 100% in some models) to serve the decarbonization targets of the grid at an affordable LCOE. Additionally, the technology can bring along all its attributes when running on natural gas, including synchronous inertia and frequency response, to help maintain a stable grid. Examples of how the aero technology can help the frequency and voltage regulation on the grid (11):

- PFC, Primary Frequency Control. PFC control will control the gas turbine unit to a pre-selected load set point, such that it will respond to frequency excursions that exceed the dead-band setting by adjusting load in response to frequency change to help maintain the grid frequency.
- RMC, Regulation Margin Control. RMC control permits the gas turbine to operate at an output power close to its maximum output without being driven to base load throughout the day as the ambient temperature changes. The RMC set point is selected as function of percentage from 0% to 12.5% below maximum output base load capability of the gas turbine.
- Secondary Frequency Control. Secondary Frequency control feature consists in restoring the frequency and powers exchanged by the local grid and other connected networks at their preset values.
- Synchronous condensing. During operation in Power Generation mode, the aero gas turbine generator would produce Real and Reactive power to the utility grid. When operating in Synchronous Condenser mode, the AC generator is supporting the utility grid with voltage provision and export/import reactive power (MVARs) to desired set point and not consume fuel. The aero GT package can achieve this via clutched or clutchless solutions, subject to the GT configuration.

7.0 Conclusion

The trilemma of energy transition (sustainability, affordability, and reliability) has to be considered with a holistic view to tackle each element while keeping an eye on the others. The paper proposed an alternative on the path towards decarbonization with the aeroderivative technology running on green hydrogen, for short to seasonal durations, with gradual blends with natural gas to remain affordable and most importantly help leverage all these technology attributes, that includes the fast starting and ramping as well as synchronous inertia to support a stable and reliable grid. The introduction of new innovative technologies will always be considered to blaze new trails towards the grid of tomorrow, however, the re-deployment of current well proven technologies to co-exist with different methods can help ensure a solid bridge towards a stable, more affordable grid with less CO_2 emissions.

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Ihab Chaaban is a global technical and commercial development leader with over 30 years of experience in the Power Generation and Systems industry, 16 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 and Services via global assignments in the Middle East, Africa, Germany, 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 his current role in GE Vernova to support the grid firming segment including Aero gas turbines in hybrid and green hydrogen applications with renewable assets and battery energy storage systems. 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).

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