GAS TURBINES FOR ENERGY NETWORK SYMPOSIUM
BANFF, ALBERTA, CANADA
OCTOBER 2019

19-GTEN-105

LOW COST PEAKER INSTALLATION WITH "ZERO-HOUR" REFURBISHED AERO ENGINES

Landon Tessmer*†, David Rose*

***ProEnergy Services LLC; 2001 ProEnergy Blvd.; Sedalia, MO 65301**
(†LTessmer@proenergyservices.com,)*

Keywords: *Peaking Power, Energy Storage, Refurbished Gas Turbines, Grid Stability*

Abstract

With continued non-dispatchable capacity growth from renewables, peaking capacity has become more critical to grid stability. As capacity reserves are diminishing, quick and economical peaker installations have become a market need. Aeroderivative gas turbines and piston generator sets have achieved quick response startups and load ramps facilitating rapid-dispatch generation that ensures grid stability; however alternative approaches appear to be the preference of many jurisdictions. Some have elected to repurpose base load facilities, accepting the increase maintenance cost of off-design operation, while some have deployed storage technologies that are costly, and may not actually meet their perceived savings in greenhouse gas (GHG) emissions.

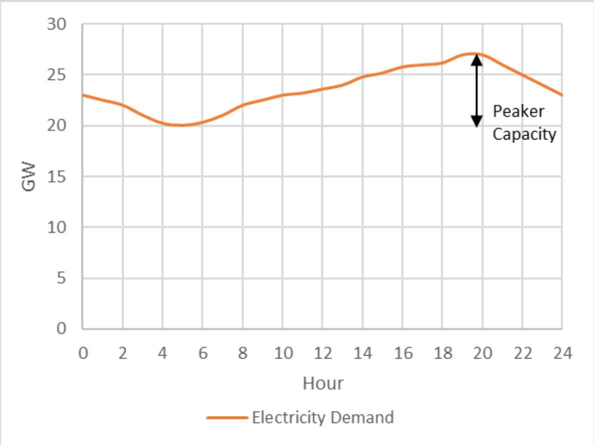
Used gas turbines have seen an active market for many years now due to increasing price sensitivity in global markets. The relocation of units to better capacity markets is becoming increasingly common though the reliability of aging assets challenges the long-term viability in many cases. A new strategy to maximize reliability while keeping costs competitive is converting and packaging refurbished "zero-hour" aero engines for effective and efficient stationary power generation. Standardization of engine and auxiliary packages, along with repetitive installation and engineering brings the installed cost (equipment, engineering and construction) consistently under $500/kW USD. This, along with the heat rate of an aeroderivative gas turbine makes for an attractive project, was previously not possible through traditional methods. Inhouse prefabrication of the engine, equipment enclosures and skids yield minimum lead times for those few items left to be outsourced. Standardized equipment arrangements reduce engineering needed for site development and adapted foundation designs. A typical two unit, 100 MW plant can be supplied and installed in 24 weeks. This paper will outline the methodology and fabrication process, with the necessary capabilities highlighted. Project examples of completed plants and those in process will be presented and detailed as case studies.

The Need for Peaking Power

Electrical demand curves in developed nations follow well-known profiles that have historically formed the basis of design for electricity generation systems. Generally, cooling seasons see peak demand in the middle of the day when temperatures are their highest, while heating seasons see peak consumption in the early evening when people return home and power up their various appliances and electronics. The exact shape of each region's electricity demand curve will naturally change based on local factors including climate and industry. However, each region's demand curve shape does not change significantly year over year, and thus, regional electricity production and planning has historically benefited from this consistency.

To meet these demand curves, electricity producing assets must take two forms: (1) Base load facilities operate year-round with steady supply to meet the constant minimum electrical demand and (2) cycling plants ramp and can be turned on and off as needed when demand exceeds the base load. These cycling facilities can further be categorized as intermediate duty generation or load following facilities that may operate seasonally or only during daytime hours while "peaker plants" are typically the last to be dispatched and may only operate a few hours a day in the highest demand seasons. The ratio of each facility type is generally governed by the local demand curves, which as discussed, have been consistent year to year. While increase in population and/or gross domestic product may raise the total demand over time, the ratio of peaking vs. baseload needs is typically consistent.

With the recent surge in renewable energy production, this traditional model has been challenged. Solar and wind energy provide power intermittently and have no mechanism of control that can be used to match demand curves. This creates a net supply vs. demand curve that the balance of output-controllable power facilities must now meet. In California, the California Independent System Operator (CISO) coined the phrase 'the duck curve' to describe the shape of their demand profile, which peaks in the evening, but is relatively low mid-day when the solar energy is at peak production. Again, these curves will change by regional climate and renewable energy makeup, but in most cases, these net demand curves are more volatile compared to demand-only curves, which results in an increased need for rapid dispatch cycling facilities that can provide electricity when solar and wind energy assets are not producing. Refer to Figure 1 below for contrast of the two curves.



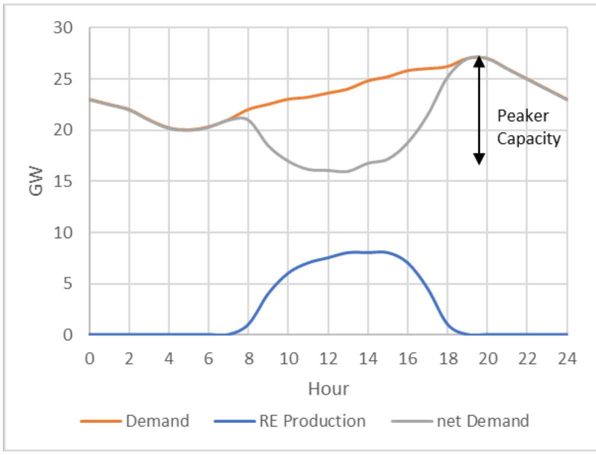


Figure 1: Demand vs. net demand curves

Mitigation strategies

This issue of volatility between demand and renewable supply is, in the eyes of many, the major roadblock in moving towards higher rates of renewable energy use. There has been much attention focused on this issue, and thus, there are many approaches that have been analysed to meet our changing needs.

Repurpose Base Load Facilities

One of the easiest and cheapest capital solutions is to simply repurpose base load facilities to operate in a cyclic manner. Many base load facilities would otherwise be decommissioned as part of the movement towards renewables, so many of these are viewed as free assets. Typically, these are large gas or diesel fired combined cycle or coal plants. These existing facilities have not been engineered for cycling and part load operation. The result is an increase in carbon emissions per kwh from operating off-design (the base CO_2/kWh varying greatly by fuel). In addition to worsened emissions, these facilities tend to experience increased outages and significant maintenance costs from cycling components that have not been designed to withstand such thermal stresses [1]. This is most commonly observed in large scale combined cycle plants featuring industrial gas turbines with multi-pressure drum-type heat recovery steam generators (HRSG). The thick walls of the HRSG drums and heavy gas turbine components limit the acceptable ramp rates and thermal gradients on the equipment. Mechanical failures are increasingly common as these facilities are dispatched and ramped more often.

Continental Transmission

Another strategy that could reduce the need for dedicated peaking production is to build a continental network of high voltage transmission lines that connect various sources of intermittent producers. One such project, the TransWest Express Transmission project, is set to begin construction next year. The project will use 730 miles of high voltage transmission to connect the high wind generation capacity in

Wyoming to the high solar production of the desert southwest. Because of higher late afternoon wind production in Wyoming, this supply would help shave the peak of the ‘duck curve’ in California but would not completely remove the need for peaker capacity. In fact, a study published in Energy & Environmental Science found that even with a comprehensive continental distribution network connecting wind and solar sources across the US, 20% of the country’s electrical demand would remain unmet without some peaker or storage capacity [2].

As a partial solution to peaking demand this seems feasible, but there are two main drawbacks with this strategy. First, the permitting process is very arduous given the many state and local authorities that must approve new high voltage lines. In the case of the TransWest Express, developers began the approval process in 2008, taking over a decade to get the thumbs up from all parties involved. This problem is exacerbated when you consider sharing across country borders, which would be required in regions where a single country does not have access to an array of geographically diverse production sources. Second, utilities have little incentive to invest in these transmission lines, as there is limited opportunity for them to recover their investment. Both problems could be mitigated by the creation of a federal agency in the US to centralize approval and help incentivize utilities, but there has been no major push towards creating such an entity.

From a cost standpoint, there are limited references available, but in the case of TransWest, current cost estimates sit at $3B USD for the 730 miles. With a transmission capacity of 3,000MW, this corresponds to $1,000 USD/kW, not including any actual cost to produce power or the losses associated with long range transmission. These factors have in fact pushed markets in the other direction towards more distributed generation where smaller scale energy producers serve the local power demand.

Energy Storage

Having the ability to store energy during high renewable production and release it during periods of peak demand would effectively reduce the need for peaker plants. Many potential battery technologies are in use or in development, utilizing electrochemical, mechanical, thermal and chemical storage mechanisms; however, a thorough review of each technology goes beyond the scope of this paper. Instead, we will discuss pump hydro energy storage, which currently makes up more than 96% of the global electricity storage capacity [3], and lithium ion batteries, which appear to be approaching commercial viability in the next decade.

Pumped-Hydro Energy Storage

The concept behind hydro storage is quite simple: Water is pumped up to a higher elevation when renewable energy production is at its peak. Then, the reservoir is drained through a turbine when electricity demand is high. The round-trip efficiency of water in such a system is approximately 80%, which means that 25% more electricity must be produced in order to achieve equivalent output. This characteristic is not unique to pumped storage. All battery technologies have a round trip efficiency that can range from 40% to 90%. There are currently 40 pumped hydro stations in the

US, which provide 20GW of power total, with discharge times that vary from 6 to 20 hours. In Canada, the Sir Adam Beck Pump Generating Station is the only pumped hydro energy storage facility in operation, but at 174 MW, this still puts pumped storage as the larges form of energy storage in Canada [4].

The primary limitation associated with pumped hydro storage is topography. Some regions simply do not have the geological structure to create water reservoirs without flooding thousands of acres. Furthermore, if water reservoirs are created in areas with heavy vegetation, flooding these lands results in drowned organic material that decomposes and releases both carbon dioxide and methane. Ignoring this impact yields a very favourable rate of emissions (between 11 gCO_2/kWh and 26 gCO_2/kWh) [5], but one study by Gagnon et al. [6] analysed a reservoir in Brazil and derived a theoretical life-cycle emission value of 237 g CO_2/kWh. Installing hydro facilities in arid regions minimizes this effect, but only adds another restriction to the geographical requirements. Note that these emissions values are for hydro production only facilities so they do not consider the round-trip efficiency in their values nor do they consider the emissions of the charging source (to be discussed in the battery section). The capex of hydro installations is also not highly competitive, ranging from $1,050 USD/kW up to $8,000 USD/kW [7]. A US EIA study placed estimates for hydro and pumped hydro installed costs at $3,123 USD/kW and $5,626 USD/kW respectively. [8]

Batteries

Many jurisdictions have moved forward with large scale lithium ion battery storage projects. California’s largest utility, Pacific Gas and Electric, has submitted approval for four facilities totalling 567 MW with a discharge duration of 4 hours. Southern Australia has already installed a 100MW / 129 MWh facility in response to recent blackouts due to grid instability, which had a capital cost of $90.6M USD, or just over $900/kW. While this installed cost is becoming more competitive, one must consider that no actual electricity production is occurring with any form of energy storage, and thus, the installed cost of the charging source must also be considered. Furthermore, batteries must be characterized on a MWh basis, as the discharge rates equally impact the cost and size of the battery. Typical large-scale battery installations offer continuous power between 30 minutes and 2 hours. Therefore, listing costs for capacity without the accompanying MWh is common way mislead the general public – and even engineers.

Batteries have several advantages that have made them an attractive choice. They can respond to the grid almost instantaneously and are highly portable if regional peaking needs vary over time. The time to install has also been a point of success for batteries. The project in Southern Australia was operational in less than 100 days, although this may not be the norm as Elon Musk used the quick turnaround as an opportunity for publicity for Tesla. Despite the energy intensity required to manufacture a lithium ion battery, the lifecycle CO2 production is just over 41 gCO_2/kWhr [9]. The more notable environmental downside is seen in water consumption. In South America, the process of pumping mineral rich brine to the surface for evaporation and recovery of lithium consumes approximately 500,000 gallons of water per ton of lithium [10]. The lifespan of a lithium ion battery is significantly shorter than competing technologies. A NREL study from 2017 showed that the lifespan for utility scale Lithium ion batteries is on the order of 7-10 years, depending on the battery's thermal environment, and how often and to what degree the battery is cycled [11].

For batteries, pumped hydro, and other forms of energy storage systems, current implementation has actually been credited for an increase in total carbon emissions. This is because many batteries charge over night when the base load generation in some markets may be coming from coal plants predominantly. The batteries then discharge at peak consumptions hours when a cleaner natural gas peaker plants would usually kick in. A study showed that the impact to net emissions can range from 104 to 407 g of CO_2/kWhr [12] depending on the generation mix.

Reciprocating Engines

Reciprocating internal combustion engines (RICE) are most commonly used in small scale projects such as combined heat and power (CHP) installations, of which there are currently over 2400 in the US. The limited power output per unit has traditionally prevented RICE from being used in utility scale power generation, but with single engine outputs now reaching 20MW per engine, there are more utilities and investors who are willing to applying the technology at a larger scale. For example, one installation outside of Dallas, Texas has twelve engines for a total plant capacity of 225MW.

A reciprocating engine's main benefit is its flexibility. An engine can reach its full load in under 10 minutes, though it should be noted that engine jacket must be kept warm (typically 70°C) and the bearings must be pre-lubricated during offline periods to guarantee these start times [13]. For a 300 MW plant, this load can reach 5MW, and if running in a peaking application, up to 16 hours of such energy consumption may be required [13]. Beyond start time, RICE installations can be reliably operated down to 25% of their design load with very little impact to heat rate. RICE also experiences minimal performance degradation at high altitude or higher temperatures compared to a combustion turbine and consumes very little water during normal operation.

When it comes to emissions, a RICE unit operating on natural gas with a heat rate of approximately 8500 btu/kWh [8] yields approximately 450 g CO_2/kWh, which is very comparable to an aeroderivative gas turbine. Where RICE fails however is in other forms of emissions. The explosive combustion cycle of a RICE unit results in significantly more unburned hydrocarbons (UHCs) being released compared to a gas turbine. High levels of SOx are also emitted as a result of burning lube oil on the cylinder walls [13].

RICE units require more frequent maintenance when compared to a gas turbine. At the highest frequency, RICE units will require replacement of engine oil, filters, coolant and spark plugs every 500 to 2000 hours [14]. A review of O&M costs across many facilities showed an average RICE facility costing $0.016/kWh compared to $0.007/kWh for simple cycle gas turbines, though it was noted in this study that in cycling applications, the O&M costs on RICE hold steady, resulting in a more comparable O&M cost versus gas turbines [14].

RICE also falls short on installed cost. According to an EIA study, an 85 MW reciprocating engine plant has an installed cost of $1,342 USD/kW [8]. The same study showed the higher end of traditional simple cycle combustion turbine plants costing $1,100 USD/kW installed, with more advanced engine designs costing $700 USD/kW for a full plant. There are several factors that contribute to the higher cost on RICE installations. RICE units are more susceptible to environmental impacts, and thus, are typically installed inside buildings, which can be costly given the relatively large footprint compared to gas turbines. RICE generates more low frequency noise which requires anti-vibration mounts and isolating pads. This combined with the sheer mass of RICE units results in 4.5 times more concrete required when compared to a gas turbine [13].

Table 1: Comparison of Technologies

Technology	Pros	Cons
Repurpose Base Load Facilities	• Low CAPEX	• High OPEX • Susceptible to outages • Poor emissions per kW
Continental Transmission	• Low OPEX • Low lifecycle emissions	• High CAPEX • Lengthy approval process • Requires regional utility investments/cooperation
Hydro pumped storage	• Fast response time	• High CAPEX • Several geographical limitations
Lithium Ion Batteries	• Fast response time • Portable • Low lifecycle emissions	• High CAPEX • Often charged with CO_2 dense sources • Short life span • Short discharge period causing the lowest capacity factors
Reciprocating Engines	• Fast response time • Good efficiency at part loads	• High CAPEX vs. other natural gas installations • High emissions of UHCs and other GHG contributors • High maintenance intervals

The next section of this paper will show how using aero derivative engine refurbishment and standardized plant designs can further increase the gap in installed cost between RICE and Simple Cycle Gas Turbines (SCGT).

Cost reduction strategies

In many regions where renewable penetration has been higher (California, Germany), the resulting cost of electricity has gone up significantly. In other regions, such as Southern Australia, grid instability has caused major headaches for local utilities and the general public. By implementing low cost peaking solutions now in the power markets trending toward severe levels of grid instability in the future, utility companies can avoid the urgent need for inevitably high-priced future solutions to curtail black outs and brown outs affecting average rate payers. Major utility companies and independent power producers globally are planning for these future states by releasing Integrated Resources Plans (IRPs) that involve more diverse energy mixes, including larger proportions of peaking power. Many utility companies are using the rule of thumb that for every 1 MW of renewable generation installed, they need to install and additional 0.8 MW of back-up peaking generation. However, owners and lenders are expecting lower-then-ever installed costs on the peaking solutions in order to supress retail electricity rate increases and retain the support of the public for the capacity additions to the grid. The following sections look at procedures that greatly reduced installed costs of open cycle gas turbine plants using aeroderivative engines.

Overhauling and refurbishing gas turbines

The largest contributor to initial cost of a simple cycle peaker plant is the gas turbine. A new aeroderivative gas turbine and package in the 40MW-50MW can approach a cost of $20M USD, or $500USD/kW for equipment only. Price sensitivity in global markets has driven an increase in installing used gas turbines recently. More mature power markets require high degrees of availability and reliability and therefore used equipment offerings often struggle to achieve the approvals necessary to be implemented. An alternative to a brand new or used gas turbine is a refurbished or overhauled gas turbine. Gas turbines typically require hot section replacements at 25,000 hours of operation and major overhauls at 50,000 hours of operation. These maintenance procedures are well established and can therefore be used as the basis for the supply of refurbished gas turbines for open cycle peaking Engineering Procurement and Construction (EPC) applications requiring a high degree of reliability but a more competitive installed cost. By following a set of thorough inspections and tests, an engine can be returned to a ‘zero hour’ state with respect to the critical wear components through a condition-based overhaul. This means the engine can be expected to have the same life span, warranties, performance guarantees, and maintenance schedule as a new engine for typically less than half the equipment cost.

The level of repair required to complete a condition-based overhaul can be estimated based on borescope inspections in conjunction with the total engine hours, the factored fired hours since the last repair and/or overhaul, and other applicable engine history. However, each engine may have its own unique repair requirements, which can only be identified upon disassembly and inspection. The following list of procedures is representative of a standard engine overhaul:

- The engine is disassembled into its individual modules. Missing or damaged external hardware is replaced.
- All accessories are inspected and serviced or replaced as needed. This includes the lube and scavenge pumps, hydraulic control units, variable geometry pumps and actuators, the starter motor, and engine actuators. All variable geometry components (arms, linkages, doors, seals etc.) are disassembled and inspected.
- The Compressor Front Frame, Compressor Rear Frame and Turbine Rear Frame are fully disassembled. All bearings are removed, inspected, and overhauled or replaced as needed. This may also include replacement or repair of cold end Teflon seals, stationary air seals, housings and bushings. The air collector is striped and repainted.
- The Inlet Guide Vanes, Low Pressure and High Pressure Compressor Rotors and Stators, as well as the Low Pressure and High Pressure Turbine Rotors and Stators are disassembled down to the piece part level. All blades, vanes, nozzles and shrouds are non-destructive tested and treated as needed. Lower wear parts such as Low Pressure Compressor (LPC) blades are often cleaned and re-used, while more critical wear components such as High Pressure Turbine (HPT) blades go through many levels of repair, and in some cases, full replacement (see below for more details). All disks and shafts are also inspected and replaced or overhauled as needed.
- A condition-based overhaul of the single annular combustor is conducted. The fuel nozzles and water injection nozzles are cleaned, inspected, repaired, flow tested and re-certified.
- Any outstanding service bulletins are implemented, which can include additional replacement or repair of engine parts.
- Upon reassembly, all rotors are carefully rebalanced (see Figure 2). Furthermore, modules are re-assembled using new consumable hardware.

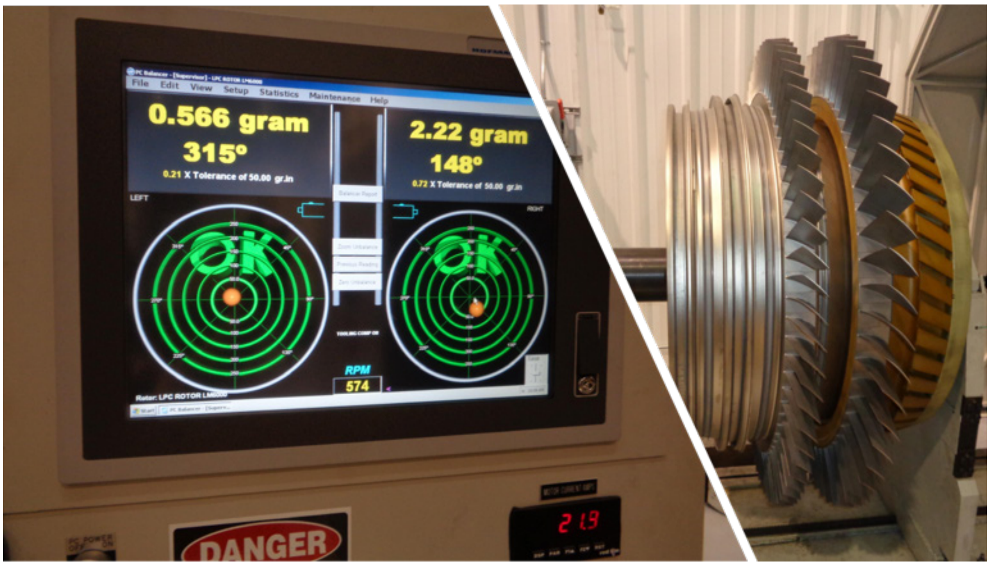


Figure 2: Rebalancing low-pressure compressor rotor

The high-pressure turbine experiences the most wear over the life of the turbine, and thus sees the greatest degree of 'fallout' (part replacement). Multiple levels of testing are conducted to determine which parts can be re-used, and which parts are not serviceable. For parts to be re-used, they go through several steps of refurbishment. For example, high pressure turbine airfoils can be stripped, hot formed and welded at cracks, tips or distressed surfaces. Parts are recoated based on their service (thermal barrier coats, PtAl coats, etc.) and airflow tested upon completion. The cost of such repairs is a fraction of an OEM replacement part. Any part deemed unrepairable is replaced with a new part or an overhauled part, depending on market availability.

The package, or housing of ancillary components, for the gas turbine can also be refurbished. A typical procedure to return the package to the original factory specifications includes the following:

- Perform a technical evaluation of the entire package in order to identify any deficiencies.
- Inspect the generator, conduct megger and low resistance checks. Inspect the bearings, windings, coatings, connections and coupling.
- Visually inspect the motors, conduct megger and low resistance checks. Inspect the bearings, windings, coatings, connections and coupling.
- Inspect the pumps, motors, valves and instrumentation for condition and correct function.
- Inspect the hoses and tubing for completeness, routing and deterioration.
- Inspect the wiring for completeness, routing and deterioration.
- Rebuild the generator as necessary.
- Repair or replace defective pumps, motors, valves and instrumentation.
- Repair or replace any defective wiring.
- Repair or replace any defective hoses and tubing.
- Repair or replace package auxiliaries, accessories, components and enclosure as necessary.
- Recalibrate the instrumentation.
- Verify controls programming, communication and function. Repair as necessary.
- Repaint the unit.
- Prepare documentation on components repaired or replaced.
- Provide the original OEM drawings, manuals and records that were received with the unit.
- Provide updated drawings for any changes made.

Vertical Integration

A business model that combines turnkey EPC offerings with a full suite of engine service capabilities allows for additional savings. For example, the ProEnergy Services main campus has a fully equipped LM6000 test facility that allows engines to be tested at the same site as its overhaul. Full load testing will include dry crank, light-off to synch idle, step wise ramps to maximum power, multiple cycles between synch idle and max power, and post test borescope inspections. Any deficiencies can be repaired on the spot.

Figure 3: ProEnergy on-site test facility

Of critical importance in mitigating the perceived risk associated with refurbished equipment is the ability to provide full life cycle support of the asset. This life cycle support can take many forms, but commonly includes:

1. Performance Guarantees – tied to liquidated damages for shortfalls
2. Extended Warranty – securitized with a warranty bond for the duration
3. Provision of a complete major maintenance and operations contract **by the provider of the refurbished equipment**. The Long-Term Service Agreement (LTSA) and Operation and Maintenance (O&M) performance is typically guaranteed via an availability and reliability requirement for the plant – tied to liquidated damages

Through the mechanisms above, public utility companies and lenders of all sizes and experience have supported the refurbished equipment strategy for EPC projects in the last 5 years. Though each case is unique, insurance providers also view the inherent risk to be equivalent to new equipment.

Standardization of Simple Cycle plant offerings

Rather than executing custom designs for gas turbine power plants, a business model that focuses on standardized offerings built upon limited engineering, reliable supply chains, and inventoried critical components further reduces the EPC cost and lead time, which also indirectly reduces cost by decreasing the financing requirements and on-site time during the construction period. The short lead time will also put simple cycle plants in a position to make more competitive offers in situations where unexpected grid instability has created an immediate need for peaking capacity, as seen in southern Australia.

Although each site will be impacted by its own unique features including varying ambient conditions, seismic criteria, emissions and noise regulations, performance targets, etc, standard plant designs will still govern fundamental design aspects of the plant. Standard layouts including fixed turbine models, turbine spacing, motor control center/control room placement, and ancillary skid locations allow for repeatable cable sizes/lengths, pipe sizes/routings and many other design aspects. Varying soil conditions results in the binary selection of foundations with or without pilings.

The Standard of the 2xLM6000PC Texas Plant (Case Study)

Successful implementation of a standard 2xLM6000PC simple cycle plant has been implemented into the Electric Reliability Council of Texas (ERCOT) market at 3 different sites. The standard turnkey EPC scope includes, but is not limited to, the following:

- 2x LM6000PC Gas Turbines
- Common Reverse Osmosis/Electrodeionized Water treatment system to generate demineralized water for NOx injection and power augmentation
- Standard Selective Catalytic Reduction (SCR) design to meet 2.5ppm NOx and 5ppm NH_3 slip from a 65' tall stack
- 2x Generator Step-up Transformers, breakers, and disconnects tied to a common dead-end structure
- Common Power Distribution Centre with Operator Work Station
- Optional Black Start Generator
- Optional Evaporative Inlet Cooling for Power Augmentation

All sites have been successfully implemented for less than $500/kW installed cost. The images below show two of the sites and their notable similarities.

Figure 4: Chamon 2xLM6000PC Site

The sites operate as traditional peaking facilities, running less than 2000 hours per year taking advantage of the reoccurring high electrical price peaks in the ERCOT market. This standard 2xLM6000 plant is now offered into markets with a <6 months lead time from Notice to Proceed until the Commercial Operation Date of the facility.

Figure 5: Port Comfort 2xLM6000PC Site

Conclusions

Many regions are trending rapidly towards high rates of renewable penetration. While there is some recognition of the impact of these volatile sources of energy (e.g. the CISO's identification of the "duck curve"), utilities do not appear to be sufficiently prepared or willing to be proactive in preventing grid instability while simultaneously controlling costs to consumers. While the science on various storage technologies is progressing favourably, each has its own set of drawbacks, including efficiency, discharge capacity, and availability of the required geographic features. Furthermore, the cost of many of these storage technologies well exceeds traditional peaking solutions without adding any actual energy to the grid. Public pressure for reduction of GHGs has made it difficult for traditional fossil fuel plants to remain relevant but cycling base load facilities or charging batteries at night with those facilities offers no improvement over a relatively clean burning natural gas plant.

The solution offered here is a substantial reduction in cost and lead time for Open-Cycle Combustion Turbine (OCCT) plants that create a value proposition that far exceeds any competing peaking or storage solution. With hundreds of aero derivatives nearing several decades of service and overhaul cycles, the process of refurbishing an engine to near-new state is well established. Renewable penetration has driven an increase in asset retirement, leading to higher availability of serviceable engines that can be acquired for a fraction of the cost. A systematic inspection of the engine and package and replacement of critical and high-wear components ensure the plants can be operated and maintained as new. Cost and lead time are further reduced by combining engine services with EPC capabilities into a single entity, while standardizing and simplifying the EPC offering. Any risk perceived by the end user is offset by including a full suite of O&M and LTSA offerings in conjunction with a turnkey EPC contract.

References

[1] Troy N, Denny E, O'Malley M. Base-Load Cycling on a System with Significant Wind Penetration. *IEEE Transactions on Power Systems.* 2010, Vol. 25, pp 1088-1097

[2] Shaner M, Davis S, Lewis N, and Caldeira K. Geophysical constraints on the reliability of solar and wind power in the United States. *Energy & Environ. Sci.*, 2018, Vol. 11, pp 914-925

[3] Gur, T. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. *Energy & Environ. Sci.* 2018, Vol. 11, pp 2696 – 2767

[4] National Energy Board, *Market Snapshot: Pumped-storage hydro – the largest form of energy storage in Canada and a growing contributor to grid reliability.* 2016. https://www.neb-one.gc.ca/nrg/ntgrtd/mrkt/snpsht/2016/10-03pmpdstrghdr-eng.html

[5] National Academy of Sciences, National Academy of Engineering, and National Research Council. *Electricity from Renewable Resources: Status, Prospects, and Impediments*. Washington, DC: The National Academies Press, 2010.

[6] Gagnon L, and van de Vate J. Greenhouse gas emissions from hydropower: The state of research in 1996. *Energy Policy*, Vol. 25, pp 7-13.

[7] International Renewable Energy Agency (IRENA) 2012. Hydropower *Renewable Energy Technologies: Cost Analysis Series* Vol 1: Power Sector Issue 3/5

[8] U.S. Energy Information Administration. *Capital Cost Estimates for Utility Scale Electricity Generating Plants.* EIA November 2016

[9] Jolliet O. Saadé-Sbeih, M., Shaked, S., Jolliet, A., & Crettaz, P. *Environmental lifecycle assessment.* CRC Press, 2015

[10] Katwala A. The spiraling environmental cost of our lithium battery addiction. Wired on Energy. August 2018 https://www.wired.co.uk/article/lithium-batteries-environment-impact

[11] Smith K, Saxon A, Keyser M, Lundstrom B, Cao Z, Roc A. Life Prediction Model for Grid-Connected Li-ion Battery Energy Storage System Proc *American Control Conference,* Seattle WA, CP-5400-67102, 2017

[12] Hittinger E. Azevedo I. Bulk Energy Storage Increases United States Electricity System Emissions. *Envion. Sci. Technol.,* Vol 49, No. 5, pp 3202-3210, 2015

[13] Perez, V. Aeroderivatives versus recips. *International Turbomachinery Magazine.* 2018, Vol. 59, No. 5.

[14] Schmeida, M. Mid-Sized New Generation: Reciprocating Internal Combustion Engines or Combustion Turbine?. *Power Engineering.* 2018, Vol. 122, Issue 1.