Firming Wind Evaluation

Prepared For: PowerPhase

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I. Executive Summary

Increased renewable energy delivered to the US energy markets requires that additional dispatchable power generation resources be secured in order to balance renewable energy supply variations. Dispatchable power generation that supports renewable energy supply variations can be referred to as "Firming Energy" because it firms or stabilizes renewable energy supply variations. "Firming Energy" ensures electric transmission system operating stability while meeting power sale hourly capacity and energy schedules. Firming Energy resources must be capable of dispatching and load following the renewable energy supply such that a constant value of scheduled energy is delivered to the transmission system when the renewable energy supply and the firming energy resource supply are combined. Typically, these firming power generation resources consist of Simple Cycle Gas Turbines ("SCGT") or reciprocating engines that are capable of fast start-up and load following.

The purpose of this study, prepared by Duff Power Services, is to provide a high level 20-year cost and net margin analysis of several technologies that can provide Firming Energy. This includes Turbophase, Aeroderivative CTs, and Reciprocating Engines. The data and conclusions are intended to be used as a tool for preliminary project screening for Utilities, IPPs, and Municipal power entities looking to firm wind generation.

PowerPhase provides a product that, when installed on an existing Combined Cycle Gas Turbine ("CCGT") unit, provides increased output at the host CCGT heat rate. The Turbophase Module ("TPM") compresses ambient air through a multi staged, inter-cooled compressor driven by a turbocharged reciprocating engine. Each module is designed to deliver air at the gas turbine compressor discharge pressure and temperature. The TPM dry air injection system provides the missing compressor discharge air the gas turbine is lacking due to environmental or operational conditions. This process provides fast start and fast-ramp incremental power delivered across all ambient conditions, up to the mechanical or electrical limits of the plant. The TPM modules are suitable for use in providing Firming Energy services for renewable energy. While TPM has been successfully demonstrated as a capacity upgrade product in the power generation market, the application of TPM as a renewables firming technology is new and requires business development to bring together the parties involved in firming renewable energy resources to produce a standard firming product. The parties involved in firming renewable energy resources include owners and asset managers of CCGT and renewables power plants in addition to municipals, cooperatives, and load serving entities that purchase firm renewable energy.

This study analyzes and compare the capital cost, operating cost and merchant energy margin for three technologies supplying Firming Energy service in order to provide a preliminary project screening function in the ranking and selection of a firming technology. The technologies are all fueled by natural gas and include: (a) TPM installed on a host 2x1 7FA.03 CCGT plant, (b) GE LM 2500+ G4 RD ("LM") aero-derivative SCGTs and (c) Wartsila 50SG Reciprocating Engines ("WRE"). Hourly energy market pricing data for calendar year 2016 in two major US energy markets was utilized.

The study results show that for 2016, TPM provided the most economical Firming Energy service among the three technologies evaluated and also provided a significantly lower cost than sourcing balancing energy in the real time market. The TPM capital cost is significantly lower than alternative firming technologies.

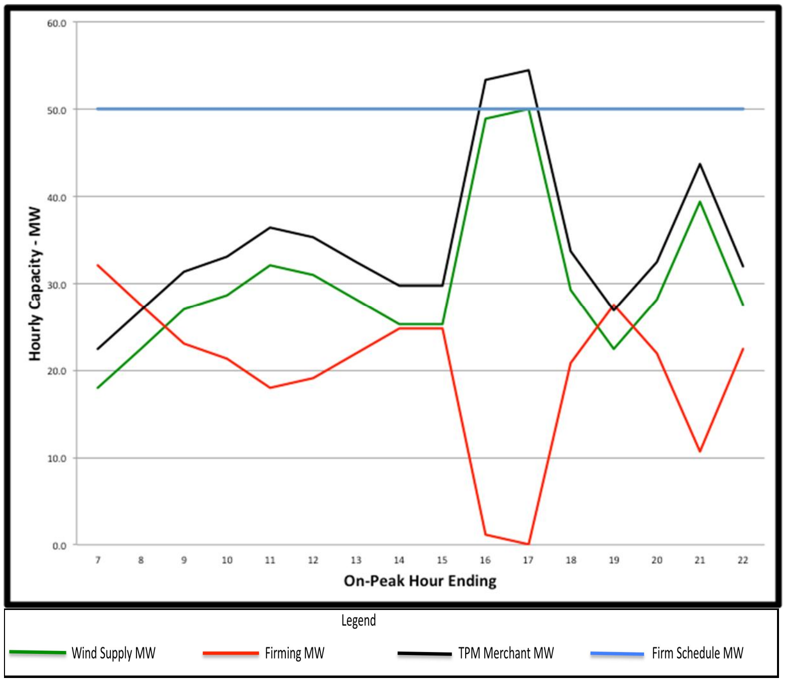
II. Analysis Methodology

Two US Energy markets were selected for analysis. The Pennsylvania-Jersey-Maryland ("PJM") market in the US northeast is a mature energy market with renewable energy supply anticipated to more than double from current levels over the next ten years. The market encourages renewable energy supply and provides a mechanism by which firming or balancing energy can be sourced from the real time market. The Electric Reliability Council of Texas ("ERCOT") market in Texas currently has significant renewable energy supply and approximately 50% of the regions energy is generated by natural gas thus providing a strong platform for CCGT based firming technologies.

This analysis considered a 50 MW firm on-peak power sale product consisting of available renewable energy balanced by the firming resource on an hourly basis.

Figure 1 represents a typical hourly dispatch schedule for wind energy and TPM firming services in ERCOT during the daily on-peak period. On-peak hours are from 6:00 am to 10:00 pm Monday through Friday excluding six NERC holidays. During the on-peak period, wind energy varies from a low of zero MW to a high of 50 MW requiring the firming services schedule to offset the hourly shortfall from the wind energy capacity in order to deliver a firm 50 MW schedule. Capacity above that required for firming service is available for sale in the real time market. This same average daily wind dispatch profile was utilized in the PJM market analysis.

Figure 1: Daily Average ERCOT On-Peak Dispatch Schedule



The analysis utilized actual ERCOT and PJM on-peak real time or spot market hourly energy pricing and average daily natural gas spot market prices for 2016. The analysis determined the dispatch cost for each technology (including costs for fuel, variable Operation and Maintenance ("O&M") and life cycle major maintenance), dispatched the technology to firm the wind supply schedule and dispatched non-firming surplus energy in the real time spot market. The analysis results provide actual market based economics that would have resulted from the utilization of these specific firming resources during 2016. This "look back" approach provides an objective historical assessment not influenced by forecasts of future natural gas prices, electricity prices, market supply and demand changes and market regulation changes.

The selection of the technologies to be evaluated considered the capacity and load following requirements of firming service. The use of gas turbines for this service requires smaller SCGT models to meet to minimum dispatch requirements. Two (2) LM 2500+G4 RD units, three (3) Wartsila 50 SG units and eight (8) TPM units provided the required 50 MW firming capacity during all ambient conditions.

In PJM, the LM and WRE technologies were not dispatched to provide firming service as the PJM market provides for the purchase of real time energy for balancing purposes at a lower cost. The daily dispatch heat rates for the LM and WRE units In ERCOT were based on the firming dispatch schedule and reflects the actual heat rate expected during load following operation.

Merchant energy sales for the LM and WRE were based on full load heat rates. The TPM technology maintains a constant CCGT full load heat rate while load following. Performance degradation from "new and clean" conditions and average degradation through the major maintenance cycles was applied to each technology with heat rate increased 2% for the CCGT and 3% each for the LM and WRE. Output degradation was applied at 1.3% each for the LM and WRE technologies with no output degradation applicable to the TPM technology.

Capital cost of the technologies were considered based on the assumption that the LM, WRE and TPM units are installed at existing power plant locations by an Engineering, Procurement and Construction ("EPC") contractor with no incremental transmission interconnection or system upgrade costs, no incremental natural gas interconnection costs, no spare parts or inventory costs, no fixed annual O&M costs, with overnight construction cost including Interest During Construction ("IDC") at 8.6%, no debt service costs, no incremental property tax and no property insurance costs. All life cycle major maintenance costs for the units are included in the variable O&M.

In order to simulate "life of project" economics in (2016 dollars) including capital costs, a twenty-year forecast was generated based on holding constant the 2016 operating results. Capital costs, firming service dispatch costs (fuel and variable O&M) and real time energy purchase costs combined to reflect the total cost of providing firming energy services. Any available capacity not required for firming service was assumed sold in the real time market and the resulting incremental energy margin was included in the projection. The 20-year total cost or energy margin is used as the economic comparison parameter to generate a net cost (or profit) per MHW of renewable energy firmed.

Key analysis assumptions are summarized in Appendix 1.

III. Results

The results of the analysis indicate that the TPM technology produced the lowest total <u>cost</u> for Firming Energy services in the ERCOT market and provided the highest <u>net margin</u> or profit for Firming Energy services in the PJM market for 2016 as compared to the alternatives evaluated.

Table 1 represents the annual operating and performance statistics from the dispatch model for the technologies evaluated. For times when the TPM host CCGT unit is "out of the money" and not dispatched, Firming Energy is purchased in the real time market. For times when the CCGT is dispatched, TPM load follows to provide Firming Energy service at the host CCGT heat rate.

The LM and WRE units are dispatched during on-peak days and load follow in order to provide Firming Energy services.

Table 1: ERCOT & PJM Operating Summary - 50 MW Firm Sale				
	ERCOT			PJM
	Turbo Phase	LM 2500	W 50SG	Turbo Phase
Number of Firming Units	8	2	3	8
Firming Units Total ISO MW	51	69	56	51
Summer On-Peak Capacity Demonstration - MW	54.4	66.4	54.6	54
Number of Host 7FA.03 GTs	2	NA	NA	2
On-Peak Capacity Factor CCGT/LM/WRE	61.2%	47.8%	57.8%	97.5%
Off-Peak Capacity Factor CCGT/LM/WRE	15.7%	0.7%	9.4%	88.9%
Average Annual On-Peak Dispatch Heat Rate - Btu/kWh LHV	6,942	10,479	9,329	6939
TPM/LM/WRE % of Firming Energy Supplied	62.0%	100.0%	100.0%	97.6%

Table 2 represents the total estimated project capital cost associated with installing the respective technology at an existing plant.

Table 2: Firming Technology Capital Cost - 2016 k$				
	ERCOT			PJM
	Turbo Phase	LM 2500	W 50SG	Turbo Phase
Capital Cost $/kW	$400	$864	$978	$400
EPC Capital Cost - $k	$21,760	$57,396	$53,361	$21,760
Substation Interconnection Cost - $k	$0	$650	$650	$0
Interest During Construction - k$	$1,871	$4,992	$4,645	$1,871
Environmental Permits - k$	$500	$500	$500	$500
Total Installed Capital Cost - k$	$24,131	$63,538	$59,156	$24,131

Tables 3 and 4 present the annual costs associated with providing Firming Energy, real time energy purchased for Firming Energy service when the CCGT dispatch cost exceeds the real time market price, energy margin captured by capacity not required for Firming Energy service and capacity revenue as applicable. For ERCOT, the scenario of purchasing 100% of the Firming Energy in the real time market is presented for comparison purposes. The LM, WRE and market "buy-through" options have a net cost to provide Firming Energy services while TPM generates a net annual profit since the merchant energy margin is greater than the Firming Energy services cost. For PJM, the "buy-through" option results in a net cost to provide Firming Energy services while TPM again generates a net annual profit. ERCOT does not provide a capacity payment while the PJM capacity payment value was assumed at $120/MW-day.

Table 3: ERCOT Annual Firming Costs & Merchant Energy Margin				
	Turbo Phase	LM 2500	W 50SG	ERCOT Real Time Buy-Through
Annual Production Cost to Firm Wind - $k	$991	$2,293	$2,240	$0
Annual Buy-Through Energy Cost to Firm Wind - $k	$584	$0	$0	$2,189
Total Annual Cost to Firm Wind - $k	$1,575	$2,293	$2,240	$2,189
Annual Merchant Energy Margin - $k	$2,497	$1,363	$1,224	$0
Annual Capacity Payment Revenue - k$	$0	$0	$0	$0
Net Annual Operating Cost - k$	NA	$930	$1,016	$2,189
Net Annual Operating Income - k$	$922	NA	NA	NA

Table 4: PJM Annual Firming Costs & Merchant Energy Margin		
	Turbo Phase	PJM Real Time Buy Through
Annual TP Production Cost to Firm Wind - $k	$1,127	$0
Annual Buy-Through Energy Cost to Firm Wind - $k	$63	$2,773
Total Annual Cost to Firm Wind - $k	$1,190	$2,773
Annual Merchant Energy Margin - $k	$3,617	$0
Annual Capacity Payment Revenue - k$	$2,389	$0
Net Annual Operating Cost - k$	NA	$2,773
Net Annual Operating Income - k$	$4,817	NA

Tables 5 and 6 present the analysis results on a 20-year basis in order to include the capital costs for the technologies. Costs are represented in 2016 dollars and include initial project capital costs and 20 years of the 2016 historical net annual costs or profits from providing Firming Energy service. As previously noted, project capital costs reflect the overnight cost to construct and commission the units but does not consider subsequent debt service or return on investment requirements of the project developer. These factors were excluded, as they are specific to particular project developers and owners. As this analysis is at the alternatives screening level, more detailed life of project costs and returns would be performed in a subsequent project development phase.

In ERCOT, TPM provides the lowest project life cycle cost at $4/MWH compared to $46/MWH and $47/MWH for the WRE and LM units, respectively. The ERCOT real time “buy through” case of $27 is addressed in the Risk section of this report.

In PJM, the real time Buy Through scenario resulted in a <u>cost</u> of $34/MWH compared to the TPM case, which produced a <u>net profit</u> of $45/MWH resulting in an incremental value of $79/MWH from TPM.

Table 5: ERCOT 20-Year "All-In" Firming Costs or Profit				
	Turbo Phase	LM 2500	W 50SG	ERCOT Real Time Buy Through
Capital Cost - $k	$24,131	$63,538	$59,156	$0
20-Year Firming Operating Costs - k$	$31,498	$45,863	$44,793	$43,790
20-Year Merchant Energy Margin & Capacity Payments - k$	$49,931	$27,260	$24,471	$0
20-Year Total Firming Cost $/MWH of Wind Firmed	$3.53	$50.83	$49.18	$27.10
20-Year Total Firming Income $/MHW of Wind Firmed	NA	NA	NA	NA
Turbo Phase Value Created - $/MWH of Wind Firmed	Base Case	$47.31	$45.66	$23.57
Turbo Phase Value Created - k$/Year	Base Case	$3,822	$3,689	$1,905

Table 6: PJM 20-Year "All-In" Firming Costs or Profit		
	Turbo Phase	PJM Real Time Buy Through
Capital Cost - $k	$24,131	$0
20-Year Firming Operating Costs - k$	$23,802	$55,467
20-Year Merchant Energy Margin & Capacity Payments - k$	$120,133	$0
20-Year Total Firming Cost $/MWH of Wind Firmed	NA	$34.32
20-Year Total Firming Income $/MHW of Wind Firmed	$44.68	NA
Turbo Phase Value Created - $/MWH of Wind Firmed	Base Case	$79.00
Turbo Phase Value Created - k$/Year	Base Case	$6,383

IV. Risk Assessment

While the analysis was based on a "look back" at results that would have occurred had the various technologies been utilized for Firming Energy service during 2016, the actual determinant of project viability is based on projections of energy prices, natural gas costs, market supply and demand changes as well as regulatory changes that may impact renewables. This analysis serves as a preliminary screening tool for Firming Energy service alternatives. Once an alternative is selected, typical project development evaluation of project life cycle financial performance provides more definitive information.

There are significant cost risks in relying exclusively on the real time market as a source for Firming Energy without providing for a physical capacity asset. In this scenario, the Firming Energy service provider assumes uncapped market risk of "buy through" energy price and availability. While PJM provides for the purchase of Firming Energy in the real time market, the price and availability risk resides with the firming service provider.

By providing a physical capacity asset, the firming service provider hedges market energy price and availability risk by capping Firming Energy services cost at the production cost of the physical asset. All three generating technologies serve to cap Firming Energy services costs. In addition to capping the Firming Energy services cost, each technology allows for capturing market price opportunities with available capacity above that required for the Firming Energy service. This results in both a risk hedge and a profit opportunity.

To address the sensitivity of these results to future changes in key market parameters on a qualitative basis, the following general observations are offered assuming only one market variable changes at a time:

A. Since the average annual heat rate of TPM is 26% and 34% lower, respectively, than the heat rate of the WRE and LM units, changes in natural gas prices would change the amount of the differential annual firming costs but the spread between the technologies would remain.

B. Increases in market prices for real time energy would increase the merchant energy margin for all technologies but would not increase annual firming cost of WRE, LM or TPM when dispatched for firming service. Since the PJM "buy through" balancing energy represents a small percentage (3% in 2016) of the TPM total annual firming cost, TPM in PJM would likely realize a minimal cost impact mitigated by the increased merchant energy margins. For ERCOT, the TPM "buy through" energy cost would increase but the CCGT dispatch would also increase as would TPM merchant energy margins thus providing inherent market price risk mitigation

C. Decreases in market prices for real time energy would decrease the merchant energy margin for all technologies but would not increase the annual firming cost of WRE, LM or TPM when dispatched for firming service. Buy-through energy costs would be reduced in PJM. In ERCOT, the TPM Buy-through energy cost would decrease; the CCGT dispatch would decrease, as would TPM merchant energy margins. Lower market prices for real time energy would reduce the spread between the annual firming costs in ERCOT.

Regardless of the changes in annual firming service costs, the TPM capital cost is about 40% of the WRE and LM capital cost and this savings remains throughout the life of the project further mitigating risks of market changes that impact annual firming costs.

V. Conclusion

As stated in the Executive Summary, the purpose of this study, is to provide a high level 20-year cost of ownership analysis of several technologies that can provide Firming Energy. This includes Turbophase, Aeroderivative CTs, and Reciprocating Engines. The data and conclusions are intended to be used as a tool for preliminary project screening for Utilities, IPPs, and Municipal power entities looking to firm wind generation.

Providing renewables Firming Energy service utilizing a physical capacity asset reduces project risk when compared to sourcing Firming Energy in the real time markets. The differentiator between firming technologies is the project capital cost, annual firming service costs and annual merchant energy margin.

When installed on an existing 7FA CCGT unit in ERCOT or PJM, the heat rate of the TPM option yields the lowest annual Firming Energy service cost and delivers a net annual profit due to the stronger capture of merchant energy sales. Capital cost of the TPM option is substantially lower than the WRE or LM options as TPM up-rates existing generating assets by restoring latent GT capacity otherwise lost due to ambient temperature or operating limitations. Leveraging existing power plant and transmission system infrastructure further reduces project capital cost when compared to alternative technologies.

The economic benefits provided by TPM as a Firming Energy resource provides a new lower cost and higher profitability option for renewables developers, renewables operators, CCGT plant asset managers and load serving entities seeking to meet renewable energy goals.

For more information or review of this analysis as well as discussion regarding the applicability of this analysis to specific fleets or markets, please contact:

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Appendix I

Key Model Assumptions

- Real time hourly on-peak and off-peak weight average electricity pricing for 2016 was used to generate average daily on-peak and off-peak $/MWH

- Daily weight average natural gas pricing for 2016 used for $/MMBtu

- 7FA.03 CCGT, TPM, LM and WRE output and heat rate adjusted for:
    - Average monthly high temperature for on-peak dispatch
    - Average monthly low temperature for off-peak dispatch
    - Degradation from "New and Clean" performance

- 7FA.03 CCGT, TPM, LM and WRE dispatch model includes fuel cost, variable O&M and major maintenance accrual

- For firming service, LM and WRE actual dispatch heat rates were adjusted for the load following dispatch profile that resulted in an average daily on-peak heat rate increase of 7% for the LM and 8% for the WRE units.

- For non-firming merchant energy sales, all technologies dispatched at full load heat rates

- ERCOT Dispatch:
    - LM and WRE were dispatched during on-peak hours to regulate and firm the renewable dispatch schedule and to provide the required capacity.
    - TPM was dispatched during on-peak hours to regulate and firm the renewable dispatch schedule when the CCGT was dispatched. When the CCGT was not dispatched, balancing energy was purchased in the real time market utilizing the CCGT capacity.
    - Real time energy purchases for 100% of the firming requirements were modeled for reference purposes.
    - All technologies dispatched off-peak for merchant energy sales when the particular spark spread was positive.

- PJM Dispatch:
    - TPM was dispatched during on-peak hours to regulate and firm the renewable dispatch schedule when the CCGT was dispatched. When the CCGT was not dispatched, balancing energy was purchased in the real time market utilizing the CCGT capacity.

  - Real time energy purchases for 100% of the firming requirements were modeled.
  - TPM dispatched off-peak for merchant energy sales when the CCGT spark spread was positive.

- Annual results for 2016 were assumed constant for a 20 year project life in order to determine an "all in" project capital, O&M cost, fuel cost and energy margin profit in 2016 dollars. A $/MWH of renewable energy firmed was used as the comparative measure between the firming technologies and real time energy balancing options.

Appendix II
Data Sources

- 2017 US Climate Data, version 2.2: Average monthly high and low temperatures
- US Energy Information Administration: 2016 Daily Natural Gas Spot Price, Henry Hub and TETCO-3 Hub
- ERCOT and PJM 2016 Hourly Real Time Pricing Data: Houston Hub and PJM Western Hub
- PJM Capacity Payment Auction Results 2017-2018: PPL Region
- 7FA.03 CCGT and TPM output and heat rate ambient temperature adjustment: PPL ThermoFlow model
- Shavel, Tsuchida & Kline; Review of the Renewable Denton Plan, The Brattle Group, June 10, 2016:
  - Figure 11: Hourly New Load and Ramping Needs
  - RICE units capital cost & operating parameters
- Black & Veatch; Cost and Performance Data for Power Generation Technologies; Prepared for the National Renewable Energy Laboratory; February 2012:
  - IDC Rates
- US Energy Information Administration; Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants; April 2013
  - Plant Costs, Fixed O&M, Variable O&M