“FUTURE-PROOFING” TODAY’S INDUSTRIAL GAS TURBINES : COMBUSTION SYSTEM FUEL FLEXIBILITY IMPROVEMENTS FOR HYDROGEN CONSUMPTION IN A RENEWABLE DOMINATED MARKETPLACE

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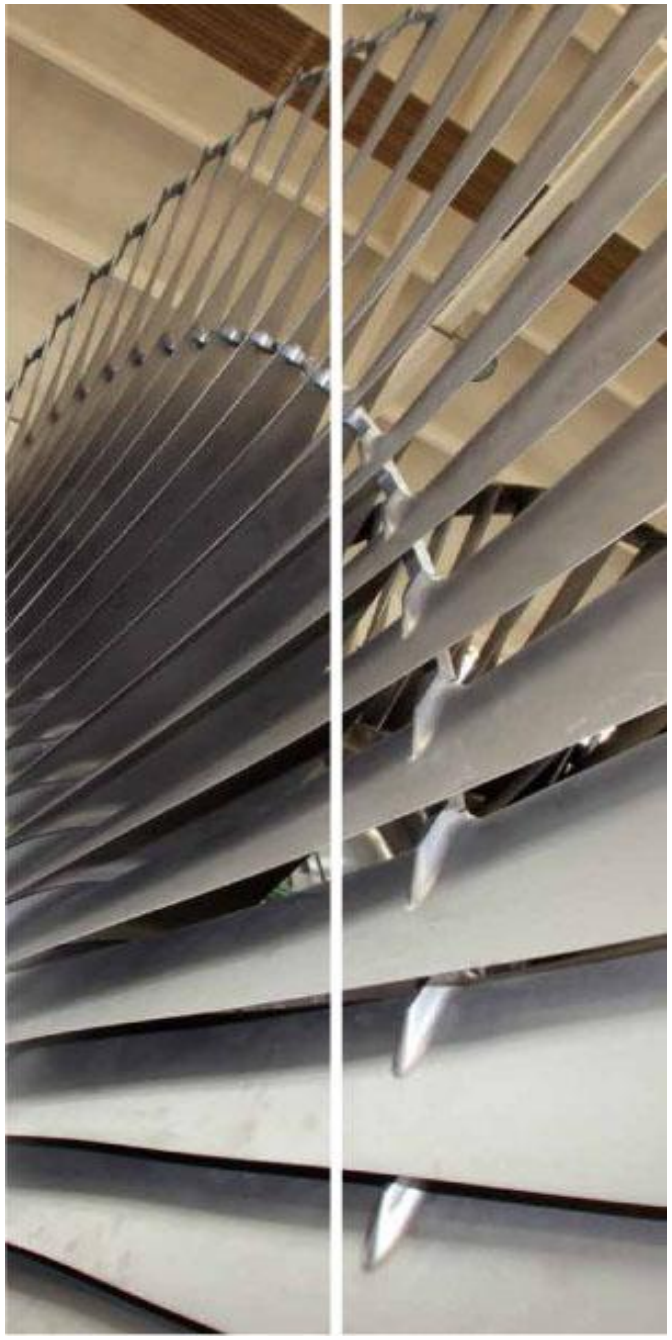
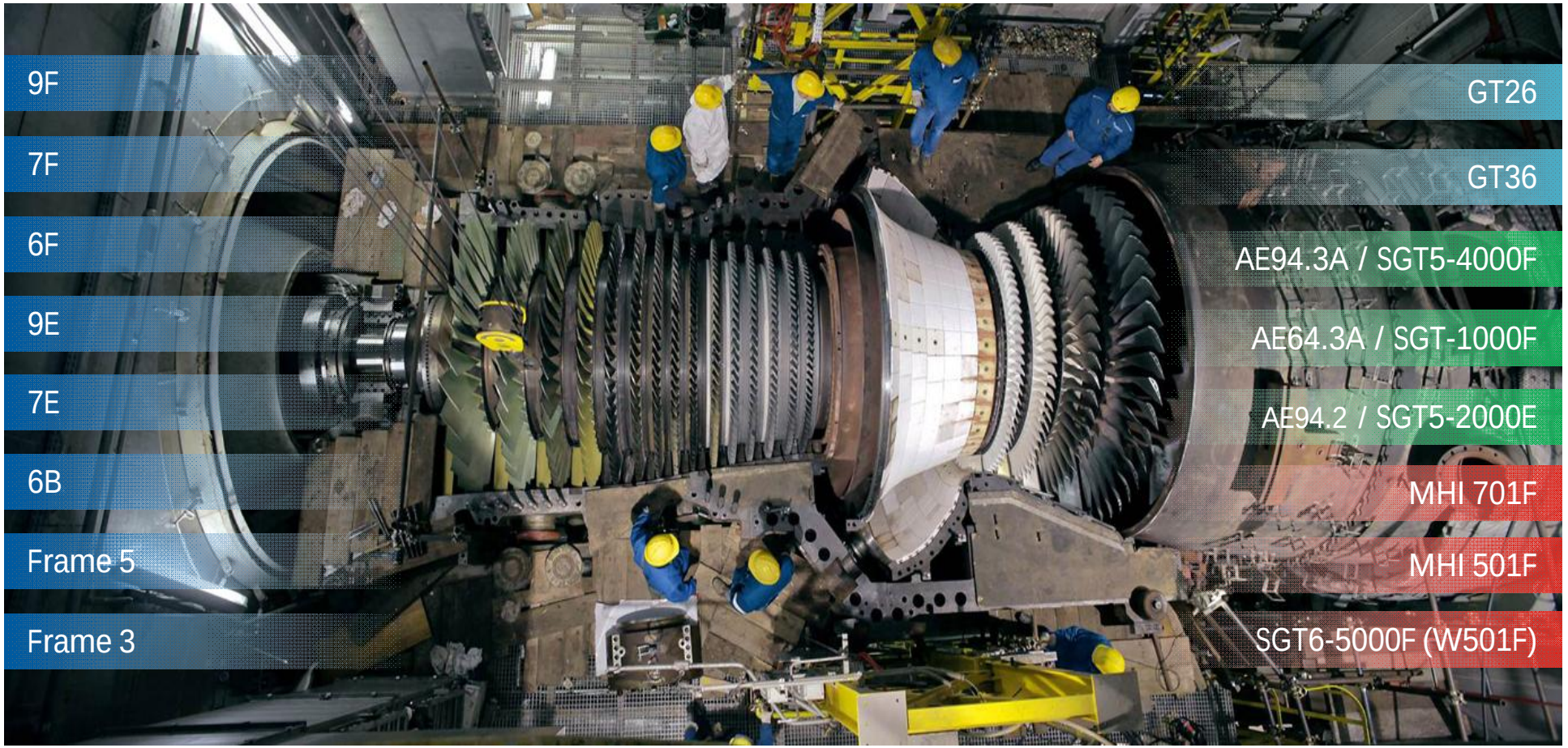
Agenda



- Gas Turbine Drivers in a Renewable Market Place
- Hydrogen Commercial Install Case Study
- Flexibility Extension
- Conclusions

Gas Turbine Service Platforms

Full Service Capabilities



Market Challenges Facing Gas Turbines

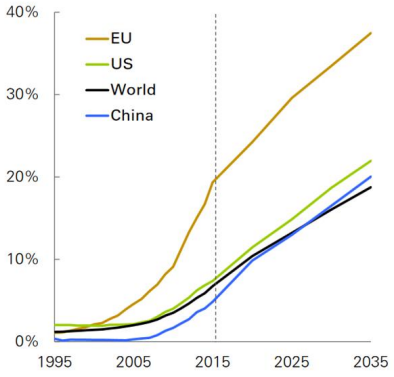
Renewables Changing Power Generation

Declining Revenue + Increasing O&M Costs =

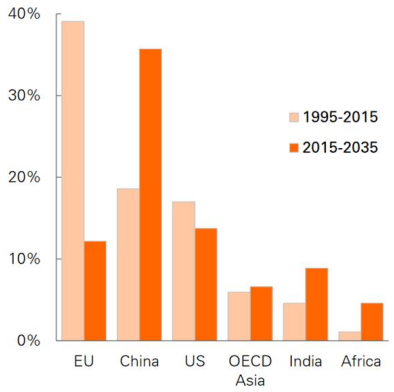
- Lower Marginal Prices
- Reduced Capacity Factors

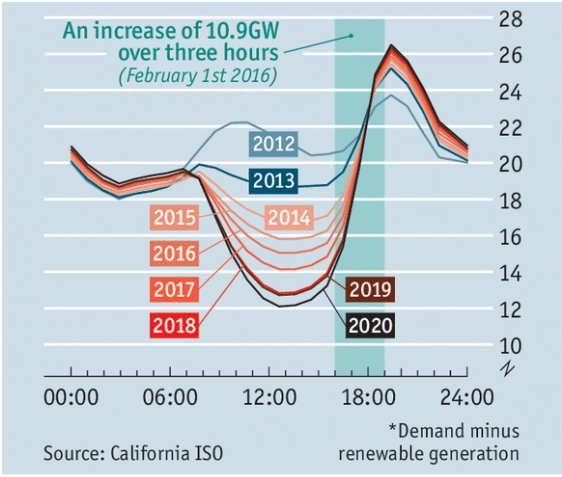
- Aging Assets
- Added Starts & Stops
- Ramping of Conventional Units

Renewable Power Generation



Relative Renewable Power Growth





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Increasing Renewable and Distributed Generation and Energy Efficiency driving need for Flexible Power Supply

Agenda

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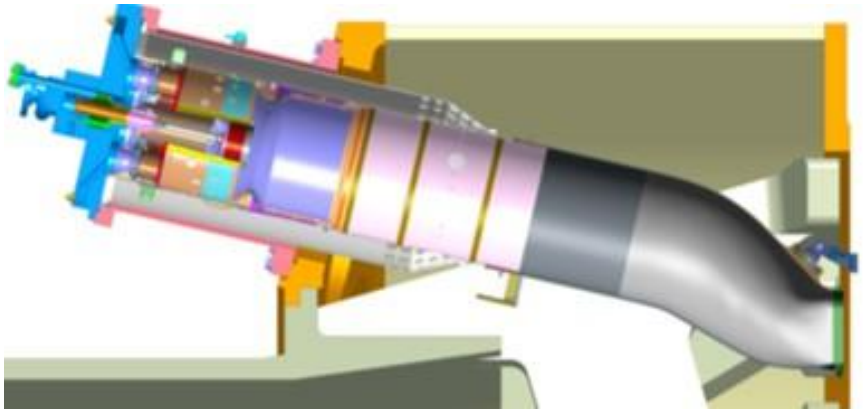
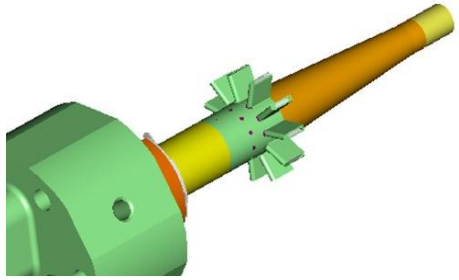
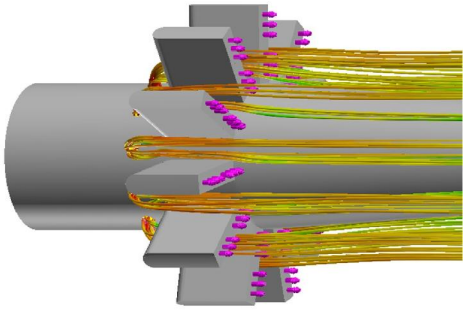
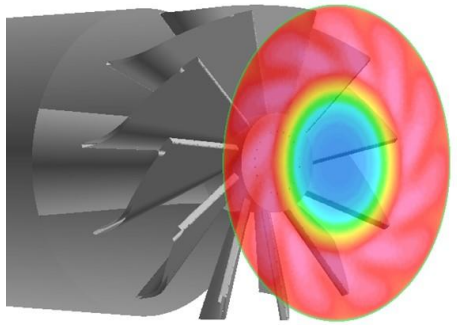
Major elements of consideration

- Combustion system
- Fuel skid
- Control System / AutoTune









High hydrogen Secondary fuel nozzle upgrade

AES Elsta Perspective – Voice of Customer

- Steam + Electrical capacity = 630MW
- 3 x GE9E MS9171E gas turbine
- 1 x GE steam turbine
- 3 x Ansaldo HRSG with additional duct firing

- Competitiveness in a changing Electricity Market within the contractual boundaries?
- Increase of production and fuel flexibility
- Availability of “Sitegas” a blend of methane and hydrogen, byproduct of a neighbouring facility
- Usage of low cost fuel and positive effect on emissions

- In January 2011 first proposal to stakeholders for increasing the H_2 percentage in the fuel mix to the gas turbines, from 10% to ..
- Begin 2017 final approval to execute the project

Technical specifications and drivers for the project

AES Elsta Perspective – Voice of Customer

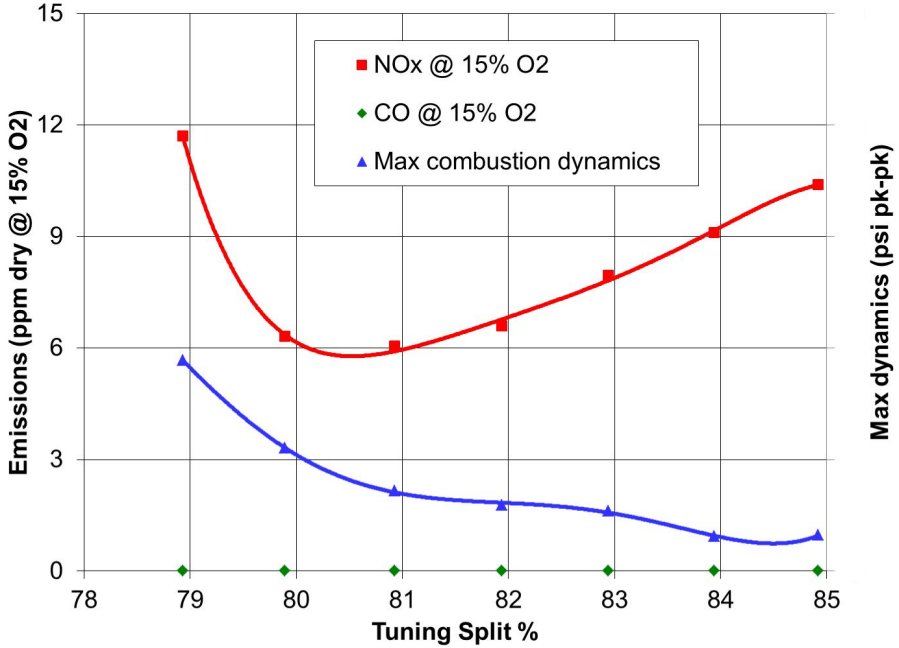
- PSM's LEC-III® combustion equipment installed in 2009/2010
- Modify the current installation with:
  - Fin mixer secondary fuel nozzles
  - CDMS and AutoTune system

- Additional equipment changed or modified:
  - Gas control valve fuel mixing station, H_2 analyzers and flame scanners
- Results of the project:
  - Maximum of 25% H_2 over the full operating range, 55 – 123 MW, tested up till 35% H_2
  - Low emissions, CO is on the edge without H_2 on minimum load
- Challenges of the project:
  - Connecting AutoTune system to the MK V control system
  - Position of the CDMS probes on the combustion cans
- Last gas turbine modified in week 23, 2018

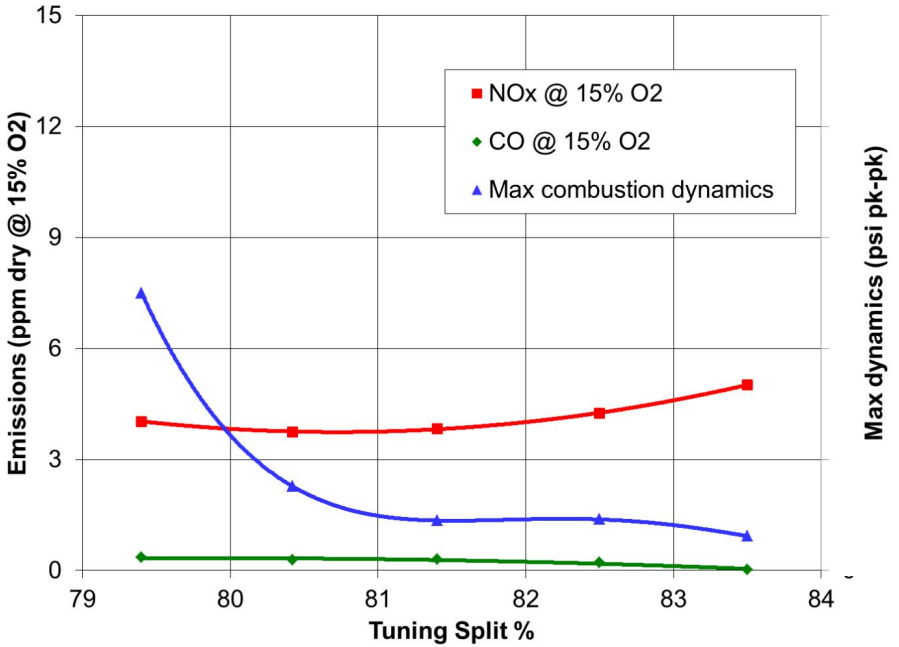
Execution of the modification of three gas turbines and test and commissioning

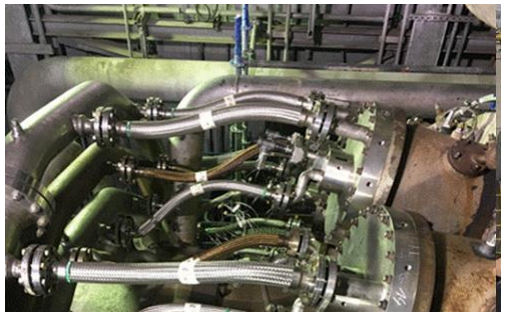
E-class Fuel Flexibility – Netherlands
9E Demonstrated Engine Operation with Hydrogen

Base Load 30% H_2

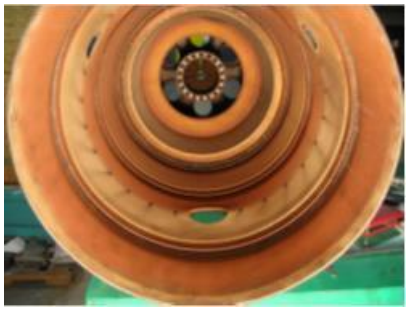


Min Load 35% H_2





Patented Automated Tuning with changing fuel constituents

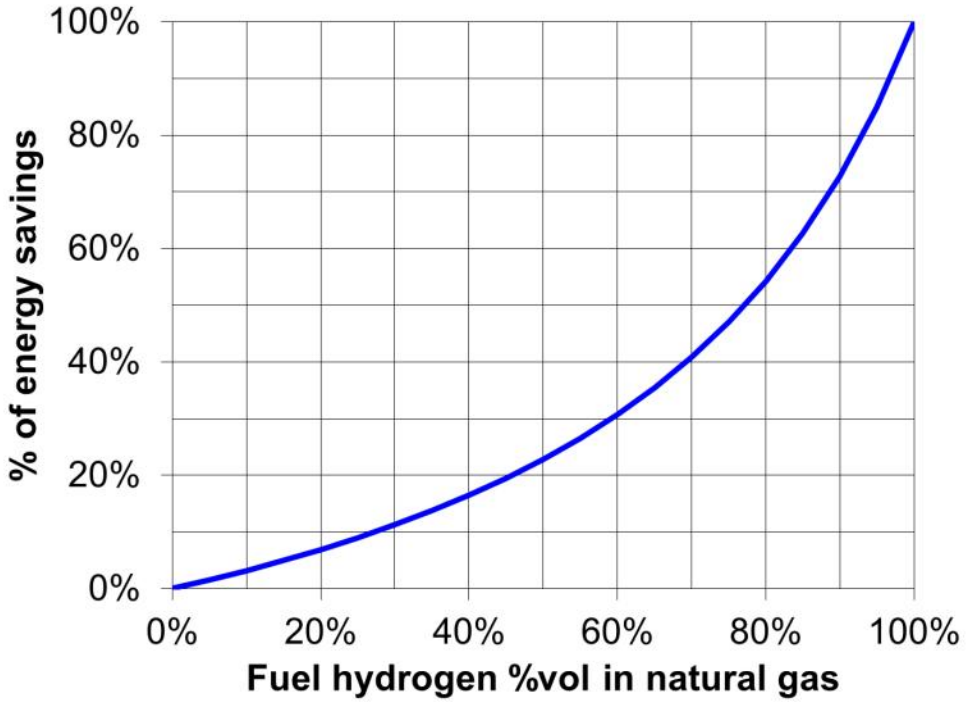


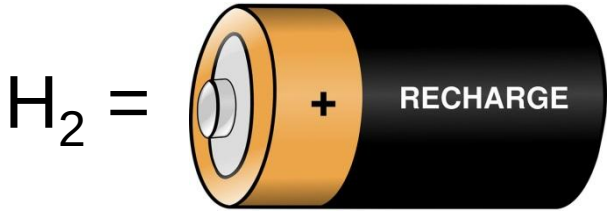
Stable, robust and flexible sub 9ppm operation from 0% to 35% hydrogen

Fuel Flexibility

Storage Fuels and Cost Offset

- Waste gas and refinery by product gas use substantially reduces the fuel bill
  - Example: For natural gas priced at ~4.5€/MMBTU (or 4.75€/GJ), a 9% energy savings on a base loaded Frame 9E.03 combined cycle would **save ~€3million/year**
  - 9% reduction CO_2 ~50,000 metric tons/year reduction in CO_2 = 10,700 cars off the road
- Low emissions gas turbine combustor is the cleanest way to consume waste gas

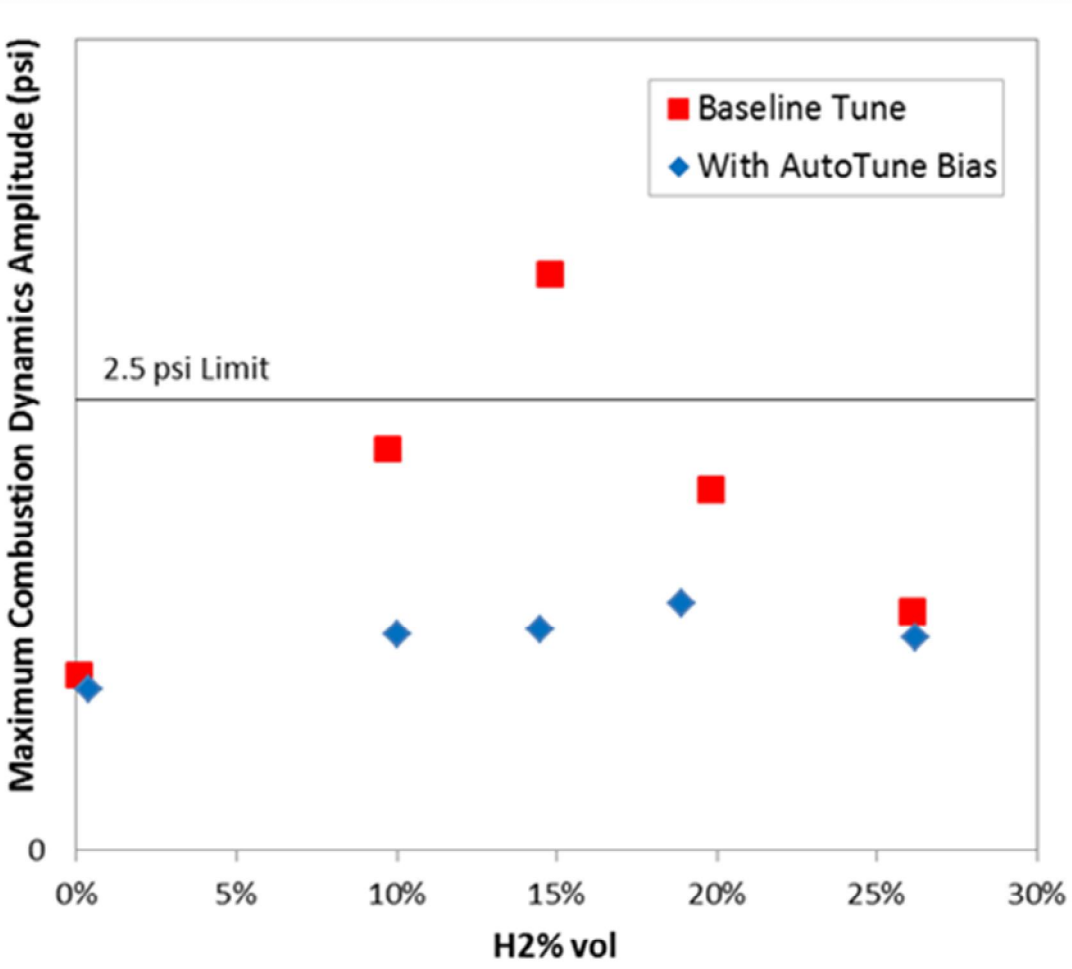


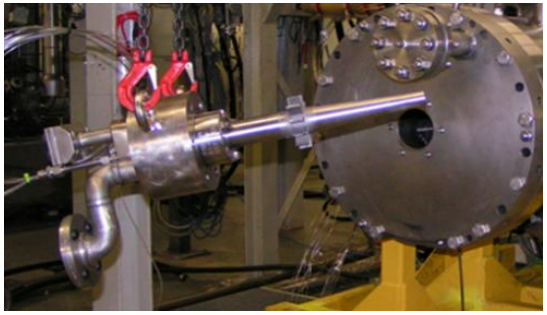


Significant Saving Potential by Using Alternative Fuel Source – Refinery, Wind, Solar

Fuel Flexibility

9E Commercial Engine Operation with Hydrogen





AutoTune Safely Operates while Keeping Dynamics Low

Agenda

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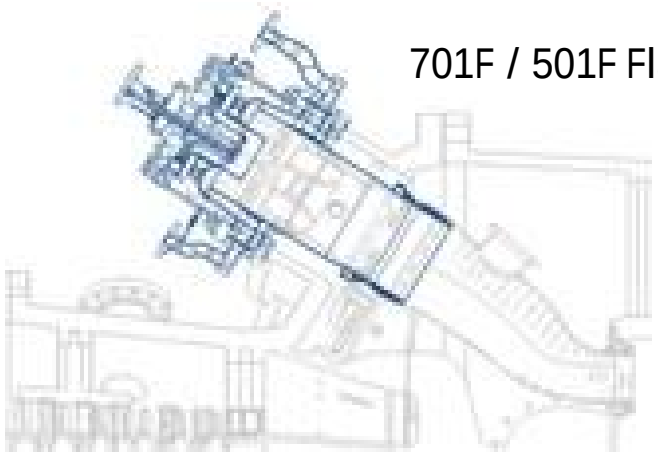
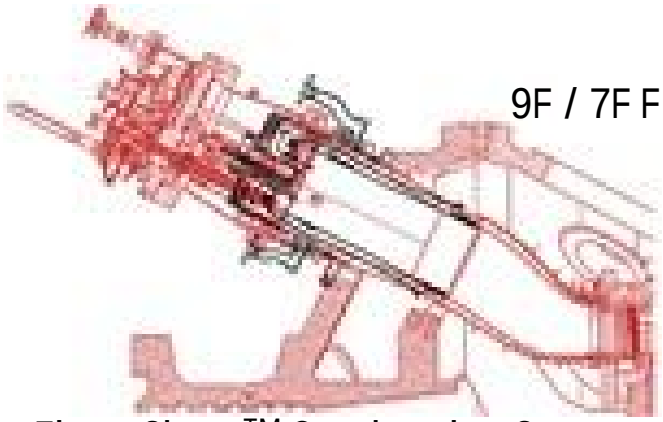
FlameSheet™ Combustion System Retrofit

701F / 501F FlameSheet™



9F / 7F FlameSheet™



FlameSheet™ Combustion Systems for:

- GE: Frame 5, 6B, 6F, 7E, 6F, 7F, 9E, 9F
- Siemens / Mitsubishi: 501F, 501G, 701F, 701G
- Siemens: 501B/D

FlameSheet™ Attributes

- *Extended* Fuel Flexibility
  - 30% Modified Wobbe Index (MWI) Variation
  - Hydrogen Up To 40%
  - C2 Up To 40%
  - Dual Fuel Capable
- Turndown as low as *30%* on Standard Firing Curve
  - Extended Turndown Also Realized On Reduced Low Load Firing Curve To Protect Unit HRSG
- Sub 9ppm NOx and CO with no diluent
- 32k hours / 1250 Starts Inspection Interval
- Drop in retrofit with common hardware across platforms

Retrofit designed for turndown, fuel flexibility & emissions capability

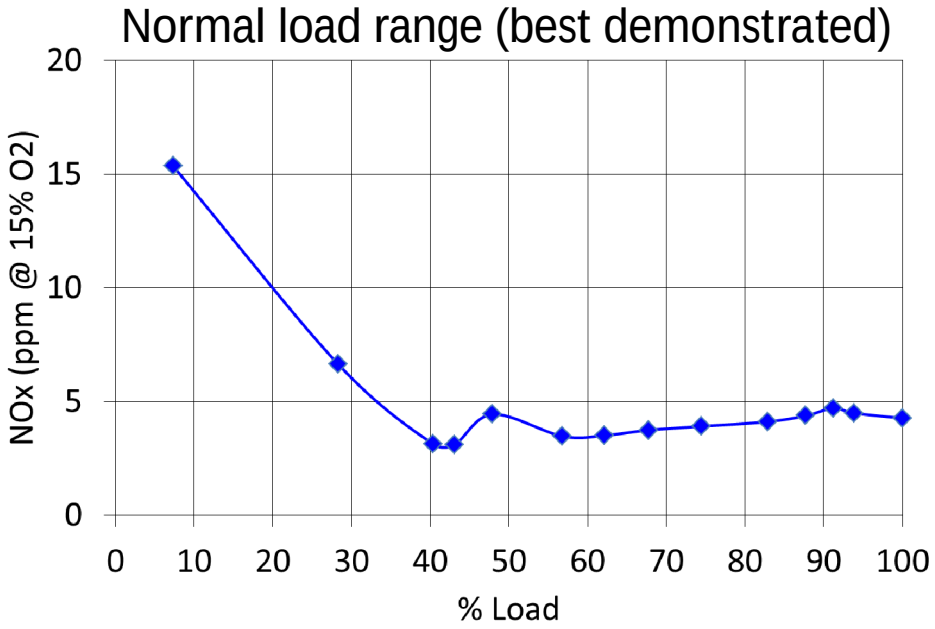
FlameSheet™ Commercial Machine Experience

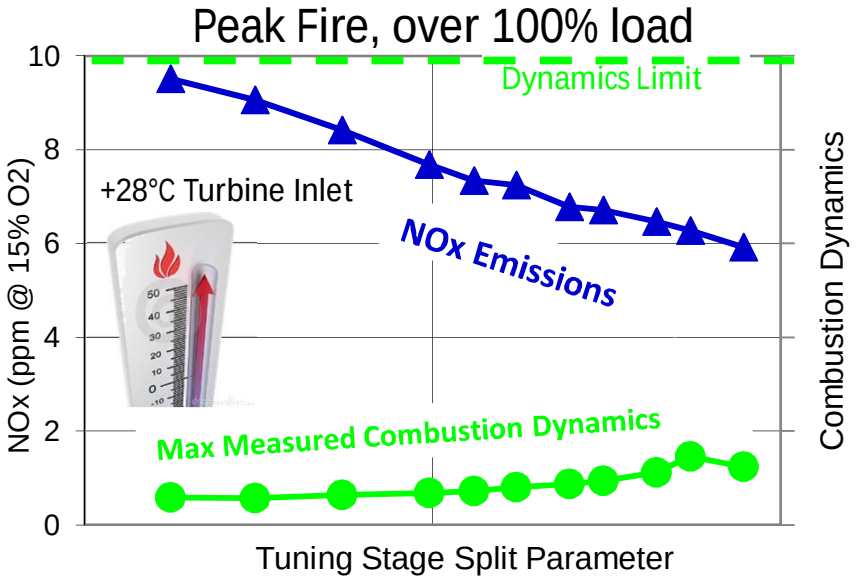
- 5 FlameSheet™ machines in operation, fleet leader at ~30,000 hours
- Key attributes - *20% additional load turndown* and *fuel flexibility*, with *sub 9ppm NOx*

FlameSheet™ retrofit enhances operational and fuel flexibility

Operational Flexibility - FlameSheet™

Commercial Engine Installation – NOx Performance





- Demonstrated Sub-5ppm NOx over normal operating range 40% - 100% load
- Demonstrated Sub-10ppm NOx above 20% load
- Demonstrated +50°C upgrade on 2 commercial F-class machines, emissions below 9ppm
- Technology applicable to E, F and H/J-class

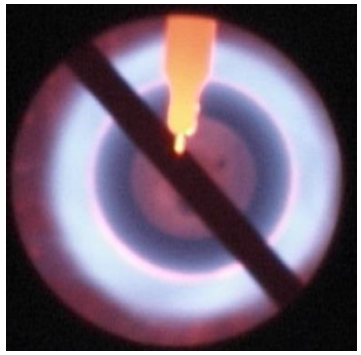
F-class FlameSheet™ substantially reduces start-up and normal operating NOx Emissions advantage from start-up to peak fire

FlameSheet™ Hydrogen Rig Experience

Enhanced Fuel Flexibility

Fuel Constituent Comparison (Premix Operation, %Vol) Current Commercial Engine Release		
Constituent	501F DLN	FlameSheet™
CH4 (min)	90%	40%
H2 (max)	0%	40%
C2 (max)	5%	40%
C3 (max)	2.5%	20%
C4 – C6 (max)	0.5%	10%

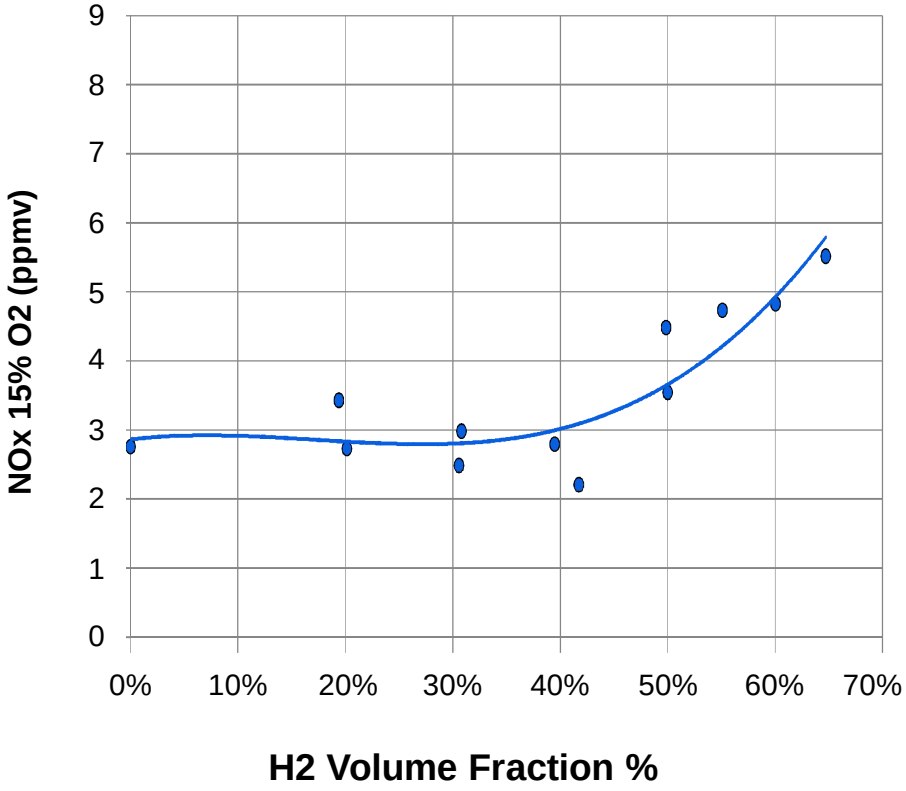
- Ability to operate with a variation in Modified Wobbe Index (MWI) of up to 30%
- Insensitive to fuel temperature



80% hydrogen operation

Hydrogen Blending

- Demonstrated capability to run with *65% blended hydrogen by volume* at baseload, and more recently up to 80%

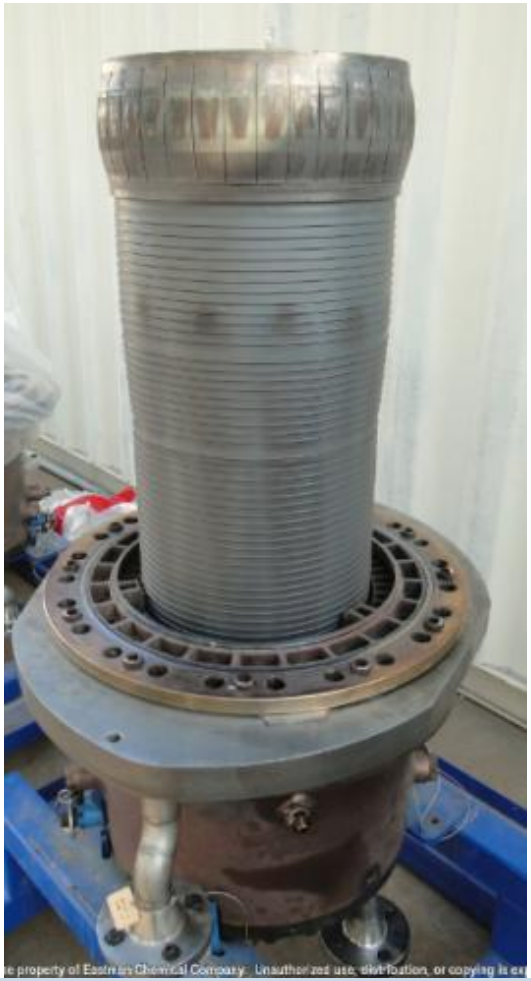


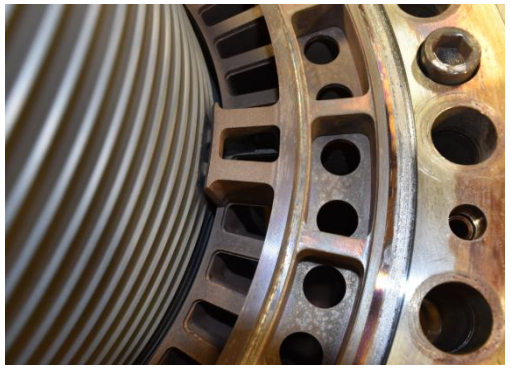
Robust operation at all fuel temperatures and over a wide range of fuel constituents

Engine Hardware Inspection

Engine Validation – Scheduled Major October 2017

- 16,300+ operating hours with 50+ starts (fleet leader continues at 30,000+ hrs)

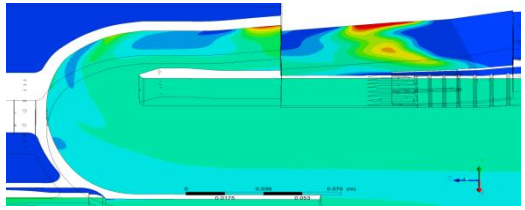


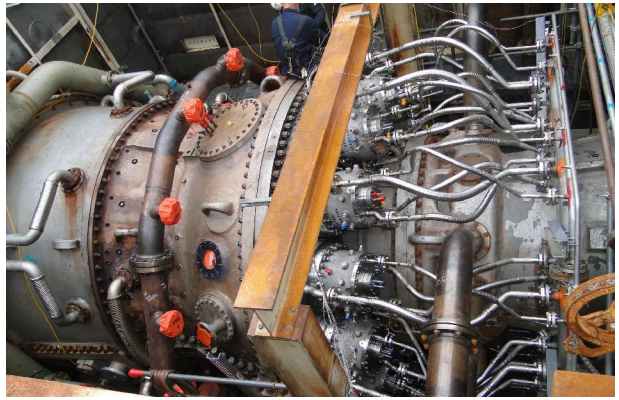


Combustion Hardware in Excellent Condition Verifying 32,000 Hour Interval

FlameSheet™ Hydrogen
Ongoing Development Roadmap

- Using *advanced analytical techniques* to demonstrate 100% hydrogen capability
- Initiate atmospheric rig tests to show *further improvement* from the already demonstrated 80% hydrogen to achieve the 100% hydrogen goal, *with no diluent*
- Complete high pressure (full-scale conditions) to verify robust 100% hydrogen operation
- Perform engine demonstrator, with combustor retrofit on existing E- or F-class machine, with fuel-switching from 100% natural gas to 100% hydrogen





Development toward 100% hydrogen flexibility

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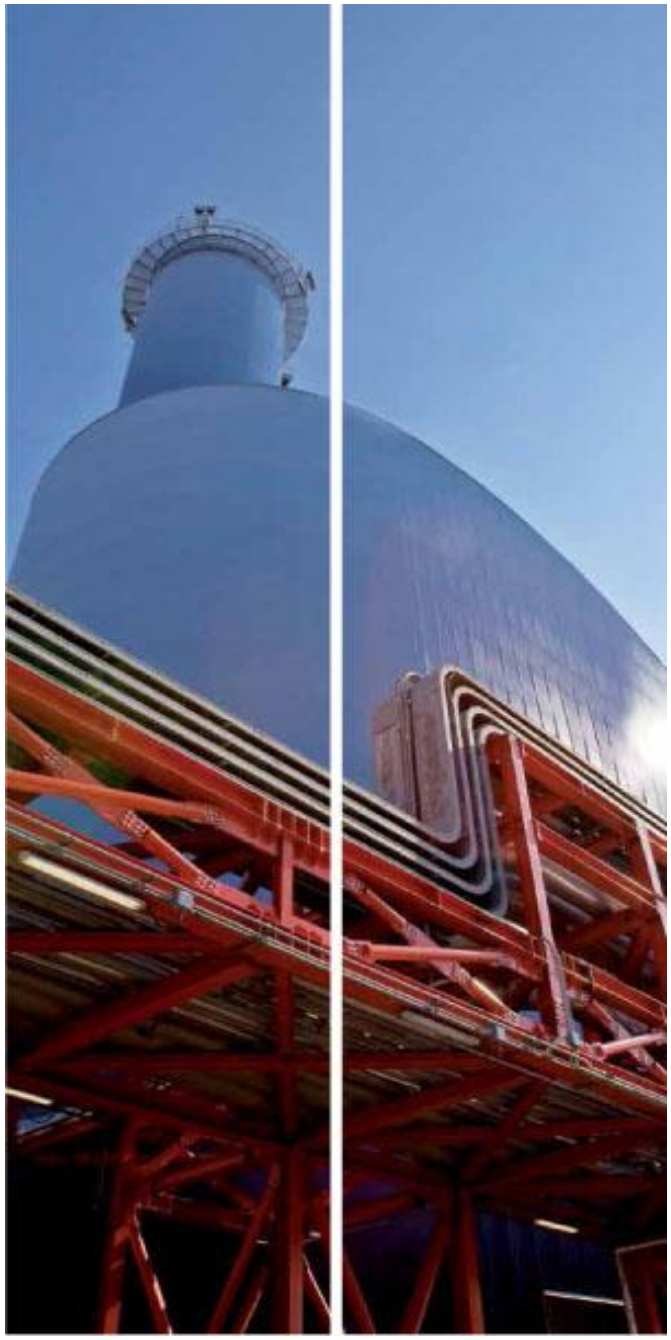
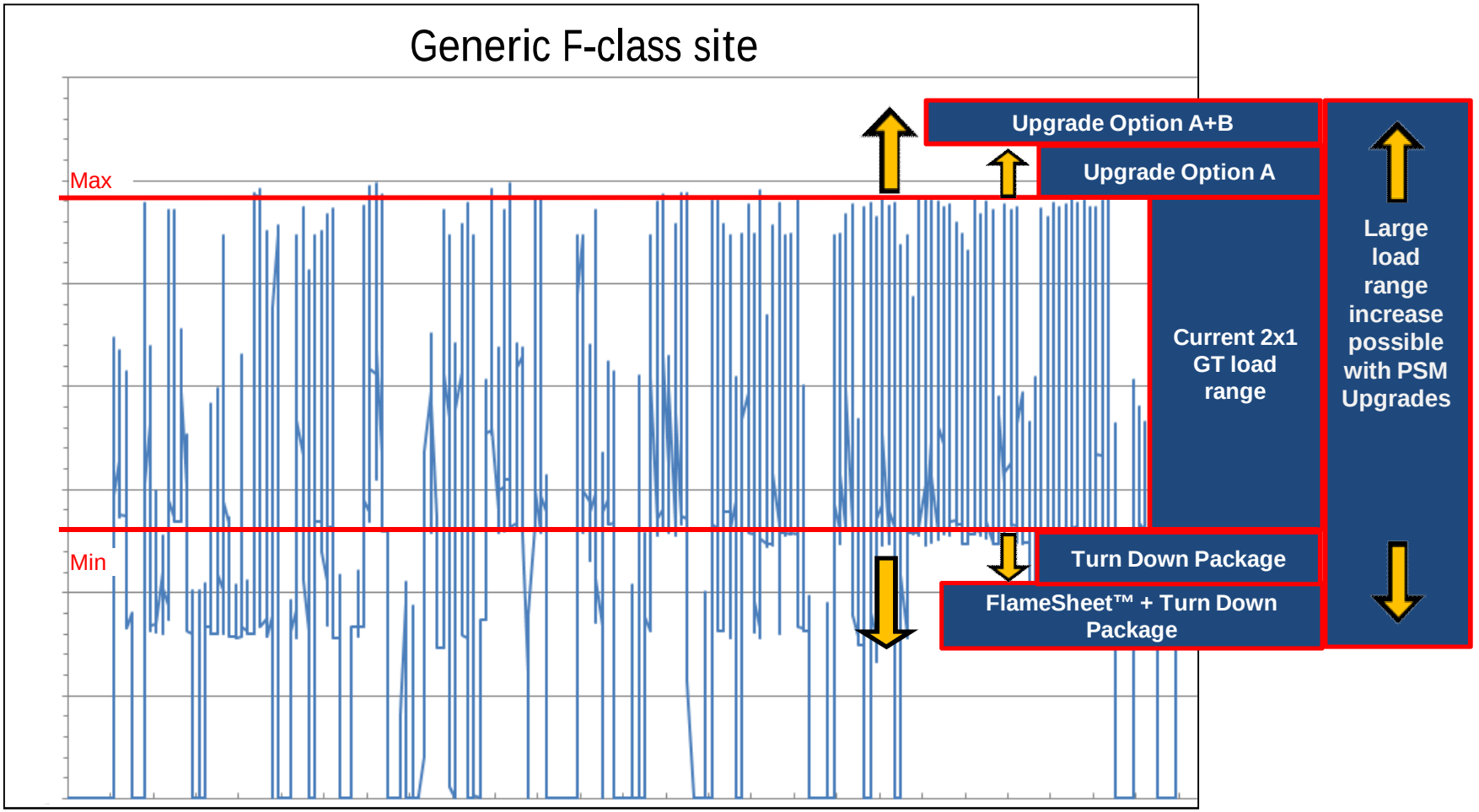


Market Based Solutions for GT Flexibility



Significant Increase in Spinning Reserve of Installed Assets Possible

Conclusions

- Gas turbines have ultimate flexibility … BUT they must be relevant for the market they serve
- Existing gas turbine power plants have unique abilities to provide support critical to the renewable grid … they just need to be re-configured to support this new goal
- Gas turbines must be cost effectively re-packaged for the demands of a renewable market place
- Renewable Retrofit Solution considers not just the gas turbine but also all the accessory equipment, including steam cycle where applicable
- Hydrogen can be an effective energy storage media
- A combustion system upgrade for flexible synthetic/hydrogen fuel operation enables existing power plants to become part of the energy storage solution
- Proven **AutoTune** and **LEC/FlameSheet™** systems provide path to fuel flexible retrofit solution for all frame machines