October 2015

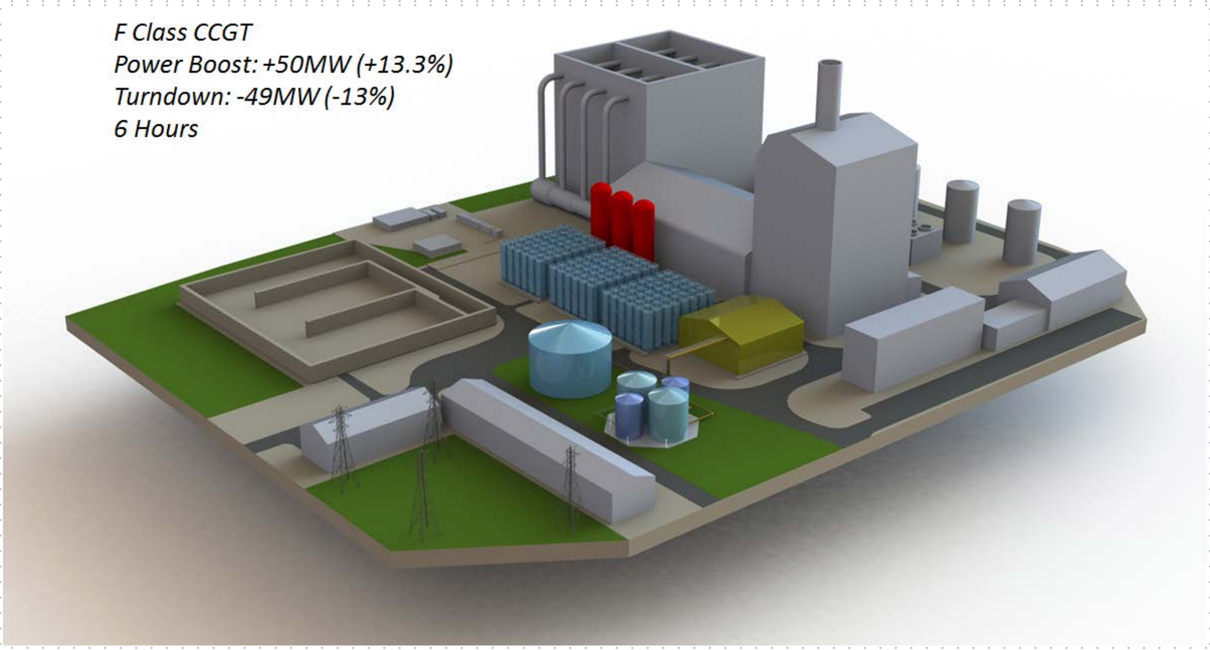
TECHNICAL REVIEW OF INNOVATIVE GTI-STORAGE SYSTEM

(GAS TURBINE INTEGRATED STORAGE)

Isentropic

3514295A

Final



Technical Review of Innovative GTI-Storage System

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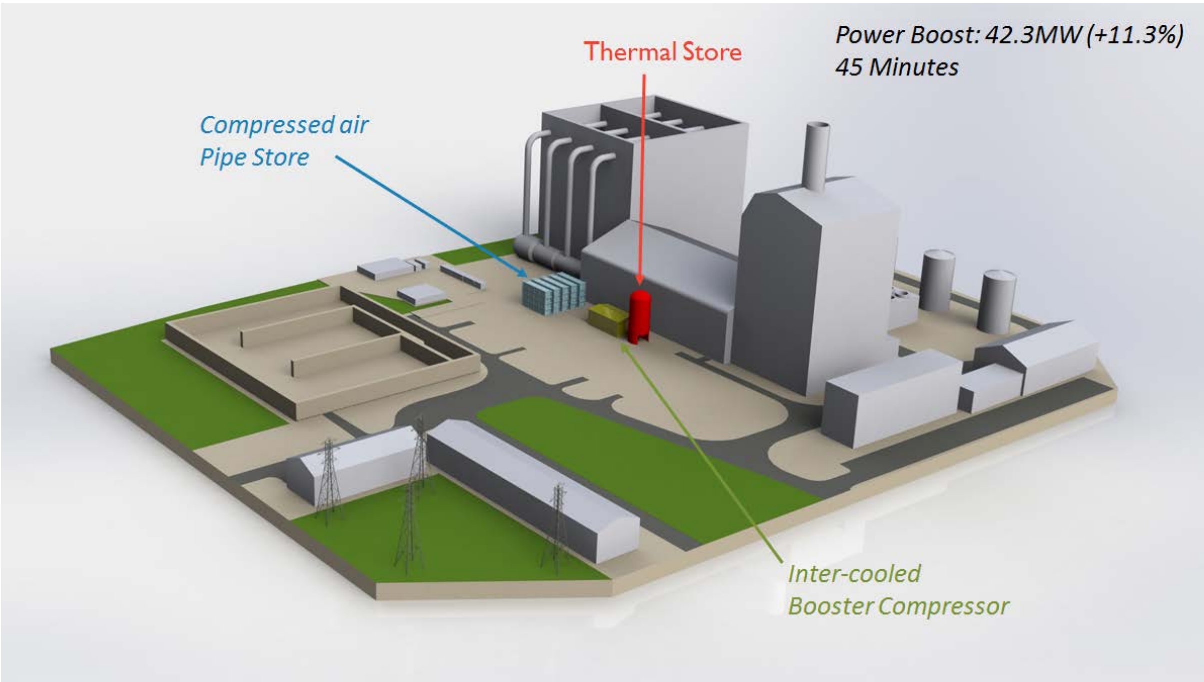
EXECUTIVE SUMMARY

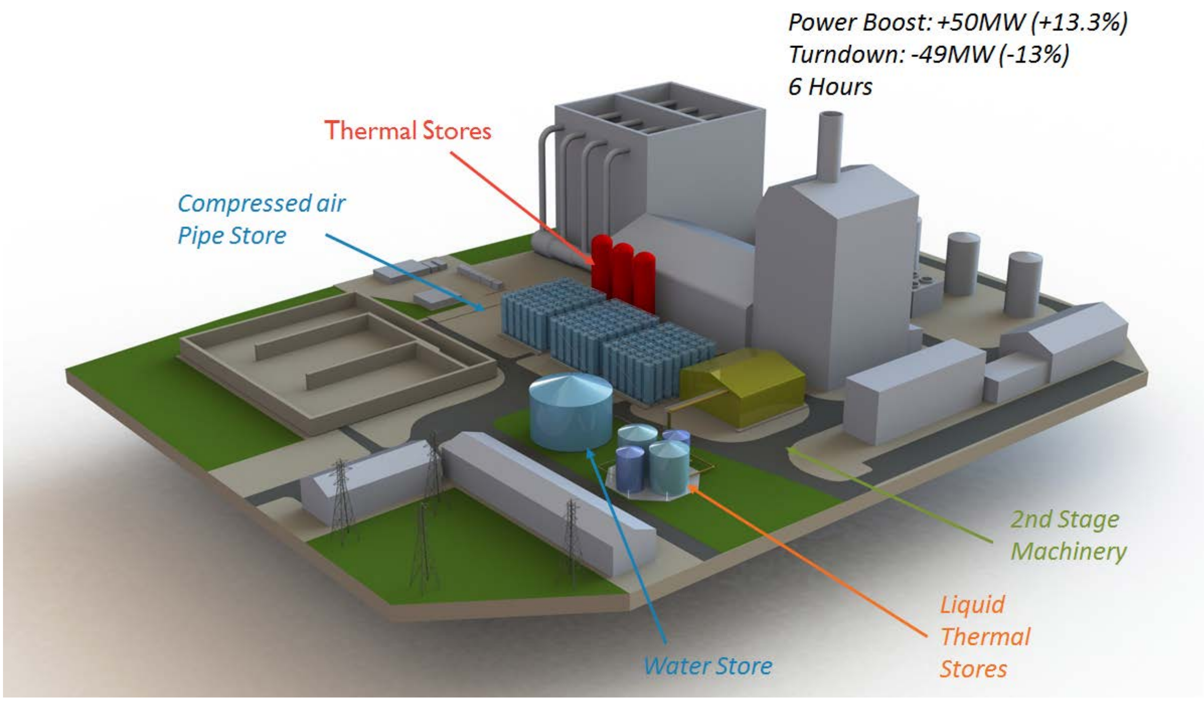
Isentropic Ltd. has developed a compressed air energy storage system intended to address the operational issues of existing and new build Combined Cycle Gas Turbines (CCGT), by allowing for faster ramping, greater turndown, and shifting of power from periods of low profitability to periods of high profitability. The system patented by Isentropic is based on the process of extraction, storage and subsequent reinjection of hot compressed air back into the gas turbine in a CCGT power plant. Air extraction and air injection has been done in gas turbine plants in the past and this system utilises this process, but with the addition of thermal storage.

Parsons Brinckerhoff was asked to develop a basic thermodynamic model to evaluate the performance of a CCGT plant incorporating the Isentropic GTI-Storage systems and to provide cost estimates for each system. Three system cases were identified, incorporated into a single shaft CCGT plant: *Rapid Response System*, *Standard Turndown System* and *Enhanced Turndown System*. These systems are assessed in detail in this report and a summary of their main benefits and operational characteristics are provided below.

Preliminary rendered drawings of the Rapid Response System and Enhanced Turndown System as it may be located on a CCGT power station site are shown in the diagrams below.



Isentropic Rapid Response GTI-Storage System



Isentropic Enhanced Turndown GTI-Storage System

System description

The Isentropic GTI-Storage system includes the following components:

- Combined cycle gas turbine (new or existing)
- Heat stores (in particular, the patented Isentropic thermal energy store)
- A pressurised steel pipe store designed to store compressed air at high pressure[1]

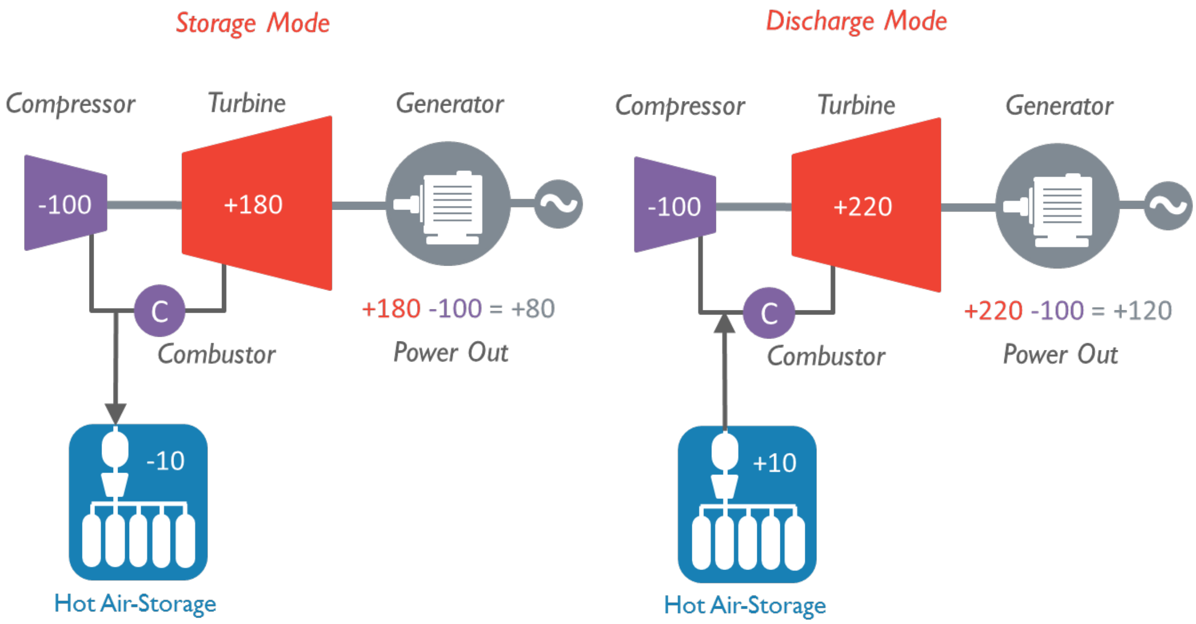
The system is located alongside an existing or new build CCGT and connects to a gas turbine via a port. The system charges by extracting hot compressed air from between the compressor and the combustor and stores the energy as heat and pressurised air. When the system is discharged or “boosted”, the compressed air is released, reheated by passing it through the thermal stores and injected before the gas turbine combustor increasing the gas turbine output and efficiency.

When compressor air is bled from the GT (charging mode), the output of the gas turbine falls, reducing the amount of power the CCGT produces. Conversely, when compressor air is injected back in (discharge mode), turbine output and efficiency increases. This is shown in the diagram below.

The diagram illustrates that if 10% of the compressor power is used to power the storage system, the plant power output drops by 20%. Similarly, if 10% of the compressor power is fed back from storage, the plant power will increase by 20%. The effect of integrated storage is therefore to amplify the storage system power swing. In this simplistic example, the amplification factor is 2. In a real-world CCGT,

[1] Additional compressors and expanders are utilised in some variants of the system (i.e. Standard and Enhanced Turndown).

the factor is in the region of 1.86. This effect reduces the cost of the storage system (both per kWh and per kW).



Source: Isentropic Ltd.

System benefits

The benefits of the GTI-Storage system include:

- The system has low capital cost compared to other storage systems due to utilisation of the existing gas turbine compressor and turbine to produce the majority of the system work.
- The system can boost CCGT output by over 10% within 5 seconds, making it capable of providing fast frequency support to national electrical network operators.
- The increase in power output can be in addition to normal CCGT maximum power. As such, the CCGT can operate at 100% of rated capacity while providing frequency support. This is in contrast to conventional plants that must operate at approximately 90% CCGT rated output to provide additional capacity for frequency response.
- Increased plant operating range for new and existing CCGTs. For example, the installation of a small GTI-Storage system could increase the operating range of a CCGT from 50-100% to 40-115% of rated capacity with minimal additional maintenance. Further reductions in plant output may be possible with increased compressor bleeding subject to gas turbine design.
- Reduction in mid-merit gas turbine plant maintenance and start/up costs by avoiding the need to shut down the gas turbine during periods of negative spark spreads.
- Reduces gas turbine degradation in mid-merit gas plants by reducing the associated EOH penalty from stopping and starting the gas turbine. This

prolongs the duration between major maintenance overhauls (in line with OEM requirements) compared to a plant with frequent start-stops.

- Enables shifting of power from periods of negative spark spread to periods of positive spark spreads.
- High system efficiency compared to other storage systems such that other storage systems cannot achieve the efficiency of the GTI-storage system when operated at optimal conditions.
- All system components except the Isentropic TES are commercially available or based on existing technology which would require limited engineering development, reducing the technical risk.
- Ease of expansion – a small GTI-Storage system can be installed initially to reduce upfront capital cost and then expanded later to defer costs, while using original common equipment such as piping and turbomachinery.
- 20 year life. As the system utilises turbomachinery and mechanical components, the design life for the system is expected to be 20 years with proper maintenance and operation of the system.
- High number of cycles over the system's life. With robust turbomachinery selection and proper maintenance, components can be fully cycled at minimum twice per day with low impact.
- Ability for part charge / discharge. Due to the mechanical nature of the system, the system can be charged and discharged to partial capacity as required.
- Potentially short turbine downtime during installation. The storage system can be installed before connection to the gas turbine, reducing the GT down time.
- Minimal degradation. With proper maintenance and operation (e.g. ensuring clean air is passed through the system to prevent fouling and corrosion), degradation of the system from common wear and tear mechanisms can be low compared to plants with a daily stop-start cycle.

Operational performance

The three Isentropic GTI-Storage systems can broadly be broken down into two operational categories:

- Rapid Response system – designed purely to provide a rapid (<5 seconds) increase in power output and targeted at providing frequency support.

  The system is designed to achieve rapid power increase above 100% nominal output (additional 11% for an 8% injection rate). This is in contrast to conventional plants which are typically despatched at approximately 90% CCGT load in order to provide the same level of frequency support. Operation at 90% CCGT load reduces both the power output and efficiency from these plants.

- Turndown systems – designed to allow plant operators to shift generation from periods of negative spark spread to periods of positive spark spread and to avoid the cost penalties associated with switching off a gas turbine.

  Rather than switching off the gas turbine during periods of negative spark spreads, the CCGT can instead be dropped below normal minimum load, minimising losses in power sales and allowing energy to be stored for use in periods of high spark spreads.

The Isentropic GTI-Storage systems provide operational benefits because gas turbines incur significant “equivalent operating hours” (EOH) penalties each time the engine is switched off and started or operated in a load following duty that involves fast load changes accompanied by rapid temperature changes. This results in higher maintenance costs (via long term service agreements) and reduces the duration between major maintenance overhauls.

It is noted that the benefit of reduced EOH depends on the operating regime against which the comparison is made e.g. the benefit is limited against a plant operating continuously as baseload.

Quantifying the economic cost of additional maintenance (or replacement) as a result of a start is difficult to do with reasonable accuracy and Parsons Brinckerhoff is not aware of any industry norms for such costs. In fact, because of the difficulty in making good estimates of the costs, the true values are often not fully appreciated by the plant operators. Estimates[2], where they have been made, vary widely from USD 15,000[3] at the low end to ten times that value at the upper end.

Nevertheless, reasonable estimates of lower bound start-up costs[4] (2012) for a combined cycle plant have been reported in the range of 32-93 USD / MW (20-60 GBP / MW). For a 400MW plant this is equivalent to 8,000 – 24,000 GBP (11,852 – 35,556 USD) per start. This is consistent with the basic calculation Parsons Brinckerhoff has made for CCGT costs but which excludes BOP (steam cycle) and other costs such as degradation and plant replacement.

The upper bound of start costs is harder to determine independently and to some extent depends on the view of the operator as to what is included and what can be measured. Intertek (2012) suggests an upper bound of $150,000[3] per start. The upper bound values are by definition, the upper extreme values and cannot be representative of the costs experienced by the majority of operating plants. Nevertheless, it is reasonable to assume that in many cases, the cost of a start will be higher than the lower bound values.

The impact on turbine degradation (capacity and heat rate) with EOH is shown in the diagram below. As shown by the diagram, reducing EOH from a stop/start reduces degradation and prolongs the duration between major overhauls and increasing utilisation.

The “baseload” data series below is taken from the KEMA report. It assumes that a baseload plant operates 8,300 hours per annum and reaches its 100,000 EOH limit (in this case it runs for 100,000 hours) under its maintenance contract in 12 years. Over the period, the plant’s output capacity reduces by 3.8% and its Heat Rate increases by 2.11%. 100,000 hours would normally represent the end of the first Long Term Service Agreement (LTSA) for a new build CCGT. At this point a life time extension would usually be planned, resetting aging and fouling to “as new” values through extensive maintenance. This resetting to “as new” values is based on the assumption that better performing parts will be available at this time as replacements, offsetting degradation in other areas of the plant. These improved upgrades are

[2] The Increased Cost of Cycling Operations at Combined Cycle Power Plants
Intertek APTECH Sunnyvale, CA USA Nov2012

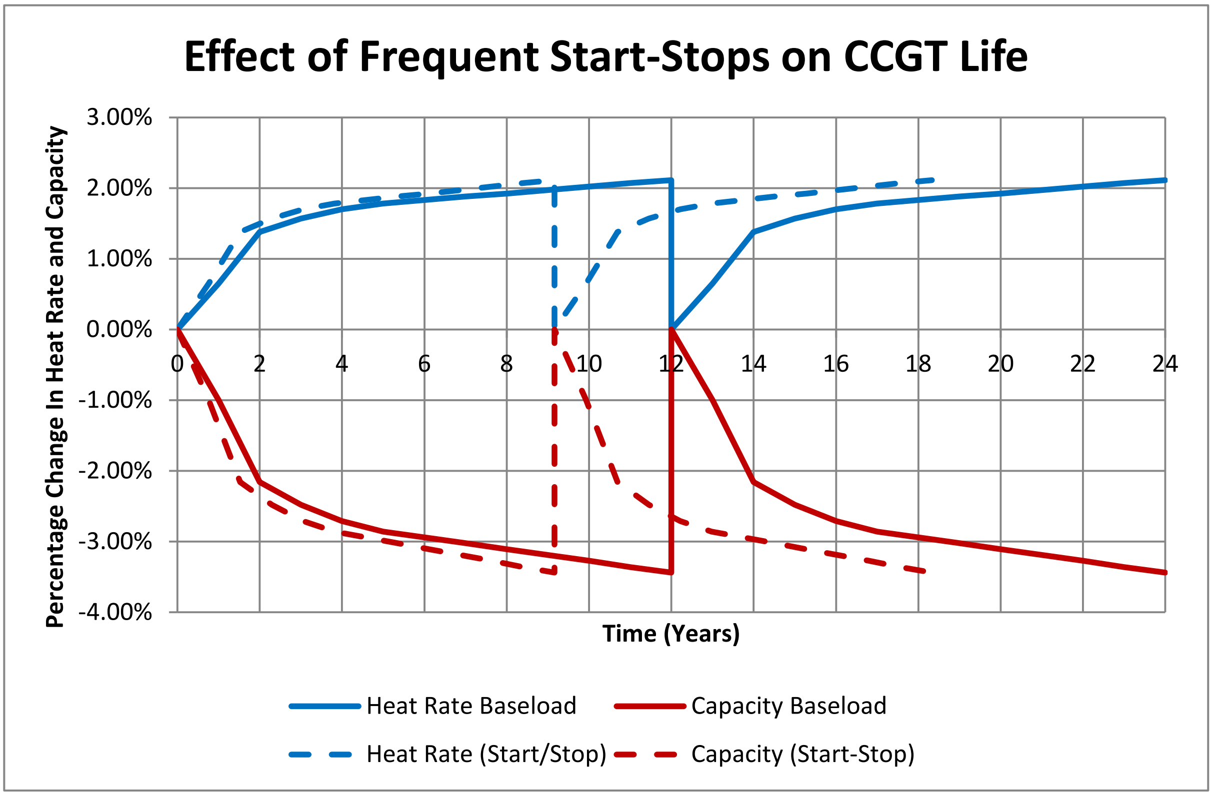
[3] Based on 2011 costs

[4] Power Plant Cycling Costs, Intertek APTECHSunnyvale, California April 2012

expected to have better performance than the original parts as they follow in the wake of evolving gas turbine technology.

The second data set "start/stop" assumes the same CCGT, but instead of operating as baseload the power plant starts up and shuts down 5 times per week, in order to avoid generating in loss making periods. The plant is assumed to operate for 18 hours per day when operating, with an EOH per start of 20, which is typical in industry maintenance contracts for a gas turbine start. The plant generates for 4,680 hours per annum, and incurs total EOH penalty of 5,200 hours per annum due to switching a turbine on and off. As such, it has a greater degradation rate than the baseload plant as total annual EOH (4680 + 5200) is equal to around 10,000 per annum in contrast to 8,300 for the baseload plant.

As a result of being switched off, the turbine degrades faster and the first major overhaul is required in year 9 as opposed to year 12. The plant also generates over 40% less output over its 10 year life, however, it does not generate during periods of loss making power prices.



Source: Reproduced from KEMA Ltd / Energy Market Authority (2008)[5]

Modelling output

[5] KEMA Limited / Energy Market Authority Singapore (2008) *Review of the LRMC costs of CCGT electricity generation in Singapore to establish the technical parameters for setting the Vesting Price for the period 1 January 2009 to 31 December 2010*

The performance of a CCGT plant with an Isentropic GTI-Storage system installed as estimated from Parsons Brinckerhoff's modelling is shown in the below tables. These values are for new and clean systems i.e. does not account for degradation.

The following is noted in regards to the below tables:

- The Rapid Response System is operated with a CCGT operating at 100% load however for comparison, an equivalent CCGT operating in frequency response mode would typically be operating at approximately 90% load.
- The Turndown Systems are operated such that bleed mode (charge) occurs at minimum CCGT load and injection mode occurs at maximum CCGT load. These loads are assumed to be 52% (gas turbine at 40%) and 100% of a standalone CCGT.

			Bleed Mode (25 kg/s)	Injection Mode (50 kg/s)	CCGT Frequency Response (85% GT load)	CCGT 100% load (No bleed, No injection)
Rapid Response	GT Gross Output	kW	229,364	291,974	215,780	252,665
	GT Gross Heat Rate	kJ/kWh	10,289	8,931	10,252	9,697
	ST Gross Output	kW	127,448	133,688	126,968	130,288
	CCGT Net Output	kW	341,554	415,969	333,463	373,704
	Output as percentage of rated (CCGT)	%	91.4%	111.3%	89.2%	100%
	CCGT Net Heat Rate	kJ/kWh	6,849	6,208	6,624	6,556
	Weighted Average CCGT Heat Rate	kJ/kWh	6,606		6,624	6,556

			Bleed Mode (50 kg/s)	Injection Mode (50 kg/s)	CCGT part load (40% GT load)	CCGT 100% load (No bleed, No injection)
Standard Turndown	GT Gross Output	kW	89,238	291,597	102,624	252,665
	GT Gross Heat Rate	kJ/kWh	14,450	8,831	13,738	9,697
	ST Gross Output	kW	89,971	133,486	100,289	130,288
	CCGT Net Output	kW	147,743	415,394	195,475	373,704
	Output as percentage of rated (CCGT)	%	39.5%	111.2%	52.3%	100%
	CCGT Net Heat Rate	kJ/kWh	8,690	6,139	7,213	6,556
	Weighted Average CCGT Heat Rate	kJ/kWh	6,808		6,780	

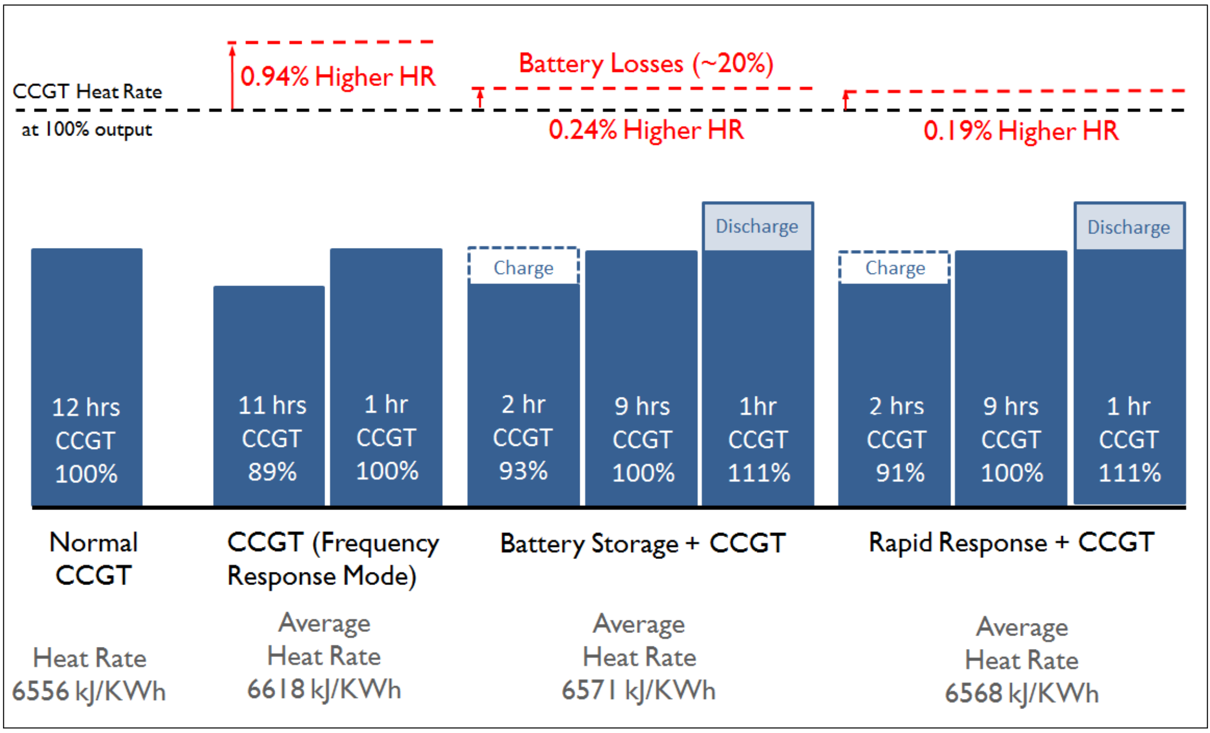
			Bleed Mode	Injection Mode	CCGT part load	CCGT 100% load

			(50 kg/s)	(50 kg/s)	(40% GT load)	(No bleed, No injection)
Enhanced Turndown	GT Gross Output	kW	89,238	291,597	102,624	252,665
	GT Gross Heat Rate	kJ/kWh	14,450	8,831	13,738	9,697
	ST Gross Output	kW	89,971	133,486	100,289	130,288
	CCGT Net Output	kW	146,626	423,433	195,475	373,704
	Output as percentage of rated (CCGT)	%	39.2%	113.3%	52.3%	100%
	CCGT Net Heat Rate	kJ/kWh	8,709	6,022	7,213	6,556
	Weighted Average CCGT Heat Rate	kJ/kWh	6,713		6,780	

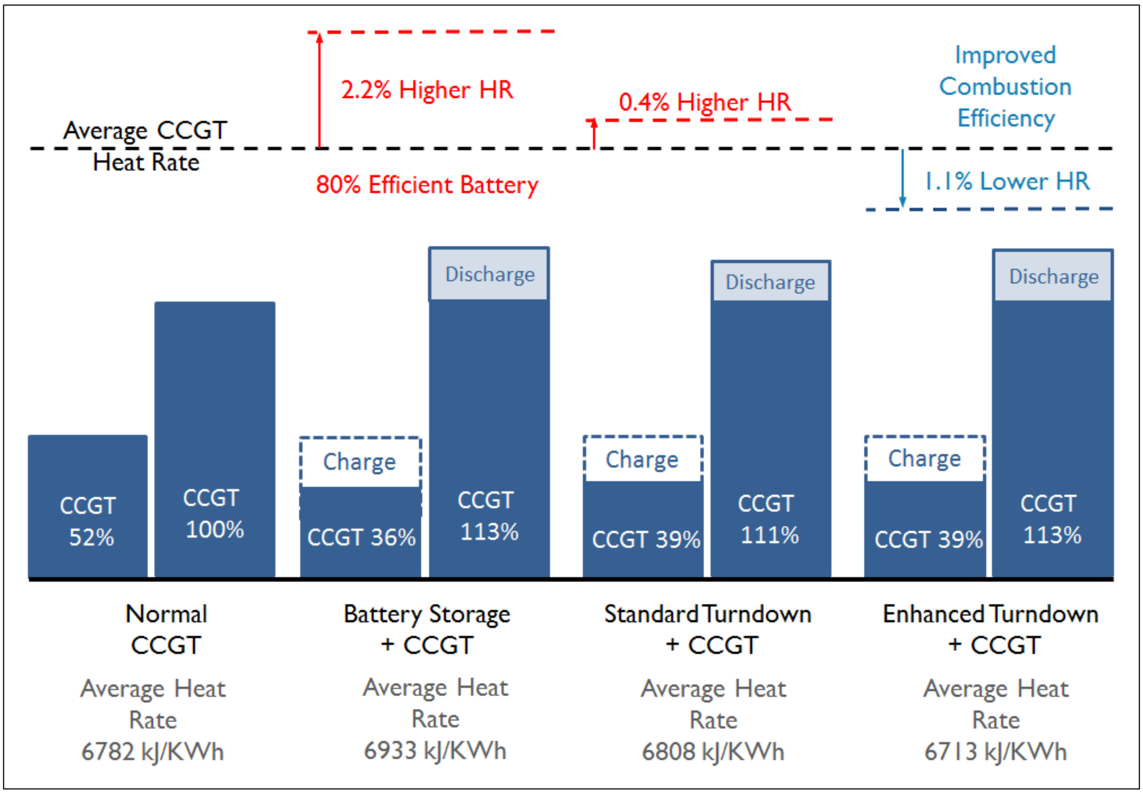
System efficiency

The three variants of the Isentropic system (denoted Rapid Response, Standard Turndown and Enhanced Turndown) can be regarded as analogous to a battery storage system placed adjacent to an existing power station in terms of its storage capability. Due to the fact that the re-injection of hot compressed air into the gas turbine while discharging the storage system boosts overall turbine efficiency, the heat rate of the gas turbine may be improved.

To evaluate the performance efficiency of the GTI-Storage system, the heat rate of a CCGT with a GTI-Storage system is compared to the heat rate of a CCGT with a battery storage system. The results of the comparison are shown in the diagram below. The heat rates of the GTI-Storage system are as per Section 5.1 with the efficiency of a battery storage system assumed to be 80%. Full calculations are shown in Appendix A.



Rapid Response System heat rate comparison



Turndown Systems heat rate comparison

The first diagram (Rapid Response comparison) shows the heat rate of a CCGT with a Rapid Response GTI-Storage system compared with both a CCGT operating in frequency response mode and a CCGT with a battery storage system incorporated to provide storage, and the ability to provide frequency response services. In frequency response, the CCGT plant integrated with the storage systems is operated at 100% rated capacity. This represents the baseline. The heat rate is weighted as per an assumed operation cycle of 2 hours charge, 9 hours store and 1 hour discharge. The figure shows that compared to the baseline CCGT heat rate of 6,556 kJ/kWh, the heat rate with a Rapid Response GTI-Storage system is 0.19% higher, the CCGT in frequency response mode is 0.94% higher and the heat rate with a battery storage system is 0.24% higher. This shows that integration with a GTI-storage system is a more efficient way of providing frequency response services than either a battery storage system or a CCGT in frequency response mode. It is noted that the weighted average heat rate for each configuration is dependent on the storage duration. It is assumed in this report that the duration is 9 hours as a likely operating regime of a CCGT plant with storage to meet frequency response. With shorter storage duration, the CCGT operates at shorter periods over a complete cycle at 100% rated output and the heat rate for a plant incorporated with a storage system increases i.e. becomes less efficient.

The second diagram (Turndown System comparison) shows the heat rate of a CCGT with the Turndown GTI-Storage systems compared to a CCGT with a battery storage system. These storage systems are designed to enhance the turndown capability of the CCGT and thus the baseline operation is a CCGT operating at 52% rated capacity for 1 hour (during charge) and 100% rated capacity for 1 hour (during discharge). The figure shows that compared to the average CCGT heat rate of 6,782 kJ/kWh, the heat rate with a battery storage system is 2.2% higher compared to 0.4% higher with a Standard Turndown System and 1.1% lower with an Enhanced Turndown System. This shows that incorporation of the Turndown Systems is much more efficient than with a battery storage system.

Incorporating a state of the art battery storage system would likely be required in order to match the Rapid Response and Standard Turndown systems. As it is impossible for a battery storage system to exceed 100% efficiency, a battery storage system cannot match the performance improvement delivered by the Enhanced Turndown.

Speed of response

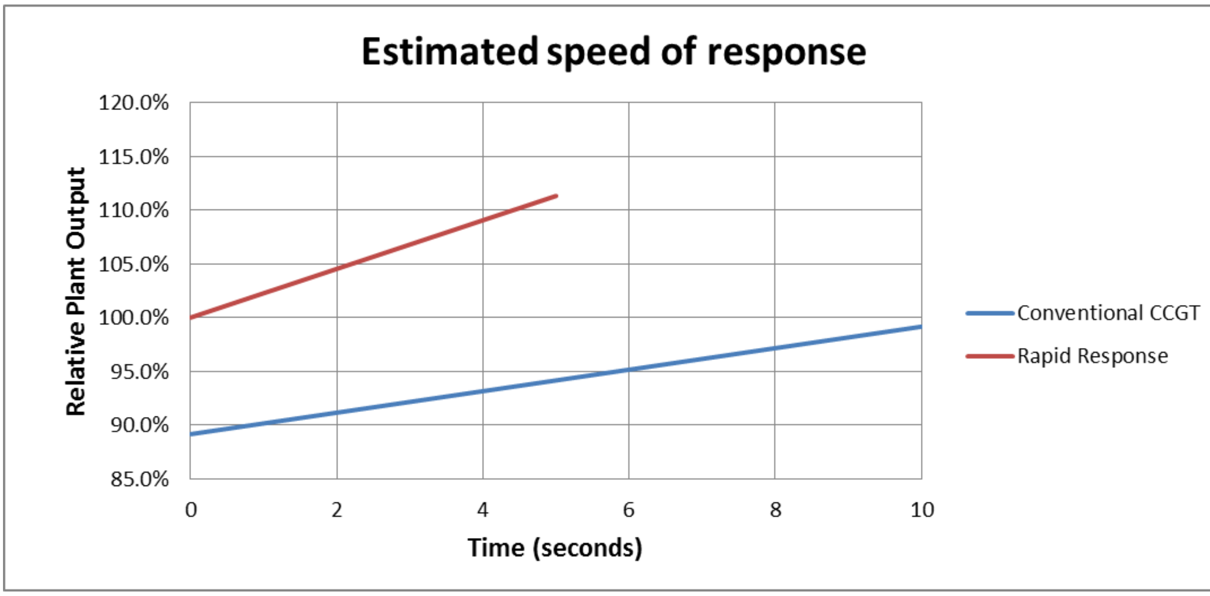
For the proposed cases, rapid load increases could be obtained through a combination of IGV operation and air injection. In the case of the Enhanced Turndown system, there will also be the benefit of the power contribution from the high-pressure expanders.

The ability to provide grid frequency support is a requirement of national network operators for all large generating units. This system is beneficial in that respect as it is able to offer a considerable rapid power increase above the nominal 100% output of the CCGT, thereby offering frequency support from the starting point of base load operation. This is in contrast to conventional plant which has to be despatched at a part load condition less than 100% in order to provide frequency support (usually approximately 90% of CCGT to provide an equivalent level of standby frequency support).

Current CCGT's provide frequency response by increasing the flow rate through the combustors via opening/closing the compressor IGV's. Opening/closing the IGV's in this fashion increases the flow rate through the combustor by approximately 10 kg/s^2, until 100 kg/s of additional mass flow is achieved, boosting CCGT output to 100% from approximately 90% within 10 seconds.

The Isentropic Rapid Response system will increase the mass flow through the combustors by 50 kg/s (half the normal frequency response level) while still providing an approximate 11% increase in CCGT power output. As such, using the same flow rate as normal IGV operation of 10 kg/s^2, full response from the CCGT is achieved within 5 seconds. On this basis Parsons Brinckerhoff would expect the Rapid Response system to be capable of increasing output by over 10% in less than 5 seconds without inducing combustion instability.

The following chart compares the response of the Rapid Response system and a conventional CCGT providing primary response.



Emission risks

A major issue for all CCGTs is the need to comply with environmental regulations. Generally, nitrous oxide (NOx) emissions increase as the turbine inlet temperature (TIT) increases and carbon monoxide (CO) emissions rise as the TIT falls. Original equipment manufacturers (OEMs) have designed gas turbines such that operation of the gas turbine between a specific range will ensure compliance to common emission standards. Operation outside this range will likely exceed these limits and is at the operator's risk.

CO_2 emissions per kW are directly proportional to plant efficiency. An increase in the amount of useful energy extracted for a given quantity of fuel will lower the amount of CO_2 per kW. For CCGTs integrated with the Isentropic GTI-Storage systems, there is insignificant variation in thermodynamic efficiency compared to stand alone CCGTs operating in similar modes. As such, the CO_2 emissions are not expected to be altered with the integration of an Isentropic GTI-Storage system.

A general assessment of the impacts of Isentropic's storage system on the plant emissions raised no concerns for the following reasons:

- Generally the systems are expected to operate within adequate operational margins and consequently NOx emission is not considered a significant risk.
- Rapid Response System: there are no major concerns over emission levels because plant operations are maintained within the permissible operational range for emissions and the TIT is unlikely to be increased or reduced during discharge or injection.
- Turndown Systems: during charge mode, the gas turbine operates at or above the OEM specified lowest TIT. A general value used to define the load limit is 40% of maximum rated gas turbine load without bleeding or injection. Isentropic intends to operate at or above the TIT limit to comply with emissions regulation and hence, CO emissions are not a concern.

  During boost, it is expected that the TIT is maintained at a constant level which requires an increase in fuel consumption. This increase may require the installation of fuel nozzles with sufficient capacity to supply the desired amount of fuel.

Surge and turbine constraints consideration

Changes to the compressor pressure ratio and the flow rates as envisaged by each system case require careful consideration of the effect on the surge margins. Surge in axial compressors occurs when the discharge flow rate does not match the operating pressure ratio and it can be physically damaging to the compressor when it occurs. The occurrence of surge in modern gas turbines is rare because of the surge margin designed into the compressors and the presence of active controls to supress surge (compressor blow-off valves).

Although the systems are based broadly on the re-use of existing gas turbine designs and connection ports (where possible), some changes to the details of the gas turbine components may need to be made in collaboration with the OEM for the reasons outlined above. The changes are not considered to be technically insurmountable and will depend on the particular gas turbine and its age but will nevertheless require development and testing effort by the OEMs.

Cost estimate

The capital cost per kW for the Rapid Response system is significantly less than the Turndown systems: $402/kW compared to $1,707/kW and $1,787/kW for a First of a Kind (FOAK) system respectively. The cost for the Rapid Response system may fall to $203-$303/kW for an Nth of a Kind (NOAK) system depending on the system size installed. The lower capital cost is primarily due to the shorter output duration of the Rapid Response System compared to the Turndown Systems.

The longer duration of discharge for the Turndown systems means that the capital cost is higher but the cost ($/kWh) per unit of energy stored is lower. The FOAK estimate for the Turndown Systems is approximately $285/kWh and $298/kWh compared to $536/kWh for the Rapid Response System. The NOAK cost for the Turndown system may fall to around $153/kWh to $200/kWh. If these costs are realised, they would likely be significantly lower than the cost of a battery storage system, while also providing additional operational benefits.

The derived cost estimates are shown in the tables below. The 50 kg/s injection cases is for a system integrating into a circa 373 MW CCGT while the 150 kg/s case is for a circa 1,122 MW CCGT.

Rapid Response	50 kg/s Injection 374 MW CCGT		150 kg/s Injection 1122 MW CCGT
	FOAK	NOAK	NOAK
Capital cost (MM USD)	**17**	**13**	**26**
Incremental net power (kW)	42,265	42,265	126,795
Injection duration (hr)	0.75	0.75	0.75
Incremental energy (kWh)	31,699	31,699	95,096
Capital cost $ / kW	**402**	**303**	**203**
Capital cost $ / kWh	**536**	**404**	**270**

Standard Turndown	50 kg/s Injection	150 kg/s Injection

	FOAK	NOAK	NOAK
Capital cost (MM USD)	**71**	**43**	**115**
Incremental net power (kW)	41,690	41,690	125,070
Injection duration (hr)	6	6	6
Incremental energy (kWh)	250,140	250,140	750,420
Capital cost $ / kW	**1,707**	**1,029**	**918**
Capital cost $ / kWh	**285**	**171**	**153**

Enhanced Turndown	50 kg/s Injection		150 kg/s Injection
	FOAK	NOAK	NOAK
Capital cost (MM USD)	**89**	**60**	**163**
Incremental net power (kW)	49,729	49,729	149,187
Injection duration (hr)	6	6	6
Incremental energy (kWh)	298,374	298,374	895,122
Capital cost $ / kW	**1,787**	**1,199**	**1,093**
Capital cost $ / kWh	**298**	**200**	**182**

Comparison costs with batteries are shown below

The tables below show a comparison of GTI-Storage with other forms of storage systems. The tables are derived from GTI-storage information from this report and information for other storage systems from Purdue University[6] and DOE/EPRI (US)[7]. A detailed comparison of the different storage systems are outside the scope of this review. As such, Parsons Brinckerhoff has not independently validated the values from the quoted sources but confirms that the values are as listed in the Purdue report and/or in line with the range of values provided in the DOE/EPRI report.

Power Management Storage Systems

Technology	GTI-Storage Rapid Response	Combined Cycle Gas Turbine	Open Cycle Gas Turbine	Flywheels	Advanced Lead Acid Battery	Lithium Ion Battery
Total Cost $/kW*	203 - 402	700 - 900	500 - 700	1,950 – 2,200	950 – 1,590	1,085 – 1,550
Cost $/kWh*	270 - 536			7,800 – 8,800	2,770 – 3,800	4,340 – 6,200
Typical Installation Power (MW)	50 - 150	500	100	20	1 - 100	1 - 100
Duration	45 min	24/7	24/7	15 min	15 min to 1 hour	15 min to 1 hour
Lifetime (years)	20	25	25	20	<7	10

Energy Management Storage Systems

[6] Table 5.2 on Page 73 Utility Scale Energy Storage Systems (State Utility Forecasting Group – Purdue University 2013) http://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf

[7] DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA (produced by Sandia July 2013) http://www.sandia.gov/ess/publications/SAND2013-5131.pdf

Technology	GTI-Storage Standard Turndown	GTI-Storage Enhanced Turndown	Pumped Hydro (small)	Pumped Hydro (large)	CAES (under-ground)	Lithium Ion Battery	Vanadium Redox Battery
Total Cost $/kW*	918 – 1,707	1,093 – 1,787	2,500 – 4,300	1,500 – 2,700	950 – 1,590	4,420 – 4,981	3,335 – 3,734
Cost $/kWh*	153 - 285	182 - 298	420 – 430	250 – 270	60 – 125	996 – 1,105	747 – 834
Geographical Constraint	No	No	Yes	Yes	Yes	No	No
Typical Installation Power (MW)	50 - 150	50 – 150	280 – 530	900 – 1,400	135	1 – 10	10 – 50
Duration	6 hours	6 hours	6 – 10 hours	6 – 10 hours	8 – 20 hours	4 – 5	4 – 5
Lifetime (years)	20	20	40	40	20	15	15

*The costs ($/kW and $/kWh) are taken directly from the quoted sources. These are taken from a variety of sources and as such, different costs may have been included for each estimate e.g. green / brown field, utility connection, soft costs etc.

Summary of costs and performance

The Rapid Response system offers a low cost solution for CCGTs to provide frequency regulation without losing capacity or efficiency compared to current CCGT operation for frequency response. The capital cost of the Rapid Response System is low at $402/kW for a FOAK system and as low as $203-$303/kW for a NOAK system. Rapid Response allows a CCGT to respond quickly to system variations (potentially as fast as within 5s compared to 10s with inlet guide vanes). Injection of air into the gas turbine will increase the exhaust gas flow at the exit of the turbine but at a reduced temperature and subsequently these two opposite effects will likely keep the performance of the HRSG constant. Subsequently, steam production will be minimally affected meaning that integration of the GTI-Storage system into a CHP plant could be possible.

The Standard Turndown and Enhanced Turndown systems offer the ability to reduce the minimum power output and increase the maximum power output of a plant for long durations (hours). The systems are analogous to very high efficiency, low cost, long life battery storage systems placed next to the CCGT. The systems can reduce the effect of negative spark spreads and allow a plant to reduce the number of start/stop cycles. An additional benefit of the turndown systems is the reduction of Equivalent Operating Hours (EOH) associated with a start/stop. This reduces degradation in efficiency and capacity of the gas turbine and increases the time between maintenance overhauls by potentially three years (subject to LTSA).