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APPROVALS FOR THIS ISSUE

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HISTORY OF ISSUES / APPROVALS

REV	DATE	DESCRIPTION OF CHANGES	FILE NUMBER
1	21/07/22	Updated as per email from Liam Mcbrierty	1403-RG-0001-R1

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1.0 INTRODUCTION

In 2017, Fingleton White (FW) at the request of Gas Networks Ireland (GNI) carried out a feasibility study for the implementation of turboexpander technology on pressure reduction stations on the GNI Network. The feasibility study is detailed in *"1093-00-RG-0001-R1 Turboexpander Feasibility Report"*. The report found that the implementation of turboexpander technology would lead to operating cost and carbon emissions savings, however, the financial payback period was found to be prohibitive. For that reason, FW did not recommend the implementation of turboexpander technology on the GNI Network. Further study was recommended if one of the two below conditions were met to make the financial payback more appealing:

- The extra thermal load could be provided by waste heat from a host site
- The electricity generated is used by a host site to offset electricity imports

This report assesses the feasibility of coupling turboexpander technology with data centre sites. Data centres are large energy consumers in Ireland consuming 14% of metered electricity consumption in 2021, equating to 3,993 GWh (CSO 2022). Data centres also produce waste heat from cooling of servers and on-site electricity generation.

This report will determine required heat load and potential electrical power production capacity for a turboexpander coupled to an AGI located adjacent to a data centre, for a given range of gas pressures and flow rates. The following assumptions were made to facilitate the high-level analysis contained in this report including:

- The data centre's primary source of electrical power is from on-site gas fired generators. The gas requirement at a data centre is constant all year round.
- A suitable legal and technical arrangement can be found whereby the data centre operator can operate a turboexpander located at a GNI AGI facility.
- Gas inlet temperature to the AGI is 6°C and minimum outlet temperature is 2°C.

2.0 THEORY

The gas passing through the turboexpander is isentropically expanded resulting in a decrease in enthalpy. This ideal process is both adiabatic and reversible therefore the work done by the turboexpander is equivalent to the change in enthalpy. However, a decrease in enthalpy and pressure results in a decrease in gas temperature. To ensure the gas exit temperature does not drop below 2°C the gas is preheated before it enters the turboexpander. A basic equipment layout is shown in Figure 1. Point 1 represents the gas entering the site, point 2 represents heated gas after the preheater and before the turboexpander and point 3 represents the expanded gas after the turboexpander.

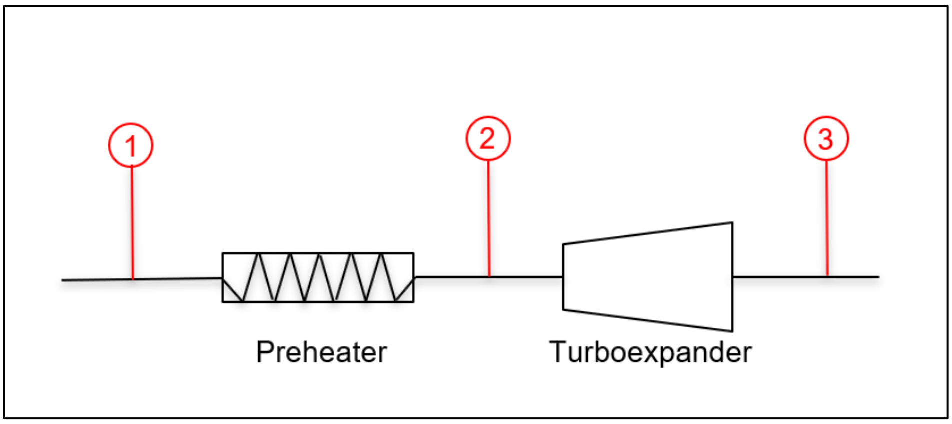

Figure 1 – Basis Turboexpander Equipment Layout Showing Preheater and Turboexpander

The composition of natural gas is variable and influences the performance of a turboexpander and the required preheat temperature of the natural gas. In this analysis, gas samples taken at Moffat and Gormanstown were considered, and a median value of heat capacity at constant pressure divided by heat capacity at constant volume was used (Cp/Cv = 1.31). Changes in gas composition from changes to the IGEM standards and hydrogen blends are outside of the scope of this study but should be considered in future feasibility studies.

2.1 Power Calculations

The pressure of the gas before the turboexpander (P_2), the pressure of the gas after the turboexpander (P_3) and the temperature of the gas after the turboexpander (T_3) are known values. Assuming isentropic expansion of an ideal gas, the required temperature of the gas before the turboexpander (T_2) can be calculated using Eq. 1.

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} \qquad \text{Eq. 1}$$

Where:
T_2 – Required inlet gas temperature before turboexpander (K)
T_3 – Required outlet gas temperature after turboexpander (K)
P_2 – Pressure of gas upstream of turboexpander (Bar)
P_3 – Pressure of gas downstream of turboexpander (Bar)
Υ – Ratio of specific heats (C_p/C_v) of natural gas

Knowing the temperatures and pressures for points 2 and 3, the enthalpy of natural gas can be calculated. The available power can now be calculated using Eq. 2.

$$W = (h_2 - h_3) \times \dot{m}_g \times \eta_t \times \eta_g \qquad \text{Eq. 2}$$

Where:
W – Power generated from the turboexpander (kW)
h_2 – Enthalpy of the gas after the preheater and before the turboexpander (kJ/kg)
h_3 – Enthalpy of the gas after the turboexpander (kJ/kg)
$\dot{m}_g$ – Gas mass flow rate (kg/s)
η_t – Efficiency of the turboexpander (%)
η_g – Efficiency of the generator (%)

2.2 Heat Load Calculations

The temperature and pressure of the gas entering the site is assumed, the pressure of the gas does not change in the preheating process and following the power calculations, the required temperature of the gas after the preheater is known. The required heat load can now be calculated using Eq. 3.

$$Q = (h_2 - h_1) \times \dot{m}_g \qquad \text{Eq. 3}$$

Where:
Q – Required heat load (kW)
h_2 – Enthalpy of the gas after the preheater and before the turboexpander (kJ/kg)
h_1 – Enthalpy of the gas before the preheater (kJ/kg)
$\dot{m}_g$ – Gas mass flow rate (kg/s)

3.0 TURBOEXPANDER ANALYSIS

The turboexpander potential power generation capacity was calculated for a range of potential pressure drop and gas flow scenarios, as detailed in Table 1.

Table 1- List of Pressure Drops and Flow Rates Analysed in this Report

Pressure Drops (Bar)	Flow Rate (SCMH)	Flow Rate (MW_{th})
70-19	10,345	100
70-40	20,690	200
40-19	41,379	400
	87,931	850

The design efficiency of the turboexpander was taken as 91.5% based on communications with a vendor in 2016 for the original turboexpander feasibility report. The calculation assumes that the design flow rate of the turboexpander is the same as the gas flow rate for each site. The generator efficiency was assumed 98.9% (Siemens 2022). The potential power produced from a turboexpander for each scenario is detailed below in Table 2.

Table 2- Potential Electrical Power Production (kW) at Design Flow Rate for a Turboexpander with Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	20,690	41,379	87,931
Pressure Drop (Bar)	70-19	394	789	1,578	3,352
	70-40	132	265	529	1,125
	40-19	204	415	830	1,763

As with most autoproduction power generation installations there are several options for use of on-site generated electrical power; export to grid and on-site use where any excess electricity is exported. This report will consider two scenarios; the first will assume that all generated power is exported to the grid and revenue is generated through the feed-in tariff. For the second scenario the electrical power generated by the turboexpander will offset a portion of the gas power generation demand with a corresponding reduction in imported gas. It is assumed that the reduction in gas is small in comparison to the overall gas demand, and that the reduction in gas flow rate will have a minimal effect on the turboexpander performance.

An estimate of the yearly revenue generated through grid export of generated power is presented in table 3 below. Note that the calculations are based on the application of the Clean Export Premium (CEP) tariff which is available for projects up to 50kW where participants will receive a tariff of €0.135/kWh in 2022. Projects with an export capacity more than 50 kW may not be eligible for this scheme and may be subject to negotiated prices on the wholesale electricity market. For the past year wholesale prices have been steadily increasing, reaching €0.293/kWh in March 2022.

Table 3 – Scenario 1: Electricity export revenue (€) using a Turboexpander with Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	**20,690**	**41,379**	**87,931**
Pressure Drop (Bar)	**70-19**	466,423	932,847	1,865,648	3,964,530
	70-40	156,491	312,982	625,948	1,330,150
	40-19	241,277	490,701	981,379	2,085,445

An estimate of the yearly savings in imported gas costs is show below in Table 4. This calculation assumes a gas turbine efficiency of 43% (General Electric 2022) and natural gas cost of €0.0613 /kWh (SEAI 2022).

Table 4 – Scenario 2: Imported Gas Cost Savings (€) using a Turboexpander with Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	**20,690**	**41,379**	**87,931**
Pressure Drop (Bar)	**70-19**	492,537	985,073	1,970,099	4,186,489
	70-40	165,252	330,504	660,993	1,404,620
	40-19	254,785	518,174	1,036,323	2,202,201

An estimate of the yearly Carbon Dioxide (CO_2) savings based on scenario 1 is shown below in Table 5. This calculation assumes an electricity emission factor of 331.9 gCO_2/kWh based on the average of the electricity emission factors for 2018 to 2020 (SEAI 2021).

Table 5 – Scenario 1: Potential CO_2 Savings (Tonnes) due to Exporting Generated Electricity to the Grid for Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	**20,690**	**41,379**	**87,931**
Pressure Drop (Bar)	**70-19**	1,147	2,293	4,587	9,747
	70-40	385	769	1,539	3,270
	40-19	593	1,206	2,413	5,127

Finally, the potential CO_2 savings associated with the reduced gas usage was calculated and shown below in Table 6. A Natural Gas emission factor of 202.2 gCO_2/kWh (SEAI 2021) was used for the calculations. Although the emission factor for natural gas is lower than for electricity, the potential CO_2 savings are higher for scenario 2 as the gas turbine efficiency was assumed 43%.

Table 6 – Scenario 2: Potential CO_2 Savings (Tonnes) due to Reduction in Gas Usage for Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	**20,690**	**41,379**	**87,931**
Pressure Drop (Bar)	**70-19**	1,625	3,249	6,498	13,809
	70-40	545	1,090	2,180	4,633
	40-19	840	1,709	3,418	7,264

4.0 HEAT LOAD REQUIREMENTS

The gas expansion process that takes place in the turboexpander can be considered an ideal isentropic process where, as the pressure reduces there is a corresponding drop in temperature according to the exponential equation Eq.1.

This temperature drop is considerable and pre-heaters must be used to prevent freezing of piping and equipment. To illustrate this point, the turboexpander exit gas temperatures without pre-heating were calculated and are presented below:

- -29°C for the 70 – 40 Bar pressure drop scenario,
- -39°C for the 40 – 19 Bar pressure drop scenario and
- -68°C for the 70 – 19 Bar pressure drop scenario.

The required heat load to ensure the gas temperature does not drop below 2°C at the exit of the turboexpander was calculated for each pressure drop and flow rate and is shown below in Table 7. The gas temperatures at the inlet of the turboexpander required to maintain a minimum gas exit temperature of 2°C were found to be:

- 41°C for the 70 – 40 Bar pressure drop scenario,
- 55°C for the 40 – 19 Bar pressure drop scenario and
- 101°C for the 70 – 19 Bar pressure drop scenario.

Table 7 – Turboexpander Gas Pre-Heat Loads (kW) for Given Gas Flow Rates and Pressure Drops

		Flow Rate (SCMH)			
		10,345	**20,690**	**41,379**	**87,931**
Pressure Drop (Bar)	**70-19**	564	1,128	2,256	4,794
	70-40	211	422	844	1,794
	40-19	265	537	1,074	2,282

The gas expansion that takes place in a conventional AGI using pressure regulating valves is also accompanied by a drop in gas temperature but differs in that the expansion is an irreversible constant enthalpy process were no work is done. As a result, the heat load requirement for a conventional AGI using pressure regulating valves is much less than that of an AGI using a turboexpander.
For comparison, the heat load requirements for an AGI with the same pressure reduction and gas flow rate requirements but using pressure regulating valves is shown in Table 8.

Table 8 – Gas Pre-Heat Loads (kW) for an AGI Using Pressure Regulating Valves

		Flow Rate (SCMH)			
		10,345	20,690	41,379	87,931
Pressure Drop (Bar)	70-19	128	256	512	1,089
	70-40	65	130	259	551
	40-19	39	78	157	333

The viability of a turboexpander project is dependent on the possibility of satisfying the gas pre-heat load demand with low-cost waste heat generated on site at the data centre.
Air cooled data centres typically emit waste heat at temperatures of 30-45°C (Capozzoli and Primiceri 2015). This low-grade waste heat must be recovered and upgraded by technologies such as heat pumps to meet the thermal load demands of the turboexpander pre-heater. Other technologies such as gas turbine flue stack economisers can be used to obtain higher grade waste heat. The calculation of the energy input requirements of such heat recovery and upgrade processes is beyond the scope of this feasibility study.

5.0 FINANCIAL APPRAISAL

To give an indication of a payback period for such a turboexpander installation, one pressure drop and gas flow rate scenario was studied. A pressure drop from 40 Bar to 19 Bar and a gas flow rate of 41,379 SCMH was selected. Based on operating and maintenance costs and capital costs estimated in the 2017 Abbotstown turboexpander report for 3 x 300 kW turboexpanders and heat pumps, a payback period between 10 and 11 years was estimated. The full calculation can be seen in Appendix 4.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Turboexpander technology has had limited application to date in natural gas pressure reduction stations due to its high capital costs, increased thermal heating requirement and requirement for a relatively constant gas flow rate. A data centre site was explored as a possible location where the electricity produced could be used by the data centre or exported to the grid and waste heat could be upgraded and used to pre heat the gas. The following conclusions were made:

1. Turboexpanders have a very large gas pre-heat demand requirement and is considerably greater than the heat demand of a conventional PRS, for the same gas pressure drop and flow rate.
2. The overall viability of the turboexpander is dependent on maximum utilization of the waste heat generated by the data centre. Typically, waste heat from data centres is low grade and the recovery and upgrade of this waste heat comes at a cost and will impact on the viability of the project. An SEAI study estimates that there is a potential to recover on average 30 GWh/year per data centre in Ireland at a temperature of 35-45°C (SEAI 2022). Further analysis is required to determine how much waste heat can be successfully utilized from various technologies such as heat pumps and flue gas economisers on a case-by-case basis.
3. The unit rate of import electricity is at least double the unit rate of export electricity. On-site generation is always more valuable if the site has a demand for the electricity. Data centres have a large energy demand and the electricity generated from the turboexpander can be used to offset a portion of the gas power generation demand with a corresponding reduction in imported gas costs.

4. Electrical power generated by the turbo expander can also be exported directly to the grid where revenues generated with depend on the negotiated export tariff.

The annual fuel cost saving and CO_2 reduction figures or the electricity export revenues presented in this report will likely be of interest to a data centre operator. However, the large gas heating demand and requirement to recover and upgrade waste heat generated by the data centre, with potentially high associated capital investment and running costs will be of concern.

This has been a high-level assessment of the feasibility of coupling data centres with turboexpanders and the following recommendations are made to progress the assessment:

1. Liaise with a data centre operator to get more detailed gas usage and waste heat data and gauge their interest in such a project.
2. Investigate the potential for recovery and upgrade of waste heat at data centres, the technologies and equipment required and associated capital costs.
3. GNI should explore the legal and operational complexities of facilitating the operation a turboexpander and other plant equipment by an external organisation at a GNI installation.
4. Other considerations such as system redundancy should be explored. It is likely that a standard PRS with heat exchanger and boiler would need to be installed in parallel with the turboexpander to allow for maintenance and provide heating at start-up.

7.0 REFERENCES

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APPENDIX 1: Turboexpander Power and Heat Calculations

Turboexpander Power Production and Heat Load Calculation

INTRODUCTION

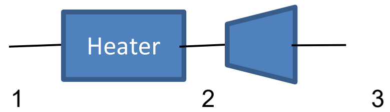
This calculation calculates the potential power generated from a turboexpander installed to reduce the pressure of gas for a selection of predefined pressure drops and flow rates. The required heat load is also calculated

ASSEUMPTIONS

Minimum gas density @STP	0.6834	kg/m^3
Maximum gas density @STP	0.854	kg/m^3
Ratio of Specific Heats	1.31	
Constant flow all year		
Turboexpander efficiency	91.5	%
Generator efficiency	98.9	%
Isentropic heating		

CALCULATION

Pressure at inlet	P1	70	70	70	70	70	70	70	70	40	40	40	40	Bar
Temperature at inlet	T1	6	6	6	6	6	6	6	6	6	6	6	6	°C
Enthalpy at inlet	H1	467	467	467	467	467	467	467	467	507	507	507	507	kJ/kg
Pressure at outlet	P3	19	19	19	19	40	40	40	40	19	19	19	19	Bar
Temperature at outlet	T3	2	2	2	2	2	2	2	2	2	2	2	2	°C
Enthalpy at outlet	H3	525	525	525	525	496	496	496	496	525	525	525	525	kJ/kg
Pressure after heater	P2	70	70	70	70	70	70	70	70	40	40	40	40	Bar
Temperature after heater	T2	101	101	101	101	41	41	41	41	55	55	55	55	°C
Enthalpy after heater	H2	722	722	722	722	562	562	562	562	627	629	629	629	kJ/kg
Pressure at outlet	P3	19	19	19	19	40	40	40	40	19	19	19	19	Bar
Temp at outlet no heater	T3'	-68	-68	-68	-68	-29	-29	-29	-29	-39	-39	-39	-39	°C
Gas flow rate	q	10345	20690	41379	87931	10345	20690	41379	87931	10345	20690	41379	87931	SCMH
Gas flow rate		106	212	424	901	106	212	424	901	106	212	424	901	MW_{th}
Mass flow rate min	qmin	1.96	3.93	7.86	16.69	1.96	3.93	7.86	16.69	1.96	3.93	7.86	16.69	kg/s
Mass flow rate max	qmax	2.45	4.91	9.82	20.86	2.45	4.91	9.82	20.86	2.45	4.91	9.82	20.86	kg/s
Power output min	Wmin	351	701	1403	2980	118	235	471	1000	181	369	738	1568	kW
Power output max	Wmax	438	876	1753	3724	147	294	588	1250	227	461	922	1959	kW
Power average	Wavg	394	789	1578	3352	132	265	529	1125	204	415	830	1763	kW
Heat Load min	Qmin	501	1003	2005	4262	188	375	751	1595	235	477	955	2028	kW
Heat Load max	Qmax	627	1253	2506	5325	234	469	938	1993	294	596	1193	2535	kW
Heat Load Average	Qavg	564	1128	2256	4794	211	422	844	1794	265	537	1074	2282	



Heat Load (kW)

Pressure Drop (Bar)	Flow Rate (SCMH)				
		10345	20690	41379	87931
	51	564	1128	2256	4794
	30	211	422	844	1794
	21	265	537	1074	2282

Total Power Production (kW)

Pressure Drop (Bar)	Flow Rate (SCMH)				
		10345	20690	41379	87931
	51	394	789	1578	3352
	30	132	265	529	1125
	21	204	415	830	1763

NOTES:

APPENDIX 2: Turboexpander Cost and CO_2 Savings Calculations

Turboexpander Imported Gas and CO2 Savings

INTRODUCTION

This calculation calculates the potential electricity cost savings for a data centre using a turboexpander.
Scenario 1: Revenue generated through export of generated electricity.
Scenario 2: Cost saving made through the reduction of imported gas used to power a gas turbine.

ASSEUMPTIONS

Microgeneration feed-in tariff	0.135	€/kWh	GOV.ie
Cost of Natural Gas	0.0613	€/kWh	SEAI
Natural Gas Emission Factor	202.2	g CO2/kWh	SEAI
Gas Turbine Efficiency	43	%	GE
Electricity Emission Factor	331.9	gCO2/kWh	SEAI

CALCULATION

Scenario 1: Total Energy Saving (€)

Pressure Drop (Bar)	Flow Rate (SCMH)			
	10345	20690	41379	87931
51	466,423	932,847	1,865,648	3,964,530
30	156,491	312,982	625,948	1,330,150
21	241,277	490,701	981,379	2,085,445

Scenario 2: Total Energy Saving (€)

Pressure Drop (Bar)	Flow Rate (SCMH)			
	10345	20690	41379	87931
51	492,537	985,073	1,970,099	4,186,489
30	165,252	330,504	660,993	1,404,620
21	254,785	518,174	1,036,323	2,202,201

Scenario 1: Total CO2 Saving (Tonnes)

Pressure Drop (Bar)	Flow Rate (SCMH)			
	10345	20690	41379	87931
51	1,147	2,293	4,587	9,747
30	385	769	1,539	3,270
21	593	1,206	2,413	5,127

Scenario 2: Total CO2 Saving (Tonnes)

Pressure Drop (Bar)	Flow Rate (SCMH)			
	10345	20690	41379	87931
51	1,625	3,249	6,498	13,809
30	545	1,090	2,180	4,633
21	840	1,709	3,418	7,264

NOTES:

APPENDIX 3: Pressure Regulating Valve Heat Load Calculations

Project: Turboexpander Feasibility Study
Project No: 1403

Equivalent AGI Joule Thomson Effect

INTRODUCTION

This calculation calculates the equivalent AGI heat load due to the Joule Thomson Effect

ASSEUMPTIONS

Minimum gas density @STP 0.6834 kg/m^3
Maximum gas density @STP 0.854 kg/m^3

CALCULATION

Pressure at inlet	P1	70	70	70	70	70	70	70	70	40	40	40	40	Bar
Temperature at inlet	T1	6	6	6	6	6	6	6	6	6	6	6	6	°C
Enthalpy at inlet	H1	467	467	467	467	467	467	467	467	507	507	507	507	kJ/kg
Pressure at outlet	P3	19	19	19	19	40	40	40	40	19	19	19	19	Bar
Temperature at outlet	T3	2	2	2	2	2	2	2	2	2	2	2	2	°C
Enthalpy at outlet	H3	525	525	525	525	496	496	496	496	525	525	525	525	kJ/kg
Enthalpy Change	(H2-H1)	58	58	58	58	29	29	29	29	18	18	18	18	kJ/kg
Gas volumetric flow rate	q	10345	20690	41379	87931	10345	20690	41379	87931	10345	20690	41379	87931	SCMH
Gas mass flow rate (min)	m	1.96	3.93	7.86	16.69	1.96	3.93	7.86	16.69	1.96	3.93	7.86	16.69	kg/s
Gas mass flow rate (max)	m	2.45	4.91	9.82	20.86	2.45	4.91	9.82	20.86	2.45	4.91	9.82	20.86	kg/s
Required heat input (min)	Q_{he}	113.90	227.81	455.60	968.16	57.64	115.28	230.56	489.94	34.81	69.63	139.25	295.90	kW
Required heat input (max)	Q_{he}	142.34	284.67	569.34	1209.85	72.03	144.06	288.11	612.24	43.50	87.01	174.01	369.77	kW
Average heat requirement		128	256	512	1089	65	130	259	551	39	78	157	333	kW

JT Heat Load (kW)

		Flow Rate (SCMH)			
		10345	20690	41379	87931
Pressure Drop (Bar)	51	128	256	512	1089
	30	65	130	259	551
	21	39	78	157	333

NOTES:

APPENDIX 4: Financial Appraisal

Financial Appraisal

INTRODUCTION

This is a financial appraisal for a turboexpander installed to reduce the pressure of gas to a data centre site.

ASSEUMPTIONS

Minimum gas density @STP	0.6834	kg/m^3
Maximum gas density @STP	0.854	kg/m^3
Pressure in	40	Bar
Pressure out	19	Bar
Gas flow rate	41379	SCMH
Turboexpander availability	95	%

CALCULATION

Primary Thermal Energy Source	Waste heat		
Secondary Thermal Energy Source	Boilers		
Average Electrical Power Generated	830	kW	
Average Gas Pre-Heat Load	1074	kW	
Power required to upgrade waste heat	358	kW	Electrical power required to recover and upgrade data centre waste heat. Based on a Heat Pump COP of 3
Parasitic Electric energy	3,135,072	kWh	
Electrical Energy Generated	6,906,001	kWh	
Electricity Exported to Data Centre	3,770,929	kWh	Net electric energy produced by Turboexpander
Scenario 1: Imported Gas Cost	0.0613	€/kWh	
Gas Import Savings	537,577	€	Gas turbine efficiency of 43%
O&M Costs	73,505	€	Based on O&M costs for a 900kW Atlas turboexpander used for the 1093 Abbotstown analysis only
Net Margin	464,072	€	
CAPITAL COSTS	4,807,000	€	Based on capital costs for 3 x 300 kW GE turboexpander and heat pump used for the 1093 Abbotstown analysis
Payback (years)	10.4	Years	
Scenario 2: Exported Electricity Price	0.1350	€/kWh	
Electricity export revenue	509,075	€	
O&M Costs	73,505	€	Based on O&M costs for a 900kW Atlas turboexpander used for the 1093 Abbotstown analysis only
Net Margin	435,570	€	
CAPITAL COSTS	4,807,000	€	Based on capital costs for 3 x 300 kW GE turboexpander and heat pump used for the 1093 Abbotstown analysis
Payback (years)	11.0	Years	

NOTES: