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An ETI Perspective

Evaluation of the NET Power low carbon power process

ETI10
TEN YEARS
OF INNOVATION
2007—2017

KEY HEADLINES

- NET Power technology has the potential to be a gamechanger.
- Modelling analysis confirms that NET Power's supercritical CO_2 power cycle has the potential to deliver carbon capture at efficiencies higher than conventional amine solutions.
- Some unpublished innovations which NET Power are protecting as trade secrets are needed to make the technology as cost efficient as an unabated CCGT, which is still improving rapidly.
- The technology is immature and has multiple development hurdles to overcome and therefore it is likely to take several years before it is commercially available at scale. It is therefore likely to be best suited for deployment once other elements of CCS have been de-risked (i.e. transport and storage) rather than in a First of a Kind full scale development.

INTRODUCTION

Followers of Carbon Capture and Storage are counting down the months until they hear about the start-up of NET Power's $50MW_{th}$ demonstration unit of their radical new gas-fired power plant design. The technology targets power production with CO_2 capture at a similar cost to a conventional Combined Cycle Gas Turbine (CCGT) without post combustion abatement, and in particular targets an efficiency of 58.9 % LHV[1]. If realised, the technology could enter the power market and offer carbon capture at zero additional cost, and the cost for fully built up CCS systems would be significantly reduced, consisting only of the much smaller costs associated with CO_2 transportation and storage. Additionally the technology could offer CO_2 for use in Enhanced Oil Recovery (EOR) application at a very attractive cost.

In 2015, the IEAGHG produced a report[2], which included an assessment of the NET Power technology, based on publically available information. IEAGHG modelling had concluded that the technology was around 55.1% LHV efficient, and in a commentary section in the report, NET Power explained that a combination of better quality vendor data and some trade secrets in their design (neither of which were available to IEAGHG) could bridge the gap to the target figure of 58.9%.

The ETI carried out simplified modelling of the NET Power process in 2013 and 2014, again using publically available information. This work was refreshed after the IEAGHG report was issued, incorporating some of the IEAGHG assumptions to ease comparison, and this paper reports these largely corroborative findings as an additional independent reference. The ETI conclusion is that the NET Power technology is at least c.55% efficient, and that NET Power's commentary on how their proprietary data and trade secrets can improve this to 58.9% applies to the ETI analysis also.

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1. Allam, RJ, Palmer, M, et al, (2013). High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide [online]. Available at: http://www.sciencedirect.com/science/article/pii/S187661021300221X

2. IEAGHG (2015). Oxy-Combustion Power Plants 2015/05. [online]. Available at: http://ieaghg.org/conferences/49-publications/technical-reports/599-2015-05-oxy-combustion-turbine-power-plants

PERFORMANCE ASSESSMENT OF THE NET POWER CYCLE

The new power cycle is shown in Figure 1. Supplies of oxygen from an Air Separation Unit (ASU) and natural gas (diluted with CO_2) are fed to a high-pressure combustor (300 Barg) and the hot combustion products of CO_2 and water are expanded through a gas turbine to 30 Barg. The water produced by combustion is condensed, and the CO_2 which remains is pressurised to a supercritical state, pumped back up to 300 Barg, and sent back to the combustor where it is used both to recycle turbine exhaust heat within the system and as coolant for controlling combustor temperatures. A slip stream is purified cryogenically and pumped to storage or sent directly for use in EOR assets.

There is no steam cycle – this is replaced by CO_2 as the main working fluid.

Features of this process include:

- Using a Gas Turbine (GT) – which under these process conditions is inherently highly efficient.
- Recycling a dominant flow of CO_2 as the combustor coolant which follows an energy path shown in Figure 2 (page 6).
- Recuperating high levels of heat from the CO_2 recycle in efficient exchangers.
- Using low-grade heat efficiently, of which there is a shortage in the process.
- Using the latest alloys, including new high Nickel alloys[3], at the top end of their performance limits.
- Developing new pieces of equipment[4] - a new combustor, turbine and possibly heat exchanger designs – each of these an achievement in its own right.

The following are key to achieving high efficiency:

- Maximising the work taken from the turbine expansion ‘2’, and minimising the work input in the compression and pumping sections shown after the coolers at ‘4’ and ‘5’ in Figure 2.
- Providing additional low/medium grade heat at ‘6’, plus full recuperation of heat (‘7&3’), so that the fuel combustion at ‘1’ adds heat at a high average temperature.

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[3] Toshiba Corporation Power Systems Company (2013). The NET Power cycle and the combustor and turbine development [online]. Available at: http://anlecrd.com.au/wp-content/uploads/2016/08/4.TheNETPowerCycleandtheCombustorandTurbineDevelopment-Nomoto.pdf

[4] Allam, RJ, Palmer, M, et al, (2013). High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide [online]. Available at: http://www.sciencedirect.com/science/article/pii/S187661021300221X

Figure 1: The NET Power process

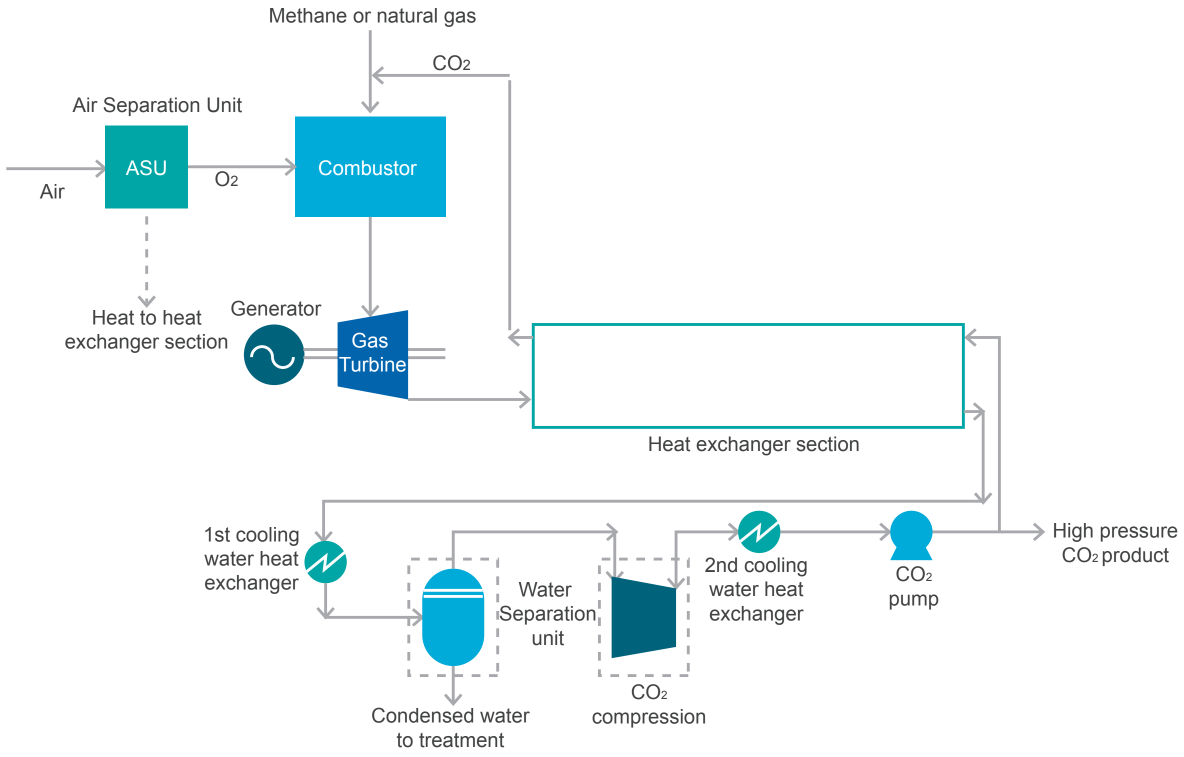
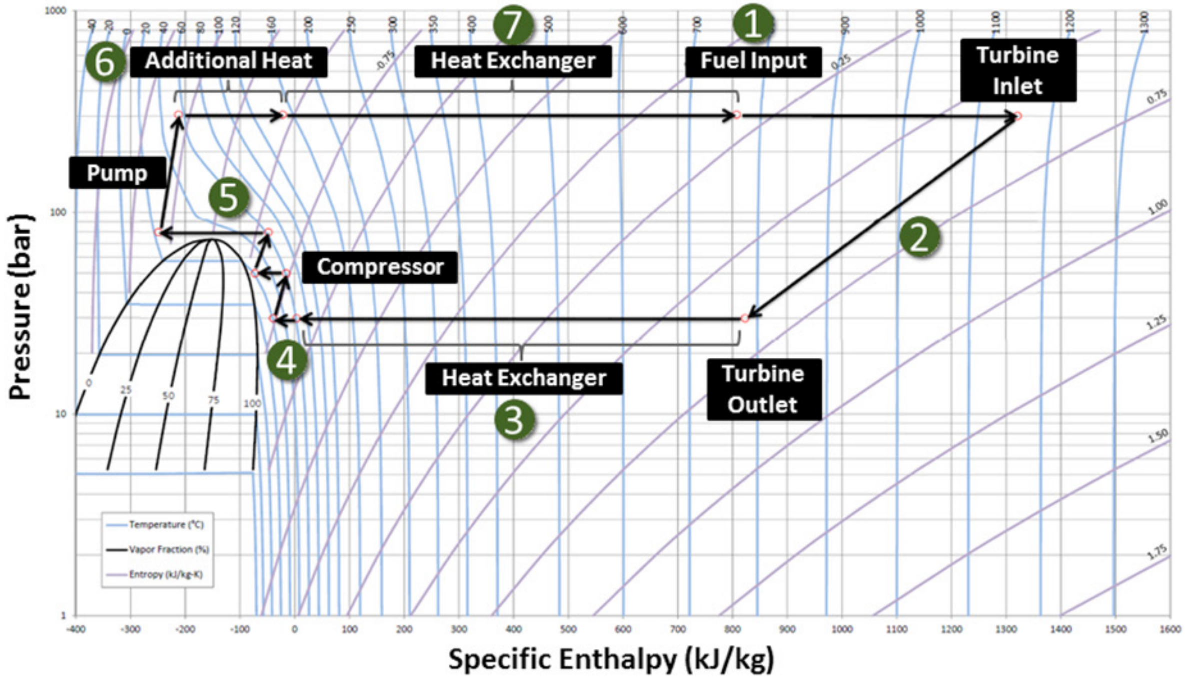


Figure 2. A pressure enthalpy diagram for the NET Power cycle in pure CO_2 (courtesy NET Power)



ETI undertook a short work program to check the validity of NET Power's claims. Process modelling was carried out by Foster Wheeler (FWEL) in Aspen Hysis and by PSE in gCCS[5]. Physical property estimation methods were tested and our learnings from this are given in Appendix 1.

The power plant was first modelled as an 'ideal' process, with pure methane, no pressure drops etc. for comparison with a NET Power patent case[6]. Modelling the process conditions and layout in the patent, it was found that the design easily met the claims of the patent in terms of efficiency (53.9% LHV).

The plant was then modelled with realistic engineering assumptions (Appendix 2) including limitations on equipment performance, the presence of inerts in the feeds, excess oxygen post combustion and pressure drops across key equipment. The ETI modelling could not meet the NET Power efficiency targets, the best case being about 55% LHV efficient.

In the IEAGHG report, the NET Power commentary included a comparison of the IEAGHG and NET Power analysis, using the assumption adopted by IEAGHG. In turn the ETI has adjusted the assumptions in its simple gCCS model to more closely reflect the IEAGHG assumptions, and has tabulated a comparison of the results in Figure 3 (page 8).

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5. gCCS is offered by http://psenterprise.com/
6. US 2013/0213049 A1

Figure 3: Comparison of the estimates of the NET Power performance – IEAGHG and the ETI’s

	IEAGHG	% LHV loss	ETI cold seawater case	% LHV loss
FEED				
Natural Gas FEED, Te/hr	118.9		113.6	
Heating value of FEED, HHV, MW_{th}	1701			
Heating value of FEED, LHV, MW_{th}	1536		1493	
TURBINE (MWe)				
Turbine Gross Output	1264	17.7	1260	15.6
PARASITIC LOSSES (MWe)				
CO_2 compress and pump	208	13.5	202.2	13.5
O_2 Compression	Included in CO_2 Compression		11.9	0.8
Air Separation Unit	170.7	11.1	171	11.5
CO_2 purification	12.4	0.8	14.2	1.0
Utility +Offsites	10.4	0.7	14.4	1.0
Cycle losses including nat gas Compression	13.9	0.9	22.67	1.5
NET PLANT POWER OUTPUT (MWe)	849		824	
Adjustment for HV losses	846	0.2	821	0.2
LHV Eff	55.1%		55.0%	

NET Power believe efficiencies of the order of 55% LHV are typical of early analysis work, and with years of process development work and vendor selection, they have stretched performance to their target efficiency.

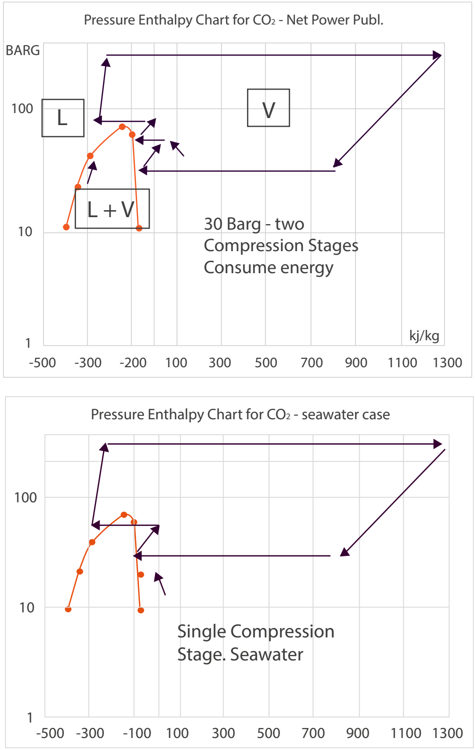
Appendix 3 lists summaries of some of the sensitivities studied by the ETI.

We explored the effects of reducing CO_2 recompression loads by elevating the turbine outlet pressure (currently constrained by the hot heat exchanger metal temperature) and using cold seawater to condense the CO_2, as shown in Figure 4.

The most impactful improvements included:

- Full utilisation of heat from the ASU or other sources
- Use of cold ‘seawater’ cooling
- Increasing the turbine inlet temperature

Figure 4: Example of sensitivity - reduced cooling water temperature



Equipment

The technology will require several novel equipment designs:

Combustor

Although the conditions are arduous (300 Barg and 1050°C), sophisticated burner designs for different applications are already in use which shield equipment from coincidence of worst case conditions[7]. Toshiba have tested a diffusion flame device in the US at full operating conditions and 5MWth scale. Oxygen in excess of the amount needed just to burn the methane will be needed to avoid partial combustion products which may cause fouling, corrosion and product specification issues. Even if 'equilibrium conditions' are achieved in the combustor, 'pure' gas streams will not be produced[8]. Extended testing will be needed to get comfortable with burner stability.

Turbine

The combination of size, high pressures, temperatures and high CO_2 content used in this technology is without precedent and a new 'CO_2' turbine design is required. It will borrow design features from both high-pressure steam turbines and gas turbines. Toshiba have a long history in turbine development and so are well equipped to make this development step. The machine has been completed and is remarkably compact[9]. The latest alloys, whose development began decades ago for use in conventional coal fired and nuclear power stations, are under test for use in this application.

High Temperature Exchangers

It is anticipated that the turbine outlet will be manifolded by pipework into the hot end of the main heat exchanger train. Lower turbine outlet pressures and turbine coolants ease the design temperature and pressure constraints at this transition. Further, the heat exchanger must preferably reheat the returning CO_2 recycle stream to within 20°C of the incoming turbine stream to retain high efficiency, so an efficient exchanger is required. The UK company Heatric have engaged with the NET Power project[10], and have a long history in construction of Printed Circuit Board Exchangers (PCBE), which suit this application, and have recently built one in Alloy 617 for use in high temperature recuperative systems such as this one. Several other designs are being tested in the US[11,12].

The effect of minor impurities (sulphur and nitrous oxides, corrosion products and combustion particles) on heat transfer surfaces etc. has not been demonstrated, although Net Power claim the fate of sulphur and nitrous oxides is predictable and innocuous[13].

With so much of the process consisting of novel equipment, the ETI did not attempt to estimate a capital cost for the plant.

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7. B Pint, J Keiser (2014). The Effect of Temperature on the SCO_2 Compatibiliy of Conventional Structural Alloys. 4th International Symposium on Supercritical Power Cycles.
8. P Strakey, O.Dogan et al (2014). Technology Needs for Fossil Fuel Supercritical CO_2 Power Systems. 4th International Symposium on Supercritical Power Cycles.

9. Utility Drive (2016). Toshiba ships turbine for NET Power superciritical CO_2 carbon capture plant. [online]
Available at: http://www.utilitydive.com/news/toshiba-ships-turbine-for-net-power-supercritical-co2-carbon-capture-plant/429513/
10. Heatric (2016). Heatric supplies advanced recuperator for NET Power's first-of-a-kind supercritical CO_2 power plant. [online]
Available at: https://www.heatric.com/Heatric_supplies_advanced_recuperator_for_NET_Powers_first-of-a-kind_supercritical_CO2_power_plant.html
11. Brayton Cycles, M Carlson et al (2014) Sandia Progress on Advanced Heat Exchangers for SCO_2. 4th International Symposium on Supercritical Power Cycles.
12. M Anderson (2012). Materials, Turbomachinery and Heat Exchangers for Supercritical CO_2 Systems, NUEP.US DOE project 09-778.
13. RJ Allam, M Palmer et al (2013). High Efficiency and low Cost of Electricity Generation from Fossil fuels while eliminating atmospheric emissions, including carbon dioxide [online]
Available at: Available at: http://www.sciencedirect.com/science/article/pii/S187661021300221X

Our process modelling showed that:

- For an idealised cycle (100% methane feed, no pressure drops etc.), NET Power's efficiency claims in its patent applications could be met quite comfortably.
- The high efficiency of the process is susceptible to:

  a) any build-up of inerts in the CO_2 loop.
  b) loss of performance in any of several state of the art equipment items, including rotating machinery, heat exchangers, the ASU etc.

- There is upside potential from:
  a) having cold cooling water available.
  b) improvements to metallurgy allowing higher temperatures and pressures in the heat exchange train.
  c) the ability to upgrade low-grade heat to power at high efficiency, if a low cost heat supply is available from other sources or auxiliary conventional generation.

Relaxing the temperature constraints on the hot end heat exchanger, and allowing the turbine inlet temperature to rise by 50°C to 1200°C increased the plant efficiency by 1.1% LHV. Increasing the turbine outlet pressure whilst maintaining the inlet conditions at base case values (300 Barg and 1150°C) also raised efficiency, as the reduction in compression energy was higher than the loss of gross turbine output. Alloy development should therefore remove constraints on efficiency, but will also improve the efficiency of conventional technologies. Historically this has taken many years and use of these alloys not only increases equipment costs, but requires more sophisticated operations, monitoring and maintenance programs.

The thermal energy needed to cool and heat high pressure, low temperature CO_2 is relatively high i.e. it has a high specific heat. In a process where high recuperation is essential to efficiency, aggressive use of all low-grade heat streams is important. The ASU air compressors are run without intercooling so that hot air is available for the process. Any other form of low and medium grade heat to help reheat the CO_2 recycle stream to a temperature close to the turbine outlet temperature helps efficiency in most ETI model runs. For those cases where there was insufficient heat to close the hot end approach temperatures (the majority), every $10MW_{th}$ added from the ASU (or other source) provided over 6 MWe of power. This also suggests that integrating the power station into an industrial plant or other power unit with surplus low-grade heat will be advantageous.

Since compressing CO_2 takes more energy than pumping it, efficiency can be improved by condensing CO_2 with the coldest medium available and minimising compression. Seawater, which has a summer peak temperatures of 15°C and an annual average of 10°C in North East England, was examined as alternative cooling water supply. The seawater case gained 1.5% efficiency, for a 4°C decrease in coolant supply temperature. The IEA GHG report studied a different range of sensitivities.

Where similar themes were examined, the results were directionally the same and of the same order of magnitude.

Modelling by the ETI, without the benefit of vendor information, but estimating all process losses, could achieve c.55% LHV efficiency. NET Power claim that this is the base level performance achievable using publically available information, without the benefit of several years of development and optimization experience with their cycle.

Commercial Entry to the Market

The NET Power technology is technically immature, in that multiple new pieces of complex equipment have to be designed and constructed, some of which uses metallurgy which has only relatively recently been commercialised. The consortia currently completing the construction of the 50MWth unit (CB&I, Exelon, NET Power, 8 Rivers Capital) can benefit from a large internal source of expertise and nationally funded technical supercritical CO_2 communities that have developed various themes of the technology in laboratory and pilot plants. However, a full cycle NET Power pilot plant has not yet been built, and development and claims are based largely on modelling, so it will take several years for a fully commercial offering to materialise.

In the meantime, competition from post combustion carbon capture technology is getting stiffer, with proven new class H CCGTs combined with engineered amine capture plants offering efficiencies of 52% LHV, each CCGT train having double the power output of the expected early oxy turbine sizes.

If NET Power fall short of their targets, and the efficiency of the NET Power process is less than an unabated CCGT (now 62% LHV), the technology may not gain the rapid commercialisation offered by the open power market without garnering additional value from the captured CO_2. Instead, it could compete in the CCS and Enhanced Oil Recovery markets with other new technologies, some of which are retrofitable to existing power stations.

Energy system modelling showed that if NET Power meet their targets, the technology could significantly displace others by 2040 and increase deployment of CCS at the expense of other low carbon options. Even if lower performance is achieved in its early years (e.g. that in Oxy-Combustion Turbine Power Plants, IEAGHG Report 2015/5) the technology could still warrant deployment.

The 50MWth demonstration plant under construction in Texas to test the full cycle, includes the new combustor and turbine design and use of modern high nickel alloys. The control scheme for the plant will also be tested for the first time. NET Power are targeting deployment of a first commercial scale (300MWe) plant by 2020.

SUMMARY

- If they meet their targets, NET Power will license a game changing technology. It has no solvent toxicity to manage, an extremely small footprint, and an impactful efficiency improvement over post combustion capture. It could enter the broader power market if it can keep pace with conventional CCGT improvements, and the CCS market with little or no subsidy requirement.

- The technology is still immature and faces several challenges on equipment design and operation. Although testing at scale is under way, it may be several years before NET Power can fully demonstrate an attractive package to the market.

- Successful development of full chain CCS projects based on conventional technologies will reduce the overall risk of CCS investments and therefore its cost. These technologies are ‘raising the bar’ through improvements from deployment, but will derisk CCS chains, and so create better conditions for market entry by novel technologies such as NET Power’s.

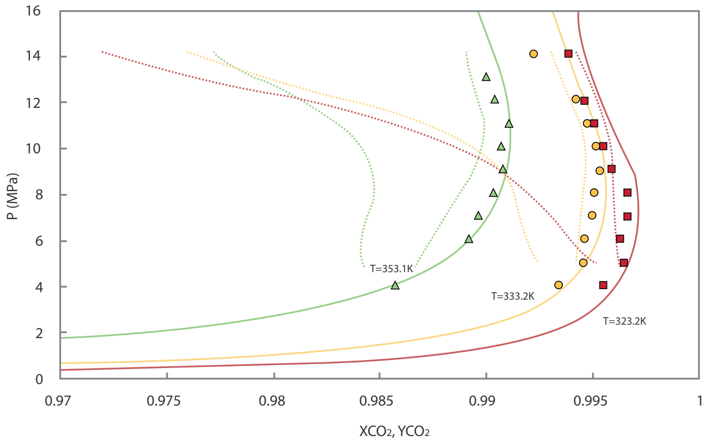
APPENDIX 1

PSE compared published experimental data[14] with the outputs of its own physical properties package gSaft, which is run in their ‘gCCS’ suite, and the properties encountered by FWEL in the Aspen Hysis suite.

Figure 5 shows the composition of the vapour phase of a binary mixture CO_2/H_2O mixture at flow point. The experimental data for three different isotherms are shown as points. The default parameters in Aspen initially used by FWEL (Peng Robinson equation) produced the hatched lines which gave poor representations of the experimental data. Tuning the Peng Robinson equation in Aspen (or Multiflash in gCCS) to match experimental results improved this, but a good fit came from gSaft without further modification. It is clear that experimental data is needed to tune models using CO_2 and H_2O around the critical point. Similarly, estimates of the condensation curves for water from CO_2 in the recuperative exchangers differ between the two methods by around 5°C. This may seem small, but the exchangers have to be designed for close temperature differentials and possibly pinch point avoidance.

Clearly when modelling plant using supercritical CO_2, experimental data is needed to tune physical property correlations. gSaft however does not need such precautions.

Figure 5: Comparison of estimates of vapour composition with experimental data.



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[14] Barnberger A , et al (2017). The Journal of Supercritical Fluids, 17(2), 97-110. HIgh Pressure (vapor +liquid) Equilibrium in binary mixtures of (carbon dioxide +water or acetic acid) at temperatures from 313 to 353OK.m

APPENDIX 2

The following is a list of the main assumptions used in ETI modelling:

- Fuel conditions
  - Flowrate: 31.5kg/s
  - Fuel composition:
    - x('CH_4') = 87.1%
    - x('C_2H_6') = 7.8%
    - x('C_3H_8') = 2.9%
    - x('N_2') = 1.5%
  - Temperature: 1°C
  - Pressure: 70bar

- Oxygen conditions from ASU
  - Rich oxygen stream composition:
    - x('O_2') = 99.5%
    - x('Ar') = 0.5%

- Combustor
  - Full conversion of fuel
  - Excess of oxygen: Molar composition of oxygen at the outlet of the combustor is 1.8%.

- Turbine
  - Inlet temperature: 1150°C
    Inlet pressure: 300bar
    Polytropic efficiency: 88.16%.

- Heat exchanger section
  - Minimum approach in hot and cold sides: 15K
  - Pressure drop in each stage: 2.1bar

- Cooling water, seawater heat exchangers
  - Minimum approach in hot and cold sides: 5K
  - Pressure drop: 0.7bar
  - Cooling water conditions:
    - Inlet temperature: 14°C
    - Outlet temperature: 24°C
  - Seawater conditions:
    - Inlet temperature: 10°C
    - Outlet temperature: 18°C

- Heat integration from the ASU is 121MW in the base case

- Compressors
  - Polytropic efficiency: 83%
  - Mechanical efficiency: 95%

- Pumps
  - Polytropic efficiency: 75%
  - Mechanical efficiency: 95%

- Cryogenic purification unit
  - CO_2 recovery: 98.3%
  - Power consumption 14.2MWe

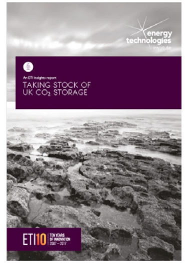
- Cooling water and seawater systems power consumption: 14.4MW

- ASU specific power consumption: 0.392kWh/kgO_2 delivering 110 bar.

APPENDIX 3 - SENSITIVITIES TO CHANGES AROUND A BASE CASE

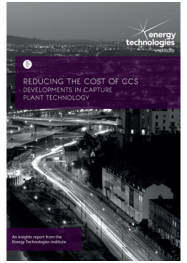
Engineering Case		30bar low pressure base case	50bar low pressure	Increased ASU integration	Cold seawater	Increaser TIT-base case (1200°C)
Turbine Outlet Pressure	bar	34	50	34	34	34
Turbine Shaft Power Output	MW	1251	1215	1260	1260	1263
Turbine Electric Power Output	MWe	1251	1215	1260	1260	1263
CO_2 Compression	MWe	115.5	60.9	112.2	105.3	112.2
CO_2 Pumping	MWe	100.5	116.5	104.4	96.9	98.5
Cycle loss and Fuel consumption	MWe	22.6	22.1	22.7	22.7	22.7
Air Separation Unit	MWe	171.0	170.9	170.9	170.9	171.0
O_2 Compression	MWe	11.9	11.9	11.9	11.9	11.9
Cooling and Seawater system	MWe	14.4	14.4	14.4	14.4	14.4
Cryogenic Purification	MWe	14.2	14.2	14.2	14.2	14.2
Total Auxilary Loads	MWe	450.1	410.9	450.7	436.3	444.9
Net Power Export	MWe	800.9	804.1	809.3	823.7	818.1
Adjustments for HV loss	MWe	798.5	801.6	806.9	821.2	815.6
Net Efficiency (LHV)	%	53.4	53.7	54.0	55.0	54.6
Inlet Power	MWth	1493.1	1493.1	1493.1	1493.1	1493.1

FURTHER READING



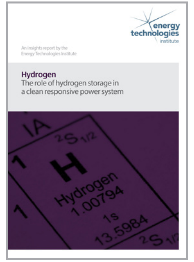
Taking stock of UK CO_2 Storage

http://www.eti.co.uk/insights/taking-stock-of-uk-co2-storage



Reducing the cost of CCS - developments in capture plant technology

http://www.eti.co.uk/insights/reducing-the-cost-of-ccs-developments-in-capture-plant-technology



The role of hydrogen storage in a clean responsive power system

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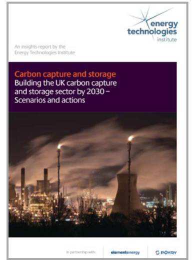
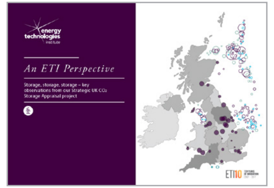


Building UK carbon capture and storage by 2030

http://www.eti.co.uk/insights/carbon-capture-and-storage-building-the-uk-carbon-capture-and-storage-sector-by-2030



An ETI Perspective - Storage, storage, storage

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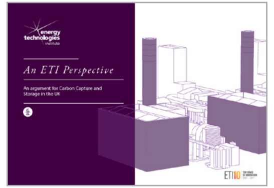

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