IGCC with Carbon Capture: A Comparison of Hydrogen and Substitute Natural Gas for Flexible Power Generation

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Agenda

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02	Wood CCS/Gasification Expertise
03	Coal IGCC - Hydrogen-Rich Gas and SNG Production
04	Wood’s Foster wheeler Vesta Methanation Technology
05	Underground Storage of Fuel Gas in Salt Caverns
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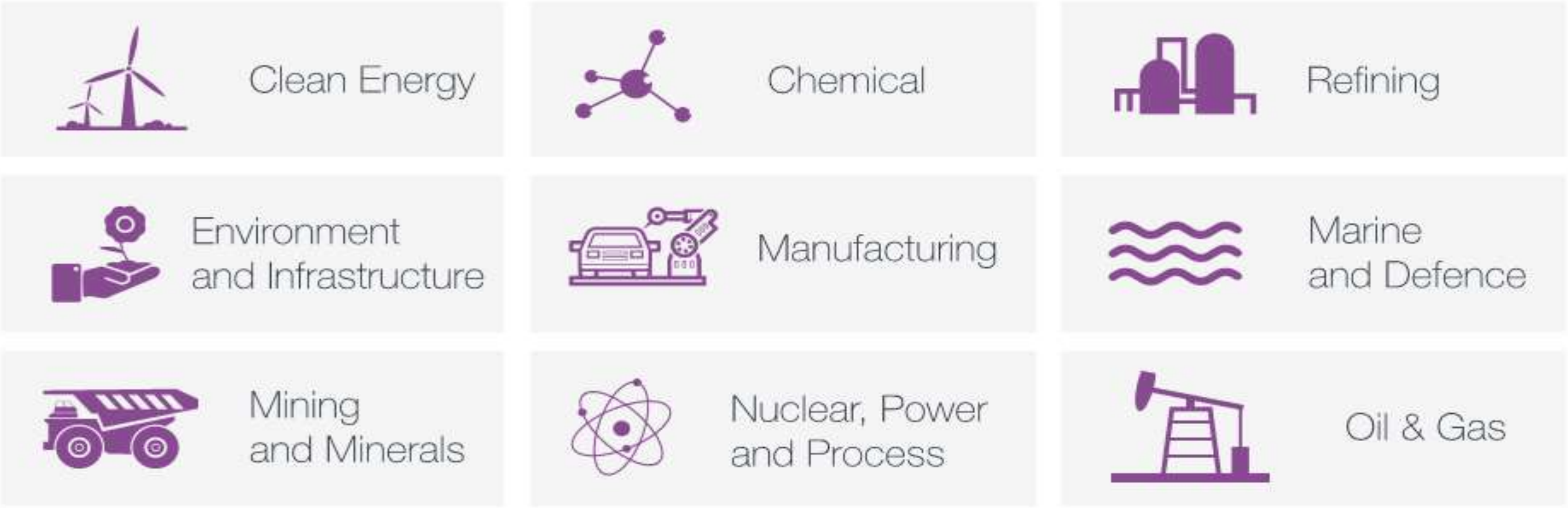
Our global footprint

- We're accelerating and expanding in new sectors and geographies
- Unlocking our technology across an incredible sector spread

Our global footprint



… with an extensive CCS/Gasification track record

Studies

Wood has performed over 60 CCS studies since the mid-1990s.

- Comparing state of the art technologies (benchmarking)
- Assessing next generation technologies

Wood has performed more than 80 gasification studies and pre-FEEDs

Full-Chain CCS Capabilities

- Capture & Compression
- CO_2 Export Pipelines
- Offshore Topside Modifications
- Onshore Permitting and DCO

Projects

Current CCS Projects

- OGCI CI Gas Power and Industrial CO_2 Capture Pre-FEED
- Equinor Snøhvit Future Phases 2 pre-FEED

Historic CCS FEEDs

- DF-1 Peterhead
- Hydrogen Power Abu Dhabi
- E.ON Kingsnorth
- Don Valley Power Project – Coal IGCC to H_2 Power
- MASDAR CO_2 Network

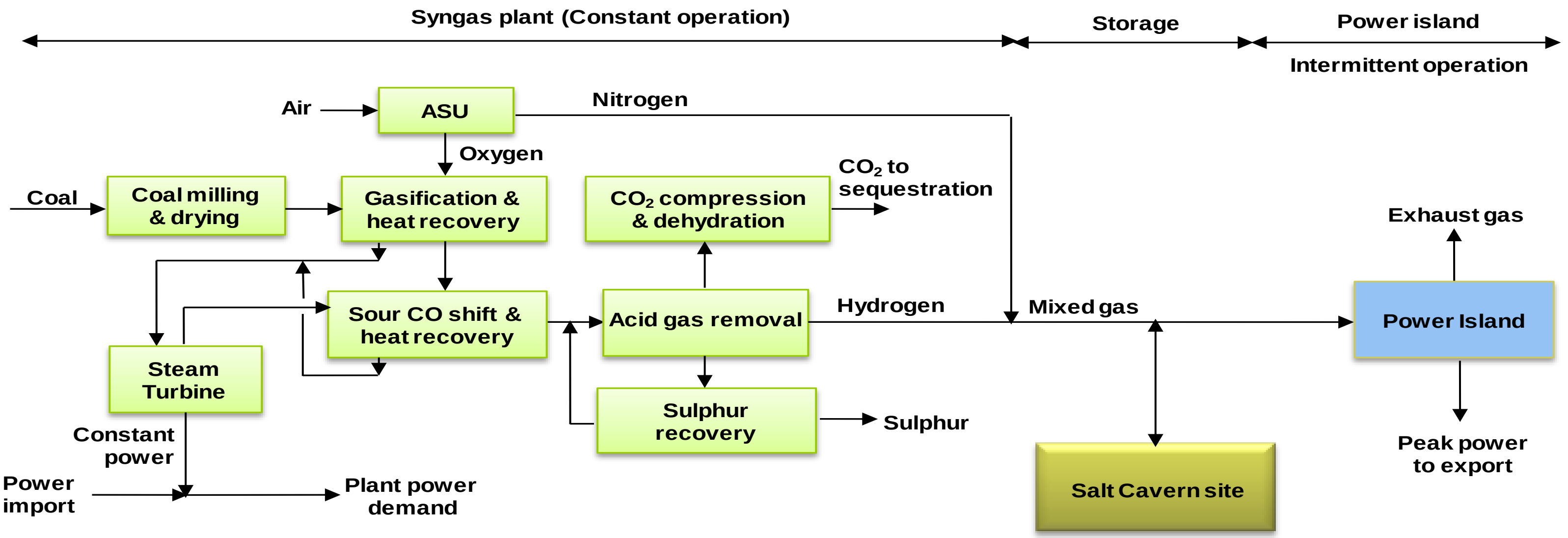
More than 10 gasification FEEDs, EPC and EPCm

Coal IGCC - Hydrogen-Rich Gas and SNG Production

Premise

- Evaluation of options for low-carbon flexible power generation by IGCC with CCS schemes incorporating underground storage of intermediate fuel gas
- Comparison of production and storage of hydrogen-rich fuel gas with that of substitute natural gas (SNG)
- Assessment of impact on overall plant efficiency, operational flexibility and cost for both hydrogen-rich and substitute natural gas storage options
- HYSYS®-based simulations of the IGCC flows scheme

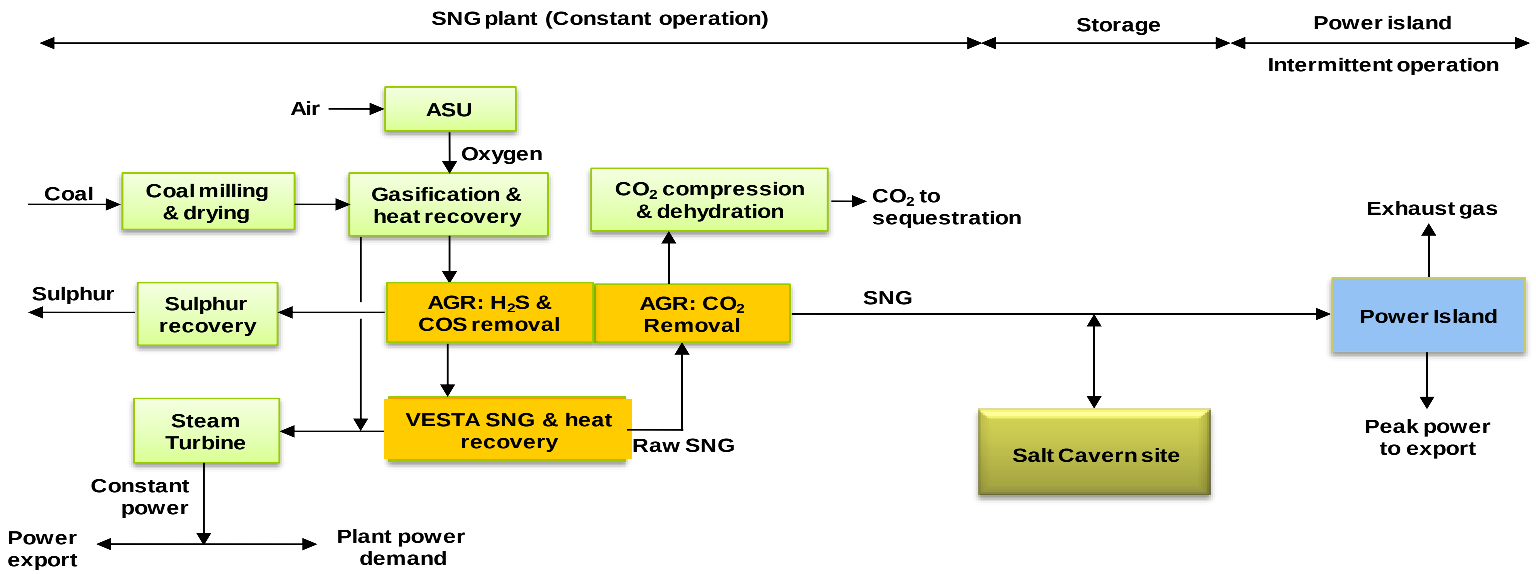
Hydrogen and Flexible Power Generation



Power Island Offline: The mixed gas will be diverted to the salt cavern

Power Island Online: The mixed gas fuel requirement for full load gas turbine operation will be supplied from both the syngas production plant and the salt cavern

SNG and Flexible Power Generation



Power Island Offline: The SNG will be diverted to the salt cavern

Power Island Online: The SNG requirement for full load gas turbine operation will be supplied from both the SNG production plant and the salt cavern

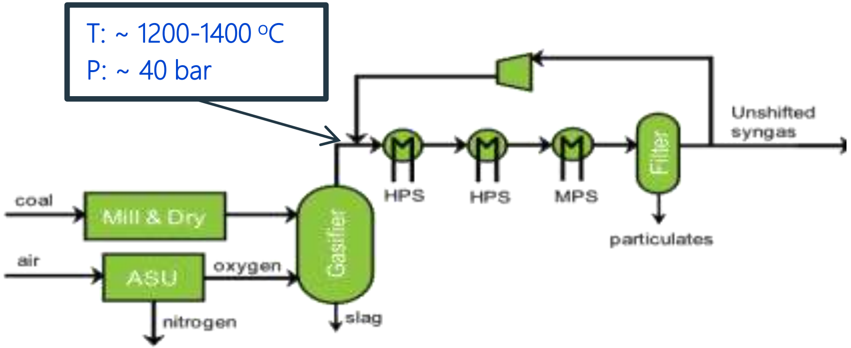
Gasification

Hydrogen Scheme

- Entrained flow dry feed gasification
- Particulate removal filtration
- Maximum heat recovery steam generation
- Air Separation Unit (ASU) to supply both O_2 for gasification and diluent N_2

SNG Scheme

- Same gasification system
- No diluent N_2 requirement from ASU



Hydrogen-Rich Gas and SNG Production

Hydrogen Scheme

- Multiple shift reactors in series with intermediate steam generation
- AGR unit to separate H_2S and CO_2 from the syngas by scrubbing with a physical solvent, e.g. DEPG, generating hydrogen-rich stream

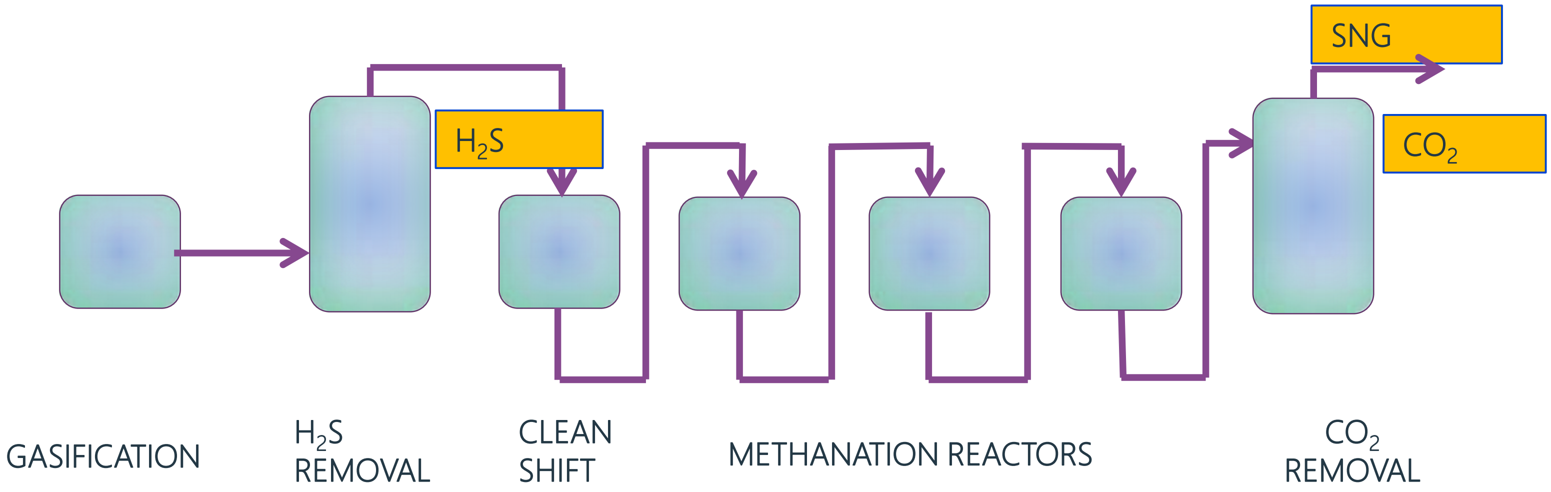
SNG Scheme

- AGR unit to separate H_2S and COS from the syngas by methanol wash
- Catalytic methanation (Wood's Foster Wheeler VESTA technology) of dry sulphur-free syngas to produce methane-rich gas
- CO_2 removal from methane-rich gas by second methanol wash stage integrated with the upstream AGR process to produce SNG quality gas

Wood's Foster Wheeler VESTA Methanation Technology

Wood - VESTA Methanation Technology

Innovative VESTA methanation technology produces Substitute Natural Gas (SNG) from gasification of fuel such as Coal, Petcoke, Waste, Biomass etc.



VESTA is a simple, safe and reliable process

VESTA Highlights

Catalytic methanation process:

- Methanation reactors filled with proprietary Clariant catalyst - Ni-based catalyst
- The catalyst has a higher conversion rate and wider operating temperature range (230-700°C) than conventional methanation catalysts.
- Long operational history and industrial references of the catalyst
- Once-through operation
- Temperature in the reactor does not exceed 550°C
- CO_2 and H_2O control the exothermic heat of reaction
- No recycle of CH_4 product to the syngas required: dilute with CO_2 and water
- No uncontrolled reaction

VESTA Highlights

Flexibility of syngas composition:

- SNG production is easy to operate and does not require strict control of the hydrogen / carbon ratio
- The product quality is therefore more stable and reliable.
- No need for sour gas shift

VESTA Pilot Plant in China

Wood (Amec Foster Wheeler) signed a cooperation agreement with Clariant International AG and Wison Engineering Ltd to build a pilot plant to demonstrate the Wood's Foster Wheeler VESTA technology.

VESTA Demonstration Plant in UK

Go Green Fuels, Swindon, UK

Project overview

Biomass to SNG project is funded by Department of Transport, UK as part of a programme to develop and commercialise technologies required to decarbonise the transport sector. The 4.5 MWth demonstration plant will produce enough compressed SNG to power 75 heavy goods vehicles.

The overall process will use Advanced Plasma Power's Gasplamsa® technology to convert biomass to syngas followed by Wood's Foster Wheeler VESTA SNG technology to convert syngas to substitute natural gas (SNG).

[Photo courtesy of Go Green Fuels & APP]

VESTA Demonstration Plant in UK

Underground Storage of Fuel Gas in Salt Caverns

Underground Storage of Fuel Gas & Flexible Power

Underground Storage in a Salt Cavern

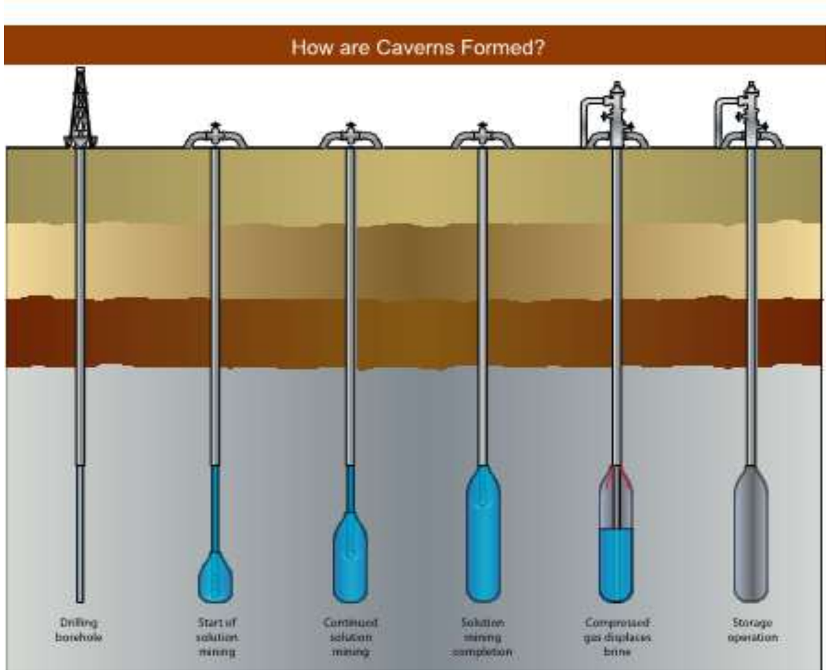
- Salt caverns are solution-mined cavities within salt domes or salt beds
- Suitable for gas storage due to its impervious nature
- Salt cavern size, the storage pressure and the operating pattern depends on thickness and depth of the halite salt bed or salt dome
- Caverns Pressure

  Constant pressure mode: Brine compensated

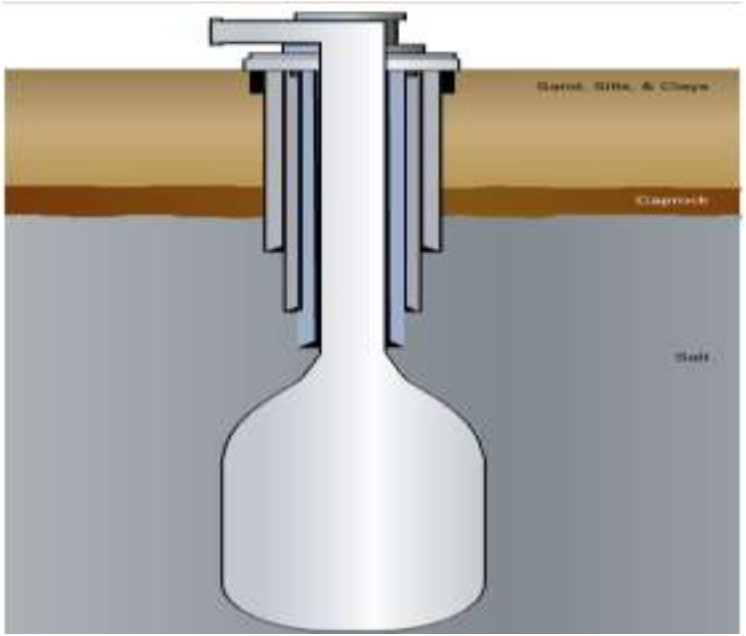
  Variable pressure mode: Pressure varies depending upon the net flow of gas into / out of the caverns
  Operating mode for the majority of current storage projects

- Cushion Gas: A certain volume of gas reserved to maintain the minimum cavern pressure and cavern safety

Underground Storage of Fuel Gas & Flexible Power



Source: TAM international gas storage, 2008

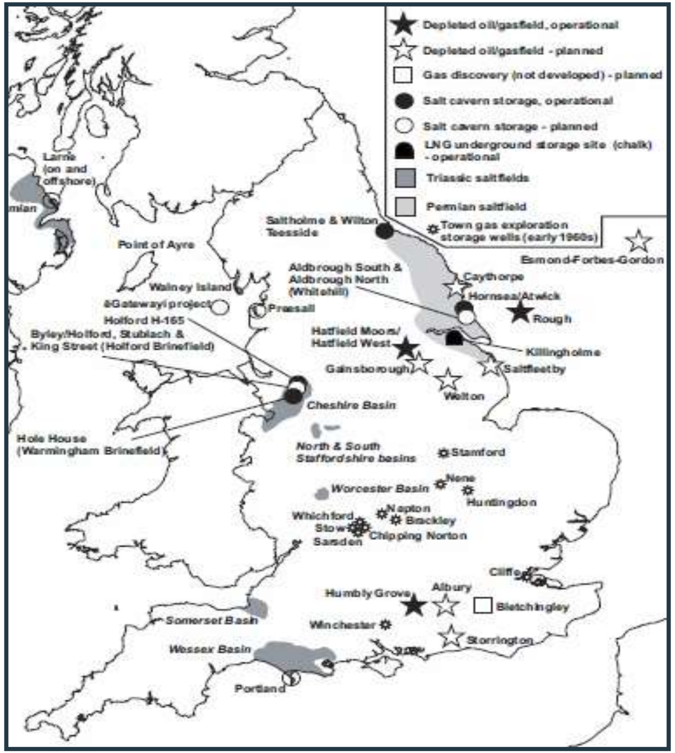


Idealised cavern in a salt dome formation

Underground Storage of Fuel Gas & Flexible Power

Salt Cavern for this investigation

- Cheshire basin as salt cavern site
- Storage pressure ~ 105 bar
- Salt cavern size ~ 300,000 m^3



Source: Underground gas storage, Geological Society, London, 2009

Flexible Power Generation via H_2 and SNG Scheme

Underground Storage of Fuel Gas & Flexible Power

Gas Turbines

Hydrogen Scheme

- GE Frame 9F syngas variant gas turbine - capable of firing hydrogen-rich gas
- Significant dilution of the hydrogen-rich fuel gas (from ~90% H_2 to ~50% H_2 in diluted syngas) required to limit NOx emissions
- Nitrogen dilution for this investigation
- Start-up with natural gas, with fuel switch-over to diluted hydrogen after the combined cycle operation has stabilised

SNG Scheme

- Conventional natural gas-fired gas turbines are suitable for SNG application
- No diluent required
- Mitsubishi 701F4 gas turbine for this investigation

Underground Storage of Fuel Gas & Flexible Power

Flexible Power Generation

The concept of flexible power generation is for the operational regime of the gas turbines to respond to market demand.

The grid demand patterns assumed for this investigation are as follows:

Diurnal scenario: 12 hours high grid demand during day and 12 hours low demand during night

Seasonal scenario: 8 months continuous peak power (winter) and 4 months low demand (summer)

Fuel Gas Storage: Fuel gas will be diverted to the salt cavern during low demand

The stored gas can be released for power production at peak times to meet the fluctuating supply/demand pattern of the grid

Underground Storage of Fuel Gas & Flexible Power

Storage Volumes and Number of Salt Caverns

Operating Mode	GT offline	Hydrogen Scheme		SNG Scheme	Storage Volume at 105 bara		Salt Cavern Size		Fuel gas to GT	
Single GT 100% load	Hours	H_2-rich gas (kg/h)	Diluent N_2 (kg/h)	SNG gas (kg/h)	Total Volume of H_2 Scheme (m^3)	Total Volume of SNG Scheme (m^3)	No. of caverns for H_2 Scheme	No. of caverns for SNG Scheme	H2+N2 gas for GT (kg/hr)	SNG to GT (kg/hr)
Reference Case (GT on 24 h)	0	56,000	276,000	62,400	-	-	-	-	332,000	62,400
Diurnal (GT on 12 h)	12	28,000	138,000	31,200	310,000	46,000	1	1	332,000	62,400
Seasonal (GT on 8 months)	2,920	37,333	184,000	41,600	25,450,000	3,765,750	85	13	332,000	62,400

Actual Storage Volume: Calculated based upon flow rate requirements for a single gas turbine operating at 100% load for different operational regimes

Total storage volume: Actual Storage Volume + Cushion Gas: ~90% for diurnal operation; ~60 % for seasonal regime

Underground Storage of Fuel Gas & Flexible Power

Hydrogen Storage vs. SNG Storage

Diurnal case: The actual cavern size for the hydrogen scheme is around three times bigger than for the SNG case

Seasonal operating modes:

SNG Scheme:

- Storage feasible using a maximum of 13 caverns per gas turbine
- The possibility of storing SNG in existing natural gas caverns enhances the project feasibility by eliminating the potential cost implications of new cavern construction

Hydrogen Scheme:

- An excessive number of caverns with the requirement for extensive and complicated cavern networking and infrastructure for seasonal operation
- The availability of suitable halite beds for such huge numbers of caverns is also questionable

Underground Storage of Fuel Gas & Flexible Power

No.	Hydrogen Scheme			SNG Scheme		
	Steady state operation	Diurnal operating regime	Seasonal operating regime	Steady state operation	Diurnal operating regime	Seasonal operating regime
Fuel gas via coal gasification						
Coal flow rate, te/h	153.5	76.7	102.3	187.5	93.7	125.0
Carbon captured, %	90%	90%	90%	67%	67%	67%
Fuel gas LHV to gas turbine, MWth	745.1	745.1	745.1	813.2	813.2	813.2
Power Balance						
Power Island output, MWe	438.0	219.0	292.0	467.3	233.6	311.5
Fuel gas production plant parasitic load, MWe	127.8	62.4	83.2	117.3	58.6	78.2
Fuel gas production plant power generation, MWe	69.9	34.9	46.6	140.8	70.4	93.9
Salt cavern power demand, MWe	-	4.6	3.5	-	1.0	0.9
Net Power Generation, MWe	383.1	186.9	251.9	490.8	244.4	326.3
Plant Efficiency (LHV), %	34.6	33.7	34.1	36.3	36.1	36.2

Underground Storage of Fuel Gas & Flexible Power

- The process plant capacity of the SNG case is increased by 22% to satisfy the higher thermal energy demand of the MHI 701F4 GT compared to GE Frame 9F gas turbine
- Parasitic demand for SNG case is lower than hydrogen scheme mainly as N_2 compressors are not required
- For SNG case, power generated in process plant is in excess of parasitic demand; power export from process plant
- Net peak power generation from SNG scheme is ~28-30% higher than hydrogen scheme
- The overall net plant efficiency for SNG case is ~1.7 percentage points higher for the steady state operation whereas ~2.1-2.4 percentage points higher for flexible power generation schemes
- 90% carbon capture achieved for hydrogen scheme compared to only 67% for SNG case without post-combustion capture from the power island flue gas

Underground Storage of Fuel Gas & Flexible Power

No.	Hydrogen Scheme			SNG Scheme		
Installed Cost	Steady state operation	Diurnal operating regime	Seasonal operating regime	Steady state operation	Diurnal operating regime	Seasonal operating regime
Fuel gas production plant, US$m	822	524	632	964	614	740
Salt cavern storage, US$m	-	195	1712	-	140	322
Power island, US$m	290	290	290	310	310	310
Total installed cost (TIC), US$m	1113	1009	2634	1273	1064	1372
EPC cost, US$m	1391	1262	3292	1591	1329	1715
Average Power Generation, MWe	383.1	186.9	251.9	490.8	244.4	326.3
EPC Cost per MW export power, US$m / MW	3.6	6.8	13.1	3.2	5.4	5.3

Note:
1) The estimate is based on 4Q 2018 price level with ±40% cost basis
2) British Pound to US Dollar conversion rate of 1.3
3) The total EPC cost is the installed cost of the plant with 25% contingency

Underground Storage of Fuel Gas & Flexible Power

Steady State Operation

- Total plant cost of the SNG system is ~ 14% higher as bigger process plant
- Cost per MW of exportable power is ~ 11% lower for SNG system as more net power output than hydrogen scheme

Flexible Power Generation

- Salt cavern cost is the differentiating factor
- Diurnal Case: The gas production plant for the SNG case is ~ 17% more expensive, but compensated by lower salt cavern cost
- Seasonal Case: The hydrogen scheme cost is nearly double the SNG case mainly because of the construction cost for the 85 salt caverns compared to 13 caverns

Underground Storage of Fuel Gas & Flexible Power

Hydrogen Scheme Highlights

- Hydrogen route is a viable option for flexible peak power generation mainly for short-term storage system
- This scheme is not attractive for long-term storage as excessive number of caverns requirement
- 90% carbon capture can be achieved
- Net plant efficiency for flexible power generation scheme is comparable with the steady state operation
- Cost per MW export power is approximately double for diurnal flexible power generation mode

Underground Storage of Fuel Gas & Flexible Power

SNG Scheme Highlights

- SNG route is a viable option for flexible peak power generation for both short-term and long-term storage system
- Diurnal storage caverns may be eliminated altogether, depending on the storage capacity of the existing natural gas network
- Cavern requirement is drastically reduced for long-term storage
- Existing natural gas salt caverns can be used for SNG storage
- Existing installed CCGT can run on SNG without any modification of gas turbine
- In markets experiencing high LNG / NG import costs, it may be attractive to install coal-based SNG to be used in existing grid power plant
- Flexibility to switch between power generation, storage and public gas supply operating modes
- ~ 0.9 and 1.3 million tonnes per annum of CO_2 captured for seasonal and diurnal operating regime respectively

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