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Overview of Advanced Hybrid Concepts

Realizing Vision 21 with fuel cell / gas turbine hybrids

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Overview

- Achieving high efficiency AND low cost together
- Fuel flexibility
- Synergistic revenue streams
- Load flexibility – the generation mix in a Vision 21 world
- Conclusions

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Achieving high efficiency AND low cost together

- Fuel cell hybrids
- Reducing $/kW for SOFC in general
- Cost benefits of pressurised operation at high temperature
- Comparison of atmospheric and pressurised systems
- Configuration , FMEA and the need for specialist turbomachinery

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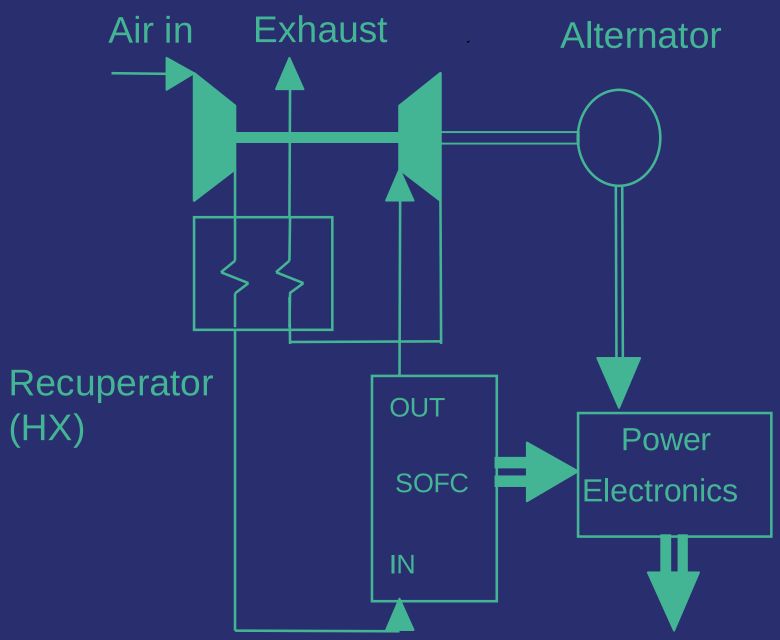
SOFC/GT hybrids

- Air side of fuel cell enclosed in gas turbine
  - – Fuel cell at pressure but separate flow
- Recuperator (Heat exchanger) allows air in to be heated by air out
- Heat from fuel cell converted into electrical power by alternator
- Heat from fuel cell provides compression for free
- High efficiency (55-70+%)
  - – Supports capital cost difference from conventional plant (GTs etc)



Simple pressurised SOFC/GT hybrid showing air side flows only

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Two ways to reduce $/kW

Reduce $

- Improve system integration
  - – Purpose-designed and integrated components can be spec'd to suit fuel cell
  - – General purpose components are over-spec'd for specific fuel cell application
- Reduce stack size and weight
  - – Reduces overall system size, weight and cost

Increase kW

- Increase stack efficiency
- Increase stack power
  - – Increasing cell current density incurs greater I^2R losses and reduces efficiency
- Increase system power and efficiency
  - – Pressurised hybrid has higher power and efficiency than raw stack
- Increases in kW show up twice in cost of electricity
  - – CoE = Fn(**$/kW**,ADR ,η)

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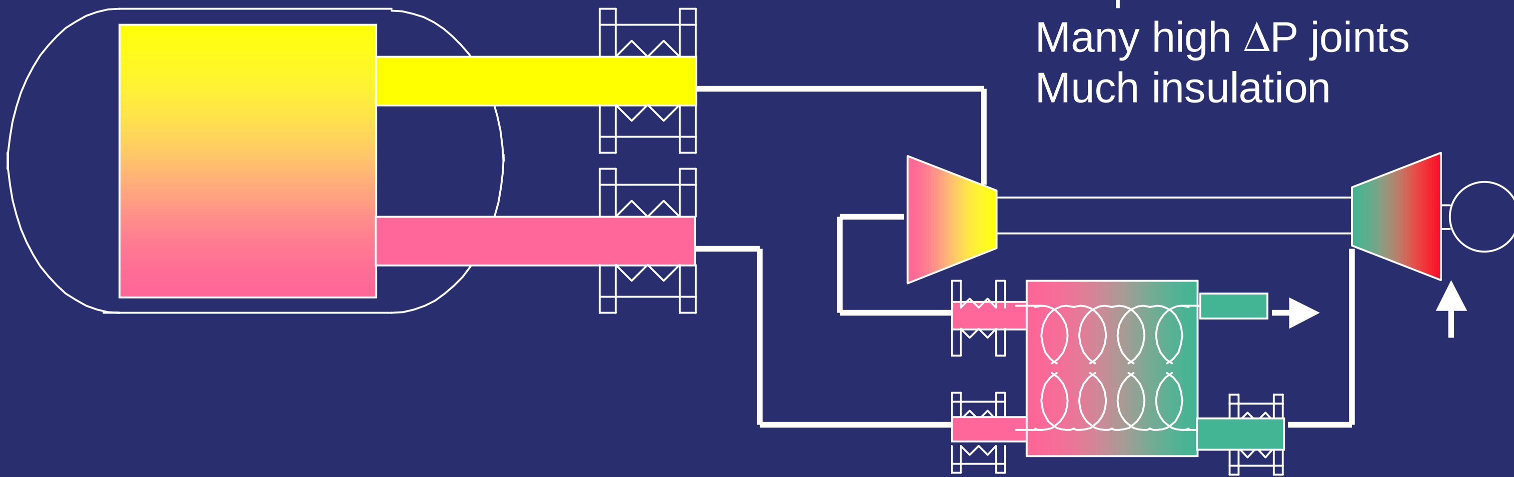
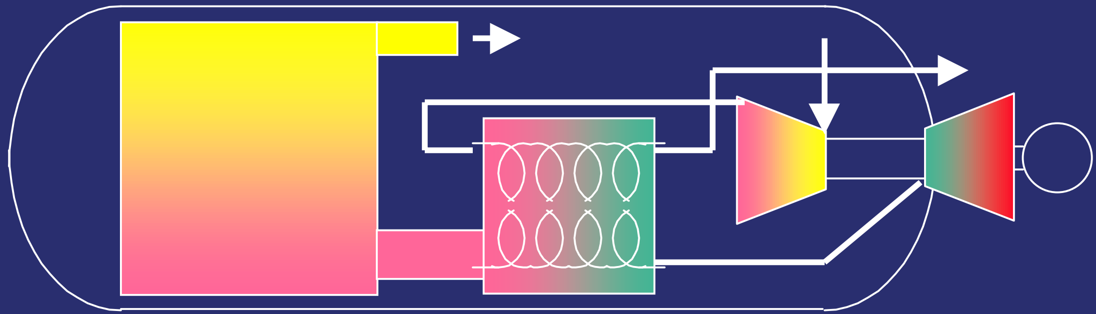
Benefits of close integration for pressurized hybrid

Non-Integrated
Hot pressure balanced bellows
Many high ΔP joints
Much insulation



Integrated
Few high ΔP joints
Careful thermal zoning



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Cost reduction with SOFC systems in general

- SOFC can use cheap electrode materials
  - High temperature chemistry has fast kinetics
- Anode exhaust provides water for reforming
  - No need for elaborate water management/humidification
- Easy to use heat output from stack
  - 800+°C difference with ambient makes thermal management simple
- Hard to poison high temp stack
  - System simplified – no need to backup fuel processing components
  - Thrives on CO
  - Happy with CO_2, NH_3

Simple fuel processing - Internal reforming benefits
  - No need for water gas shift reactors or selective oxidiser
  - Elimination of HXs – fuel at temperature
  - Richer fuel supply
- Close integration of fuel processing cuts cost
  - Internal reforming provides significant portion of stack cooling
- Affordable fuel flexibility
  - Can accommodate wide range of CO / H_2 mixtures

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Direct benefits of pressure

- Pressurisation reduces pressure drops caused by flows
- Pressurisation reduces pumping work required to overcome pressure drops
  - Allows greater power density through reduction in passage size (ΔP goes as h^4)
  - Reduction in stack volume big driver for overall system cost
- Reduces area and cost of heat exchangers
- Increases cell performance
  - 50% stack efficiency → 57% at 5 bar
  - Translates to $/kW –14%

Direct effect of pressure on key parameters	
Pressure drops	$1/P$
Pump work	$1/P^2$
Heat exchanger area (based on U_{press}/U_{amb})	$1/P^{0.5}$ – $1/P^{0.8}$
Cell performance ΔV mV	59 log Pr

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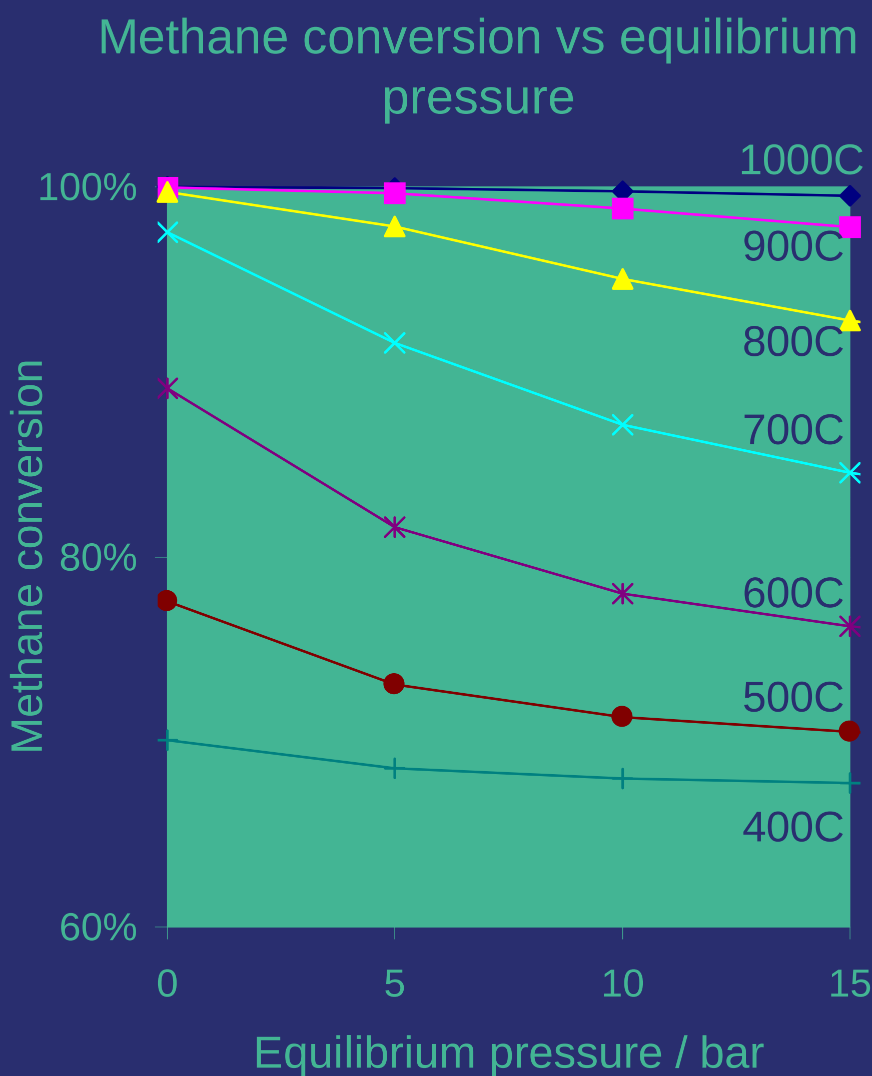
Pressurisation and temperature

- High temperature provides work to drive air through stack
  - Turbine work goes as $T_{in} - T_{out}$
- Reforming at pressure needs temperature
  - Reforming equilibrium leaves fuel unconverted at lower temperatures
  - Favourable equilibrium and internal reforming enable fuel conversion within stack
  - External reformer eliminated (unless higher hydrocarbons present)



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Turbomachinery cheaper than heat exchanger

- Incoming flows can be heated by
  - Heat exchanger
  - Compression in turbomachinery
- Fuel cell exhaust can be brought down in temperature by
  - Heat exchanger
  - Expansion in turbine
- Heat exchange is low velocity process (m/s)
  - Large amounts of metal per unit massflow
- Turbomachinery uses high velocities (300+m/s)
  - Very small amounts of metal per unit massflow
  - Lower cost than heat exchange especially for high temperatures
  - Materials used in turbines are unaffordable in heat exchanger quantities
- Turbocharging of fuel cell provides blower function
  - Work for compressor comes from fuel cell waste heat

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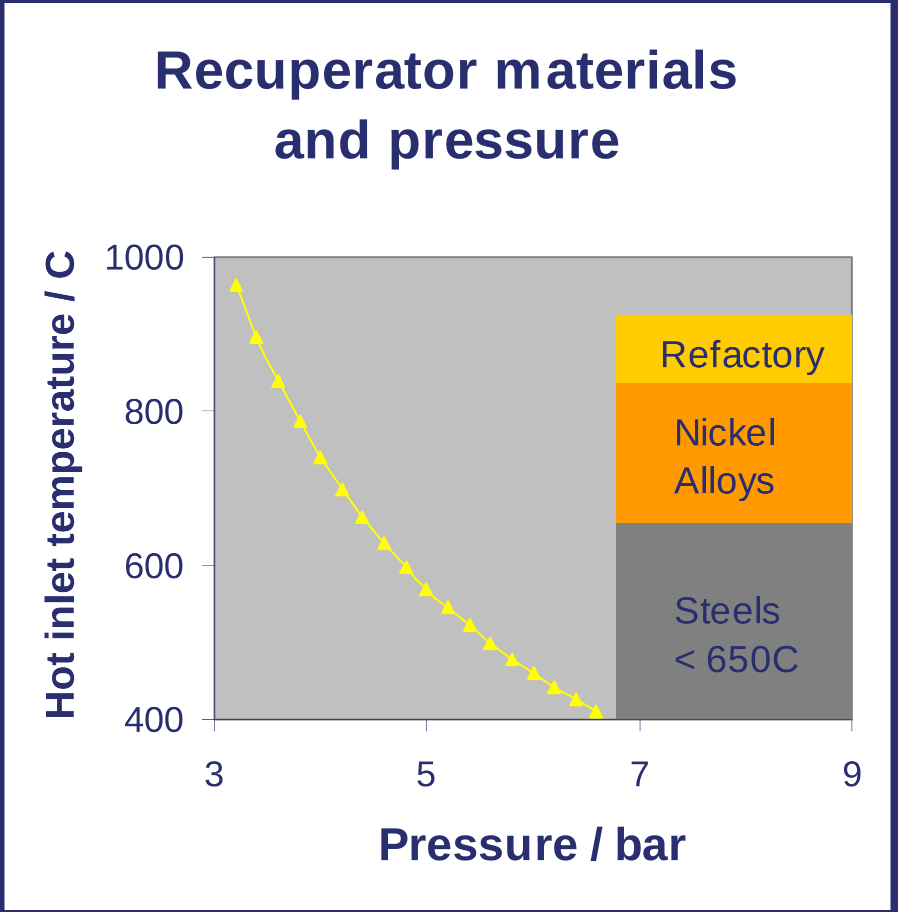
Indirect benefits of pressurisation

- Small turbine brings down flow temperature to suit low cost heat exchanger materials
- Temperature drop increases with system pressure
- Heat exchanger cost at high temperatures exacerbated by welding in heat exchanger
- Lower stack temperature? HX cost only benefits when stack temperature hits 650C
  - Too low for kinetics
  - Too low for efficient pressurisation to achieve power density



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Pressurised and atmospheric compared

- Identical stack in pressurised and atmospheric configurations
  - Near term SOFC stack
  - Underlying stack efficiency 50%
  - System efficiency exceeds stack efficiency for pressurised case
- $/kW better by 684/1051 = 0.65 at pressure if $ cost identical
  - Atmospheric recuperator must be exotic material
  - Pressurised recuperator can be stainless steel

	Atm	**Press'd**
Efficiency Net AC LHV	44%	67%
Net power kW	684	1051
Recuperator hot inlet temp °C	871	576

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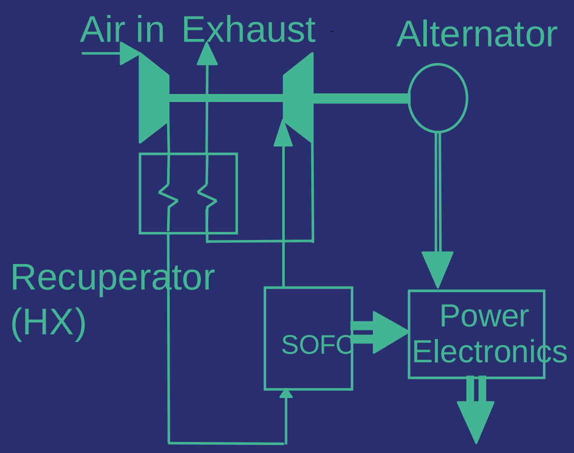
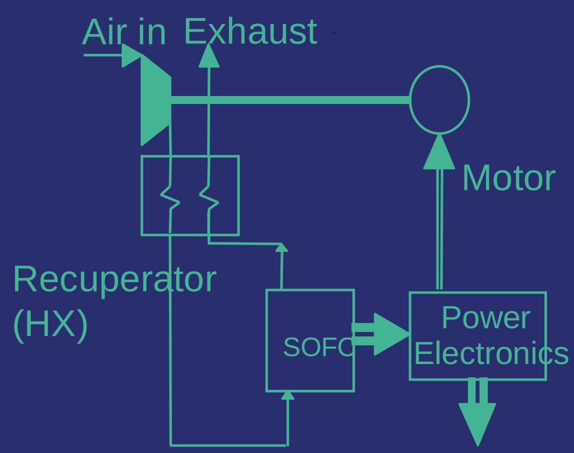
Pressurised system can be cheaper

- Atmospheric system is very little simpler than pressurised hybrid
  - Still need blower
  - Alternator changed for motor
- Savings on heat exchanger cost cover cost of turbine and pressure vessel
  - GT is much smaller than fuel cell
- Reduced volume of mature pressurised stack offers potential for pressurised hybrid cost below atmospheric system cost
  - Even before increased kW of hybrid considered





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SOFC/GT hybrid economics

System cost FOB $/kW	Net AC efficiency LHV	c/kWh	Other parameters
2000	54%	9.9	ADR = 10% 12yr capital recovery 90% Utilisation $4/MMBtu gas
1300	63%	7.1	ADR = 12% 15yr capital recovery 90% Utilisation $5.1/MMBtu gas
630	70%	3.6	ADR = 10% 15yr capital recovery 90% Utilisation $2.6/MMBtu gas

Quoted cost is Free-on-board factory gates (FOB). Calculated cost of electricity assumes installed system cost as 1.5 x FOB and includes allowances for fixed and variable maintenance

- Calculations are for hypothetical hybrids using commonly quoted costs and performance
- Cost of electricity estimates (c/kWh) are for ~MW sized units except last case
- Last case is long term for 20MW+ scale unit
  - Lower annual discount rate (ADR) on capital investment
  - Better fuel price
  - Higher efficiency consistent with more complex plant at large scale

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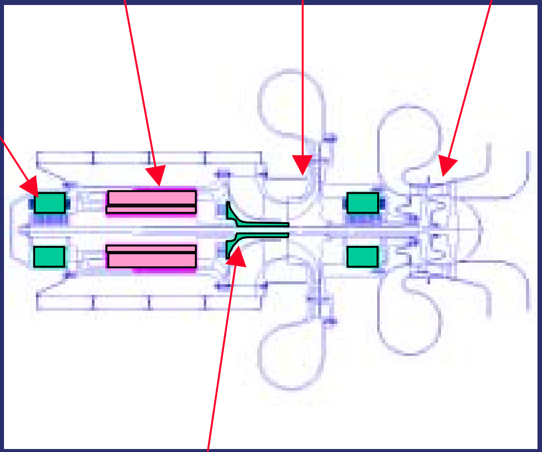
Configuration, FMEA and the need for specialist turbomachinery

- System configuration's are driven by Failure Mode and Effect Analysis
- Keeping configuration simple is key to lowering cost
- Turbomachinery needs to be designed with failure modes to suit fuel cell system
- Turbomachinery will need to be optimised to suit hybrid system cycle
  - Compressor/turbine matching, temperatures, alternator characteristics
- Significant work in this area at Indianapolis, Derby



Novel oil-free turbogenerator concept from DOE hybrid turbine programme

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Fuel flexibility – key issues for hybrids

- Widening primary fuel range of fuel cell hybrids key to strategic energy objectives
- Only methane can tolerate the stack environment of an efficient hybrid
  - Efficiency with low cost needs pressure
  - Pressure works well with high temperature
- Need specialist pre-reforming outside stack that can convert C_2, C_3 etc to methane + CO + H_2

- Sulphur tolerance has a sting in the tail
  - Poison for all fuel cells but increasingly reversible at higher temperature
  - Can design high temp fuel cell systems that permit breakthrough in some failure modes
  - **Developing fuel cells further to tolerate *bulk* sulfur will create a whole new class of emissions**
  - Advanced pre-processing is key with stack tolerance used to simplify system configuration

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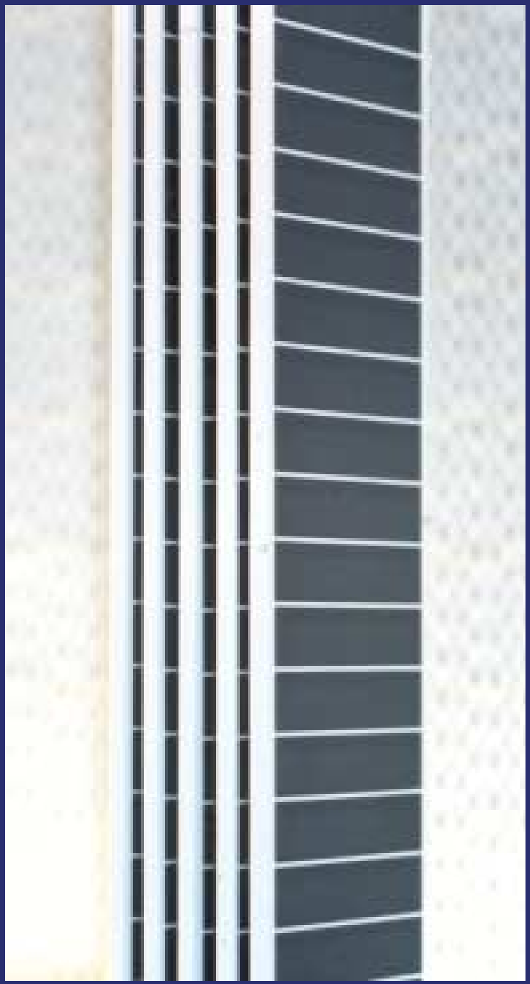
A fuel flexible stack design – purpose developed for pressurized hybrid use

- Thin flat tubes in Rolls-Royce IP-SOFC
  - High kW/litre for any given W/cm^2
  - Improved heat and mass transfer
    - Allow lamda increase for fuels with lower endotherm
- Good starting point for fuel flexible cell (although we're focused on natural gas)
  - Potential for raising operating temperature
  - Anode on the inside design
  - Cheap inert support
- Sealing is easier at pressure
  - Lower pressure drops across stack components
- Good for round holes
  - Designed for pressurized use



40 cell Rolls-Royce IP-SOFC tubes

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Additional revenue streams

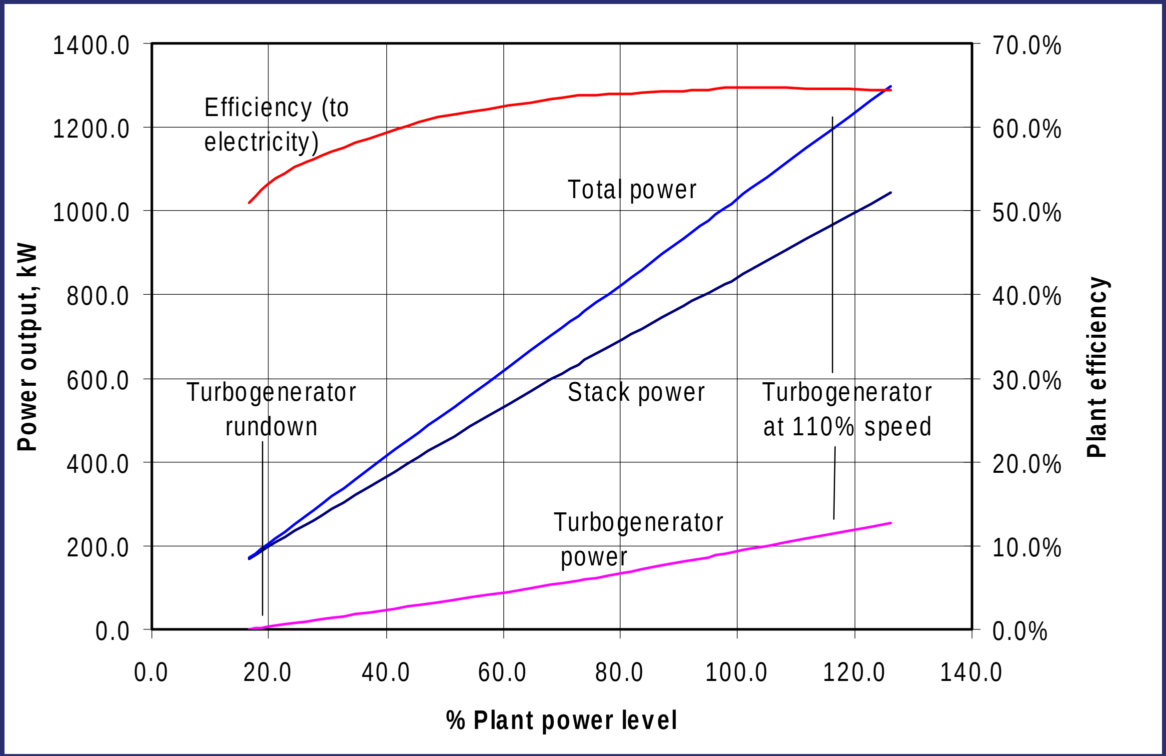
Benefits

- Unused reformate can form basis for feedstocks either directly as reformate or after processing to add value
- Sequestred CO_2 could have significant future value with carbon trading
- Concentrated anode stream from high temperature fuel cell makes both more attractive

Challenges

- Taking hydrogen bearing mixture out of stack core significantly complicates a power generation focussed plant design
- Nitrogen present in fuel makes sequestration much more challenging
  - **Sequestration much more challenging for coal and biomass than for natural gas or distillates**

Load flexibility and generation mix



- SOFC/GT hybrids have unique part load efficiency
- Significant development effort will need be expended on developing hybrid dynamics
- Conventional planar stacks could be limiting element unless other designs developed

- In a world with advanced hybrids there will be market demands to use hybrids for increasing degrees of load following
  - Especially important in developing nations wanting to trade CO_2

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Conclusions 1

- Pressurised fuel cell hybrid costs benefit directly and indirectly from pressurisation
- Combined efficiency and $/kW potential for pressurised hybrids is exceptional
- Pressurised hybrids have greater potential to exploit benefits of mature fuel cell technology
  - Can fully exploit increases in power density (kW/litre) to reduce overall system cost
- Highly integrated systems will be needed and these cannot be built from off-the-shelf components
  - Specialist turbomachinery will need to be developed

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Conclusions 2

- Additional revenue streams are attractive but will draw plant design in different direction to modular standardised designs used for DR/DG
  - Appropriate emphasis needed
- Fuel flexibility may push stack operating temperatures up
- Dynamics for load following will drive stack designs away from conventional planar design
- Specialised stacks for hybrid use need to be developed in parallel with the hybrid system
  - Significant for SECA

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