Air Handling for Fuel Cells in Heavy Duty Applications

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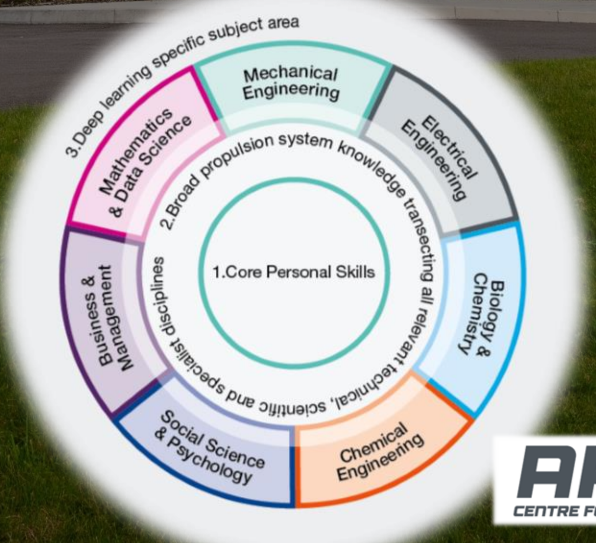
ADVANCING PROPULSION

IAAPS - overview

- A world-leading centre of excellence in advanced propulsion research and innovation.
- A new focus on transdisciplinary research through the CDT AAPS
- Engaging with industry to support the accelerated development of zero emission propulsion technologies.
- 11,500sqm of research centre Located at the Bristol and Bath Science Park.
- Funded by West of England Combined Authority, Research England and the University of Bath.



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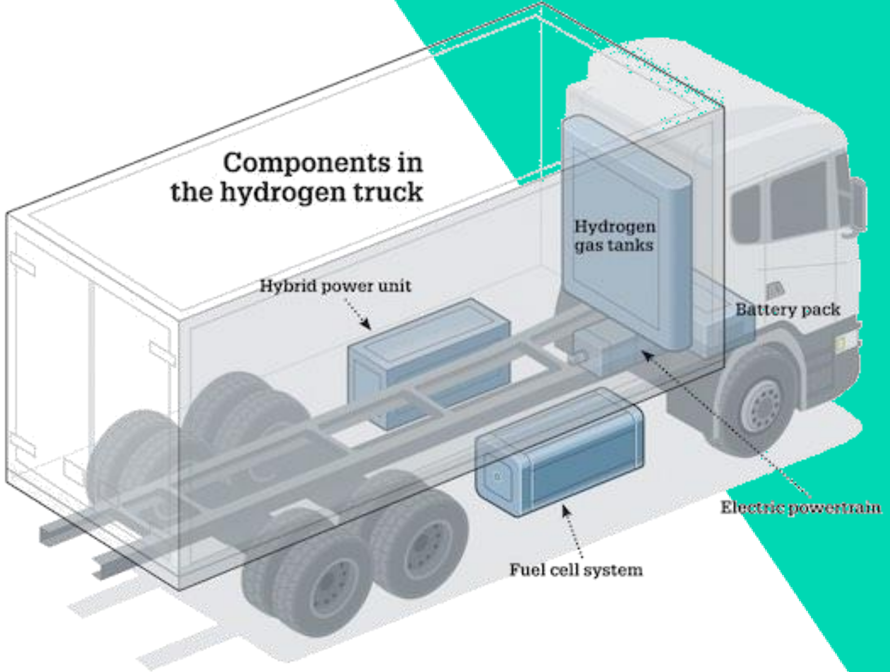
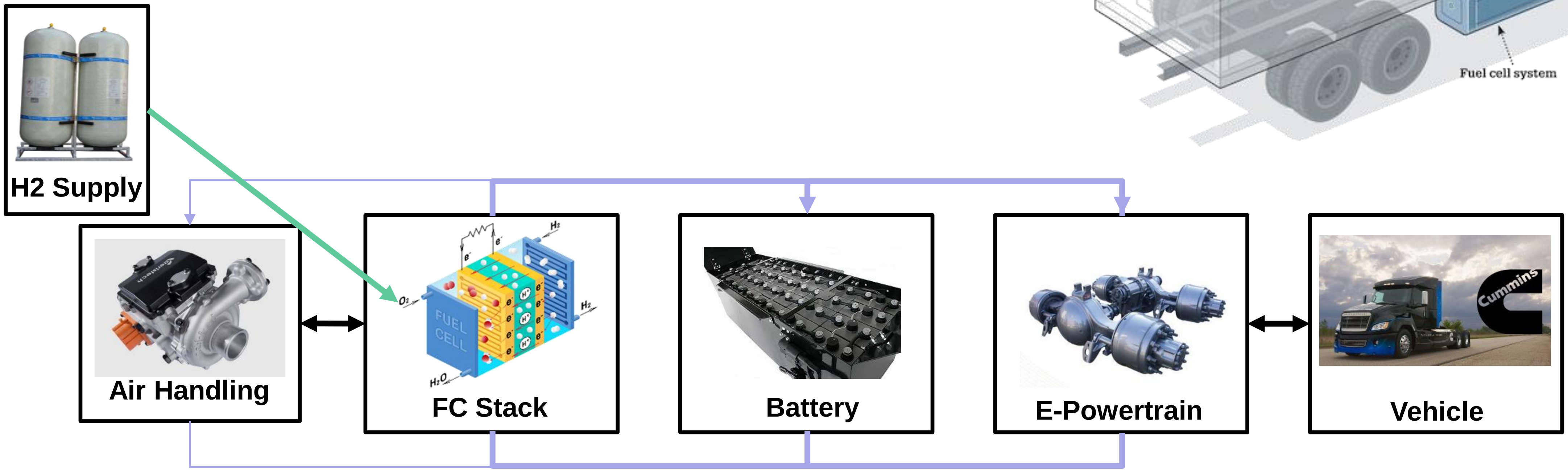
FC Propulsion System



- Primary Power Source is Hydrogen Storage
- Fuel Cell System provides electrical power
- Battery acts as energy buffer and opportunity to recuperate energy
- Electric Traction System delivers tractive effort



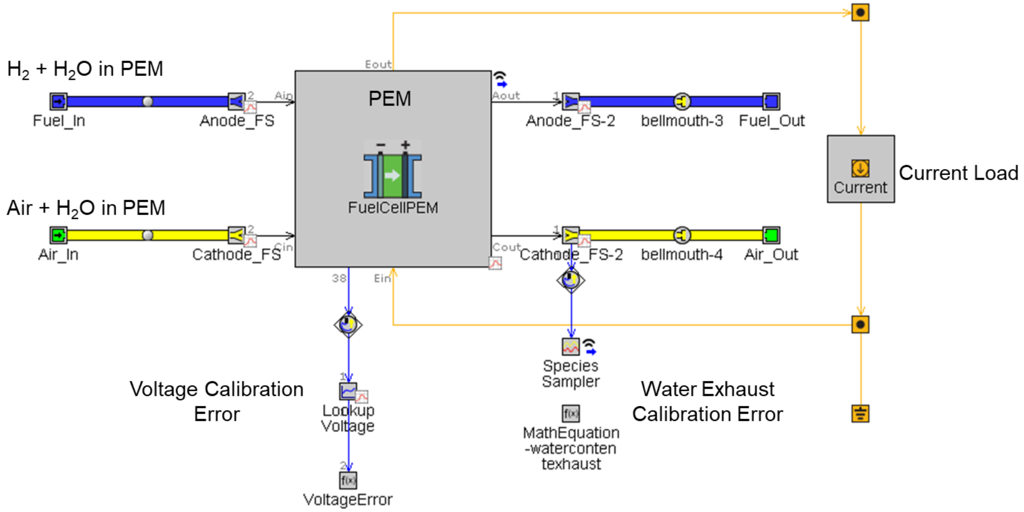
FC Stack Characteristics

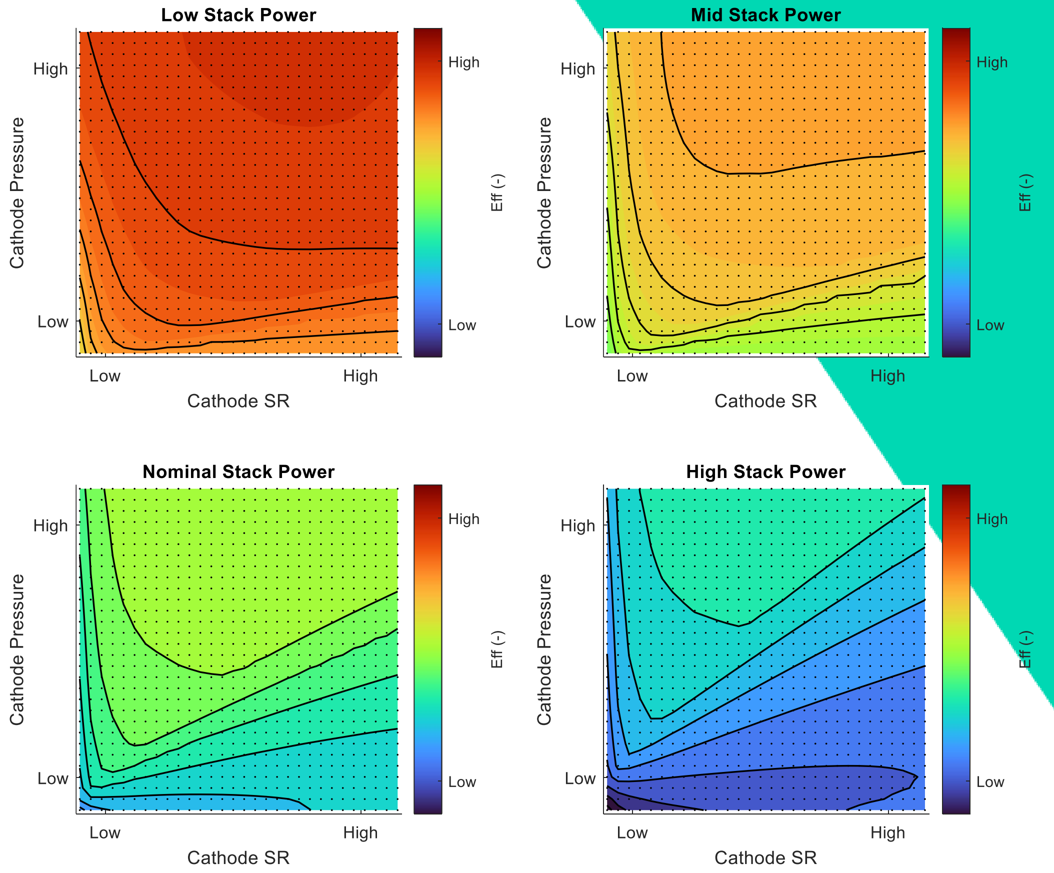
At a given power, the FC operating point is controlled by

- Stoichiometric ratio = Air flow
- Cathode Pressure

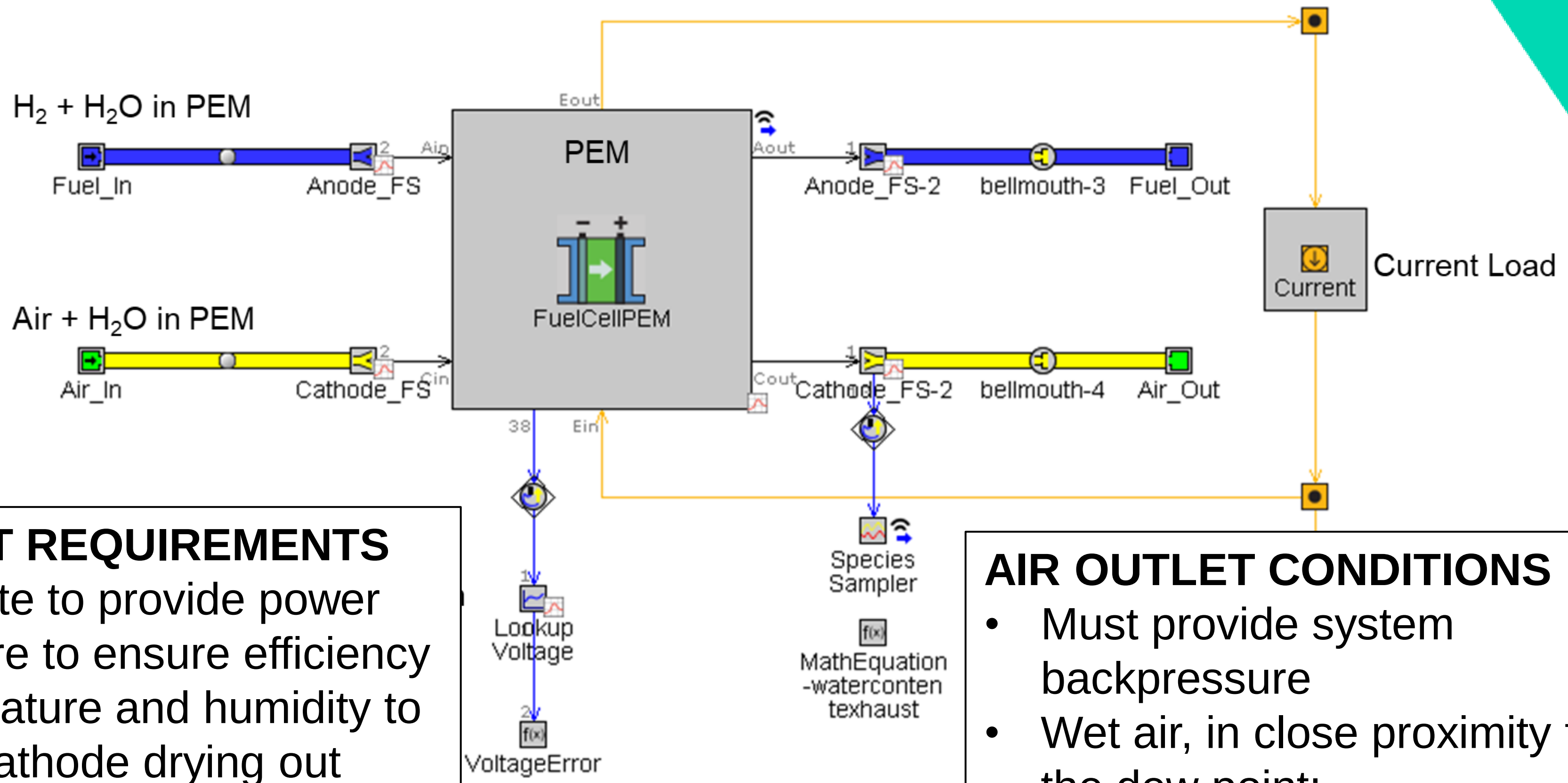
Increasing either typically leads to

- Increased stack efficiency
- Higher power requirements for the air path





Air Path Requirements



AIR INLET REQUIREMENTS

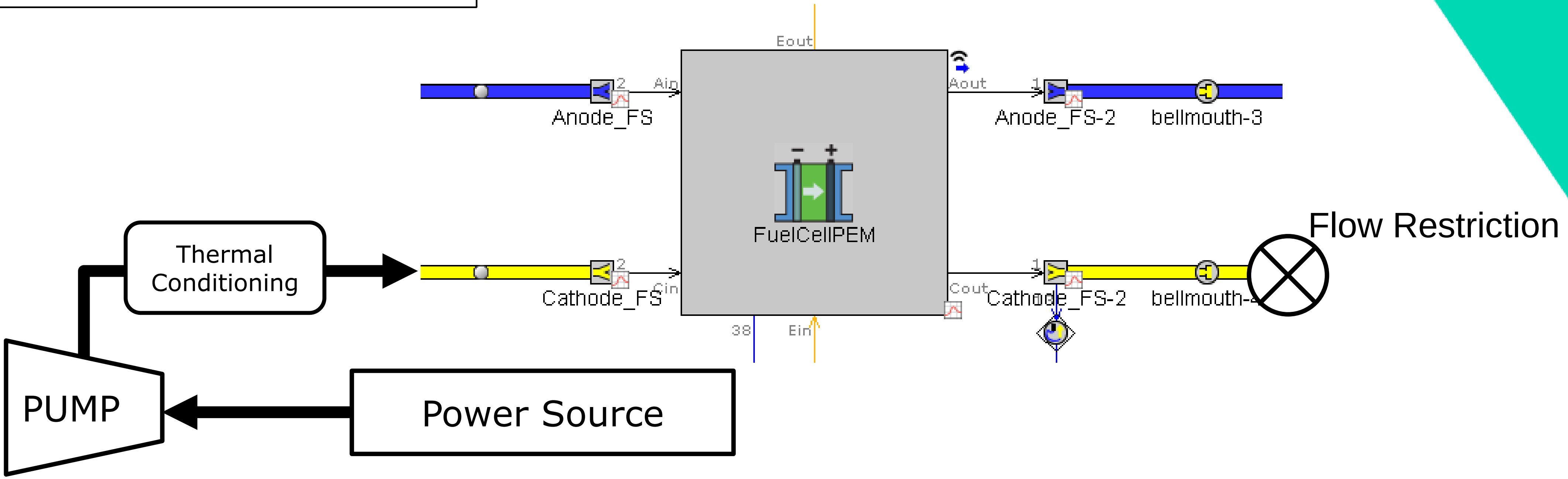
- Flow rate to provide power
- Pressure to ensure efficiency
- Temperature and humidity to avoid cathode drying out

AIR OUTLET CONDITIONS

- Must provide system backpressure
- Wet air, in close proximity to the dew point:
  - ~60°C -100°C
  - ~100% humidity

Basic Air Path requirements

AIR INLET REQUIREMENTS
- Flow rate to provide power
- Pressure to provide efficiency
- **Temperature and humidity to avoid cathode drying out**



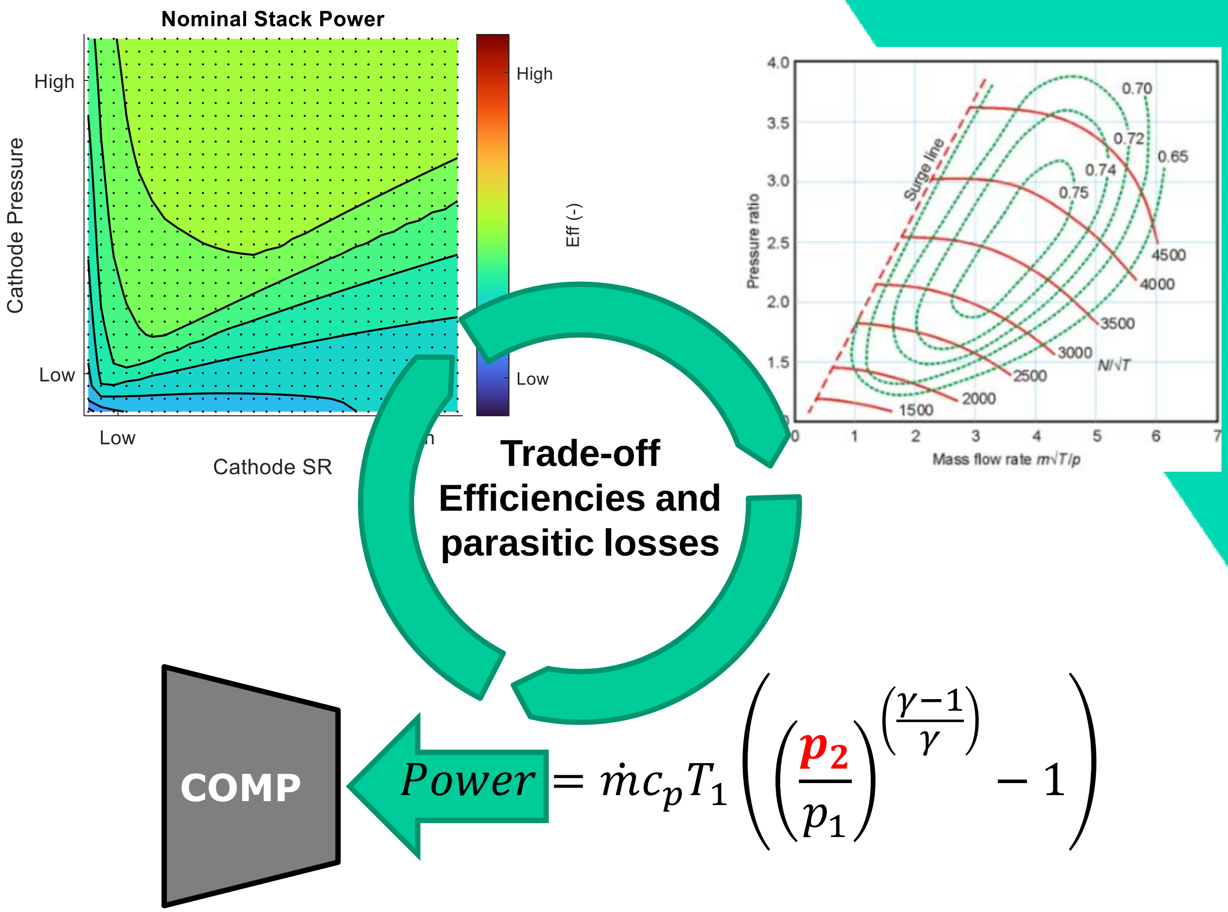
Matching Challenge

Balancing

- the stack efficiency – Which improves with higher operating pressure
- The parasitic loss of the air path – which will increases with higher pressure ratios
- The turbomachinery efficiency – which will vary based on operating point

So for example, increasing the cathode pressure may

- Improve stack efficiency +
- Increase e-compressor required power -
- Increase the compressor efficiency +
- The balance of these opposing effects will determine the optimal configuration

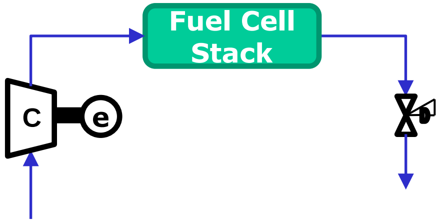


$$Power = \dot{m} c_p T_1 \left(\left(\frac{p_2}{p_1} \right)^{\left(\frac{\gamma - 1}{\gamma} \right)} - 1 \right)$$

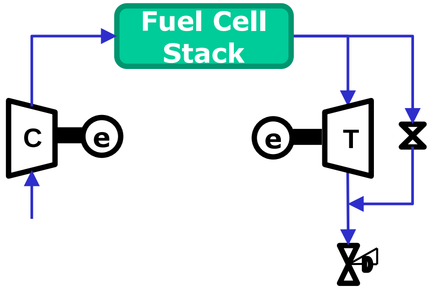
Range of Architectures

Single Stage Compression

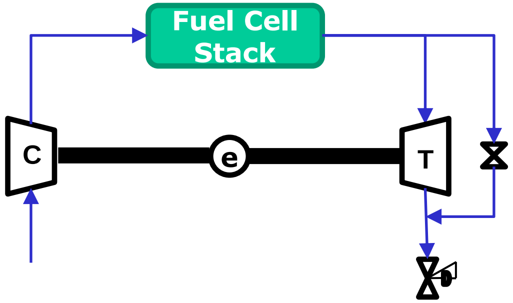
E-COMPRESSOR



E-COMP + E-TURBINE

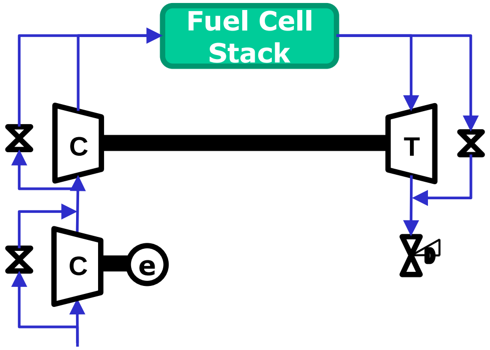


E-TURBO

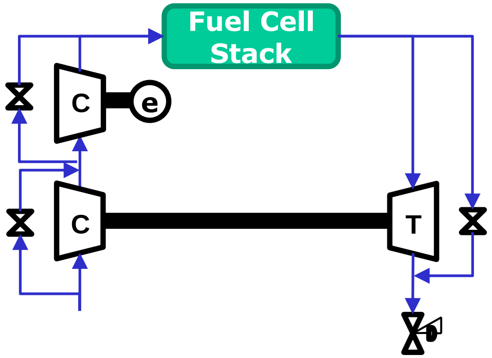


Two Stage Compression

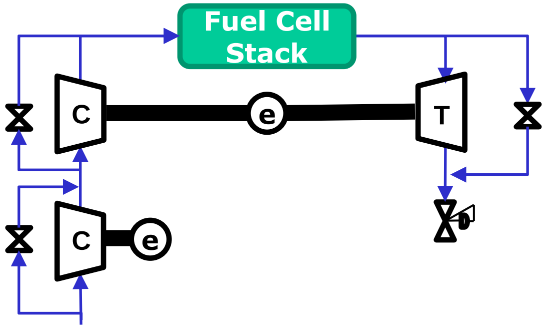
TURBO + E-COMPRESSOR



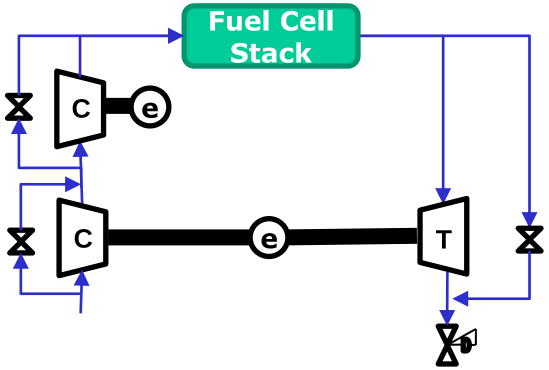
E-COMPRESSOR + TURBO



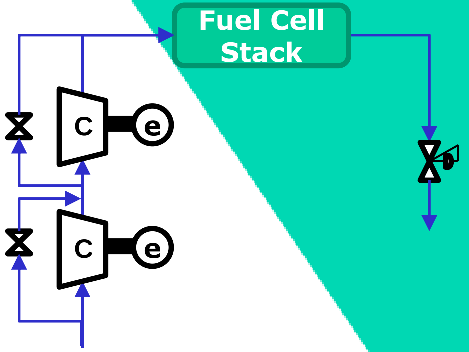
E-TURBO + E-COMPRESSOR



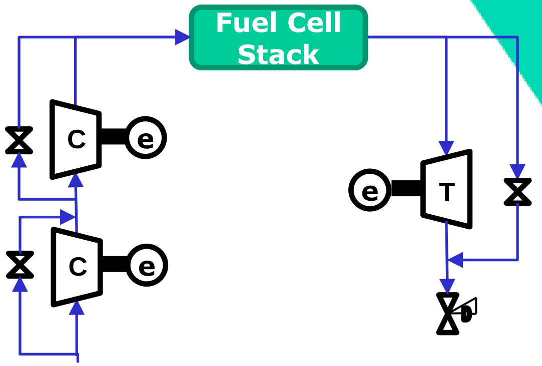
E-COMPRESSOR + E-TURBO



2 E-COMPRESSOR



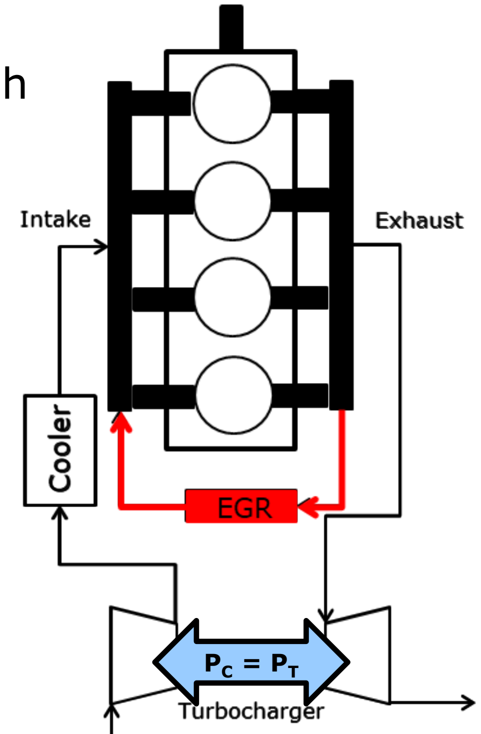
2 E-COMPRESSOR + E-TURBINE



Should we use an Exhaust Turbine?

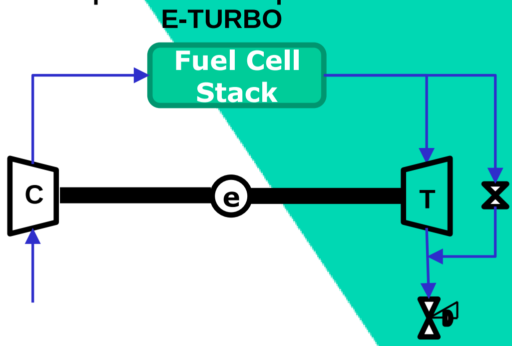
Diesel Engine

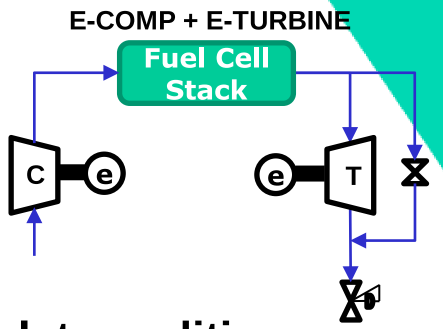
- Use of turbine is obvious – high exhaust enthalpy
- Turbine provides power for compressor
  - Constraint on turbine choice
  - At all operating points, the turbine must provide enough power to drive the compressor
- Turbine and EGR Flows
  - Lower back-pressure for low PMEP
  - High enough back-pressure to create dP for EGR flow



Fuel Cell

- Exhaust enthalpy alone is insufficient to drive compressor
- ➔ ***The argument to include a turbine is less clear***
  - AGAINST: Omission of turbine simplifies air path considerably
  - FOR: Still some power extraction possible
- ➔ ***Turbine/Compressor power balance not required***
  - More flexibility on choice of turbine
  - Coupled E-TURBO: Speed matching is still required
  - Decoupled E-TURBO: trade-off eMachine efficiency vs. turbine efficiency with eMachine cost penalty





Important comments on turbine inlet conditions

- Turbine inlet conditions are very close to dew point
- Flow is steady and not pulsating

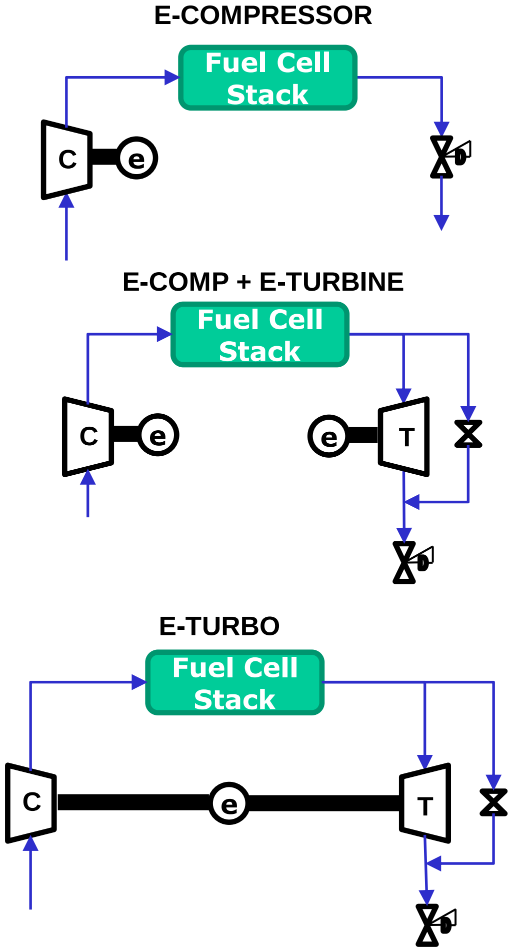
Example Matching analysis

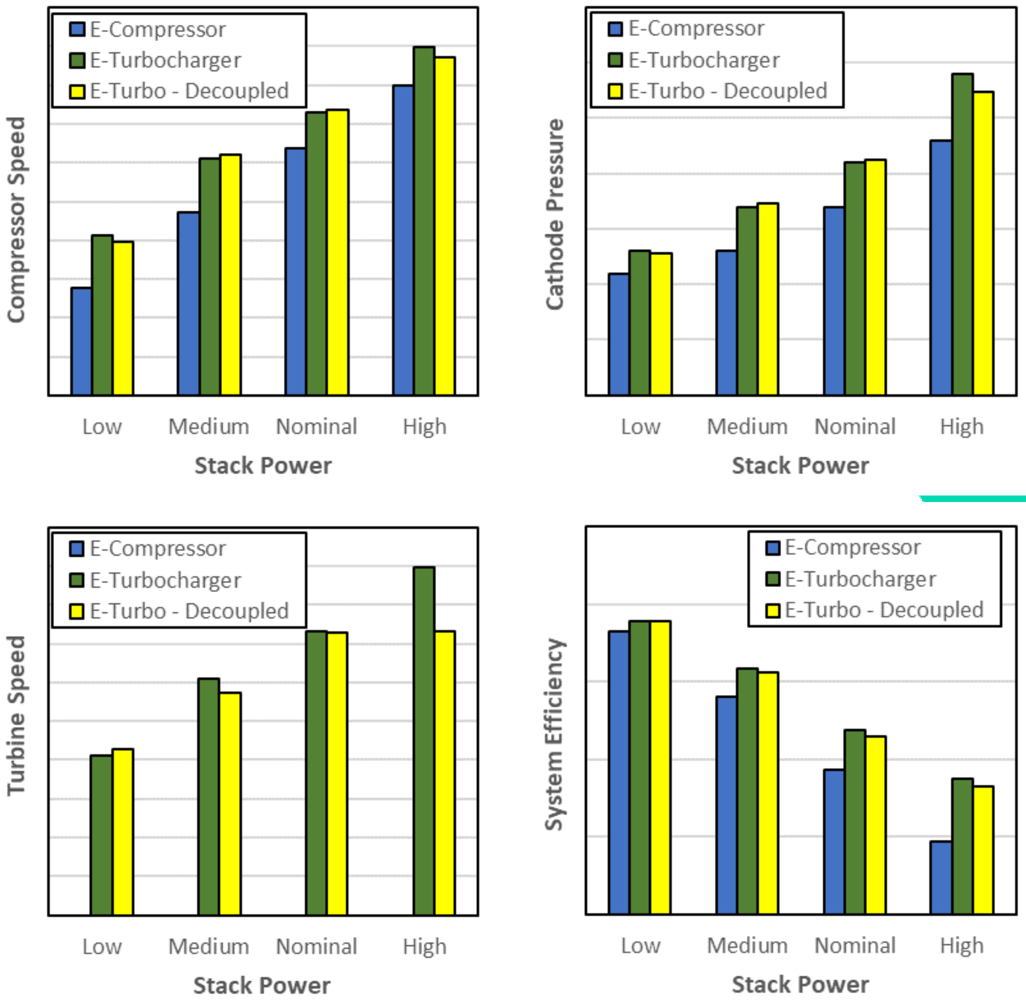
Comparing three single stage Systems

- 4 identical operating points defined by stack power output

- Use of turbine allows for lower parasitic losses because energy can be recuperated in turbine

- Turbine offers 1-4% improved efficiency





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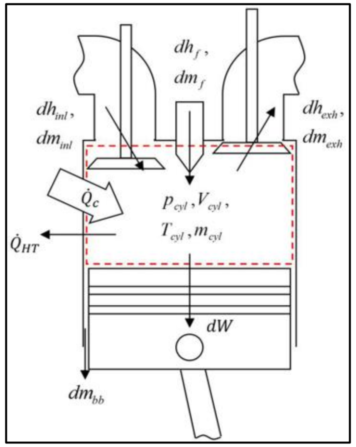
Transient Response to load increase

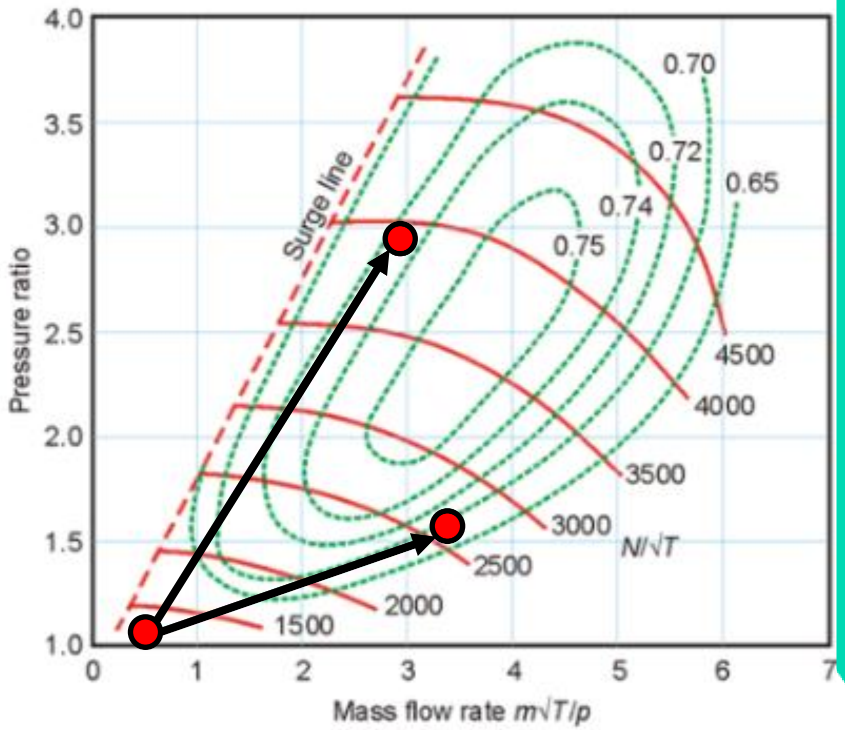
Rise in power output directly linked increased in rate of fuel consumption

- For Fuel cells and Diesel engines, this is limited by air flow rate

Diesels engines

- Air flow is dictated by mass that can be squeezed into combustion chamber
  - controlled strongly linked to boost pressure
- Increase in boost pressure is needed
- Rise is limited by ability to spool turbocharger = turbo lag



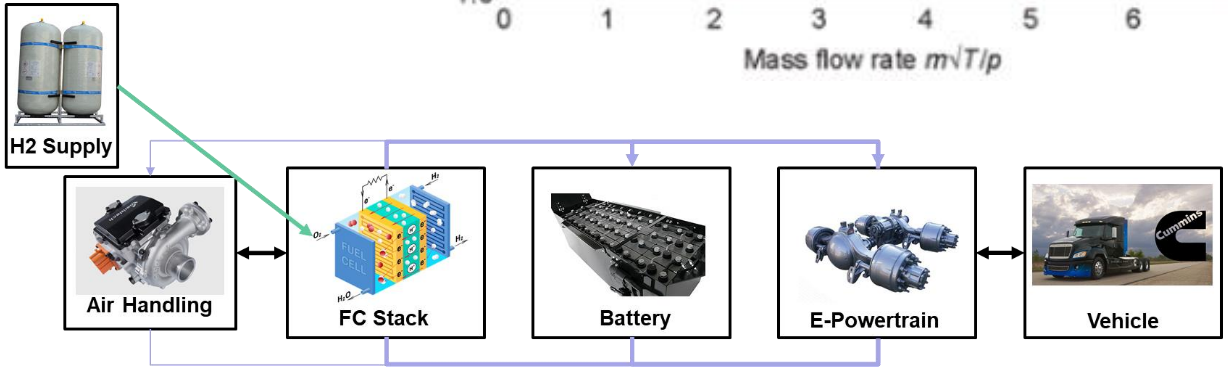


Fuel Cells

- Cathode pressure and air flow are independent
  - Air flow drives power
  - Pressure drives efficiency
  - ➔ We can increase power without increasing pressure

- Thermal limits
  - Stack is sensitive to homogeneity of temperature and humidity across
  - Thermal limit on stack temperature which limits pressure ratio rise

- Propulsion battery offers buffer that will affect transient requirements of fuel cell



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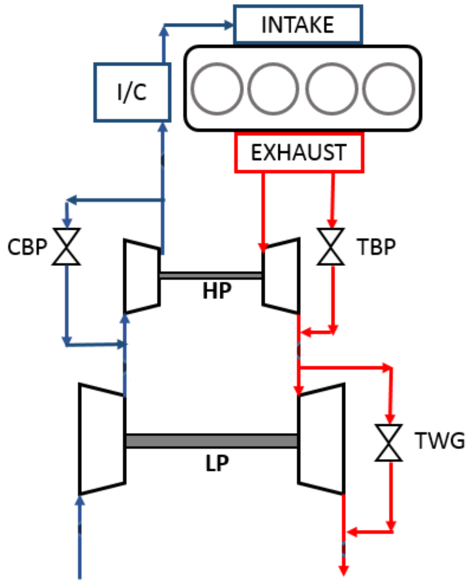
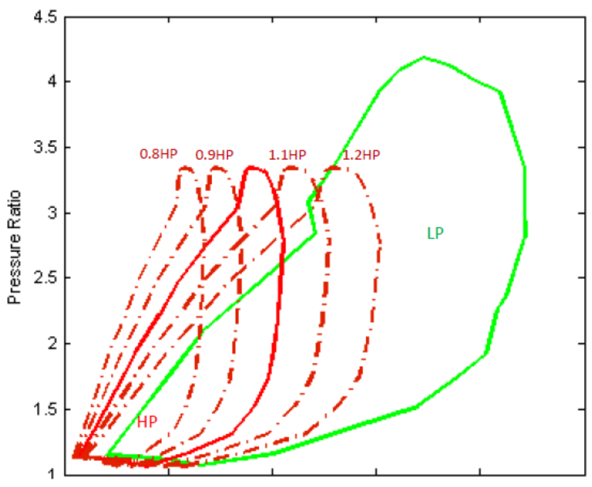
Should we use Multi-Stage Compression?

Why have we used multiple compressors in the past combustion engines?

- Improving Transient Response – *Smaller turbochargers*
- Enhancing Combined Map width – *spread air flow over multiple compressors*
- Packaging – Simpler air path rooting



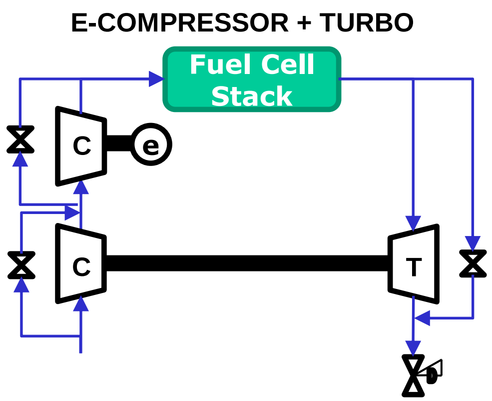


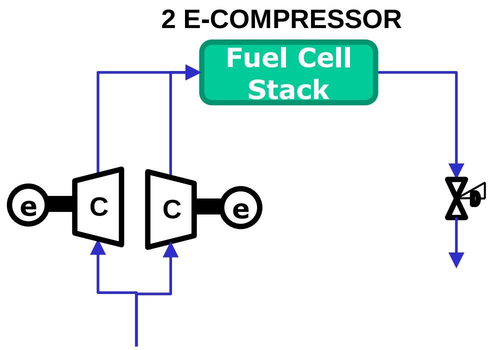
In fuel cells

- Transient response less critical due to e-machine and traction battery buffer
- Map width less critical because independence mass flow and boost pressure

So Why might we want to use multiple compressors in FC?

- High pressure ratios (altitude and aviation applications)
- Packaging may still be a factor
- Multiple compressors would allow for smaller e-machines (distributed)
- May allow for use of simple mechanical turbocharger
- Multiple e-machines offer redundancy in case of failure





Conclusions

Fuel cells are receiving serious consideration for future heavy duty applications and the impacts on air handling are very much to focus of R&D now

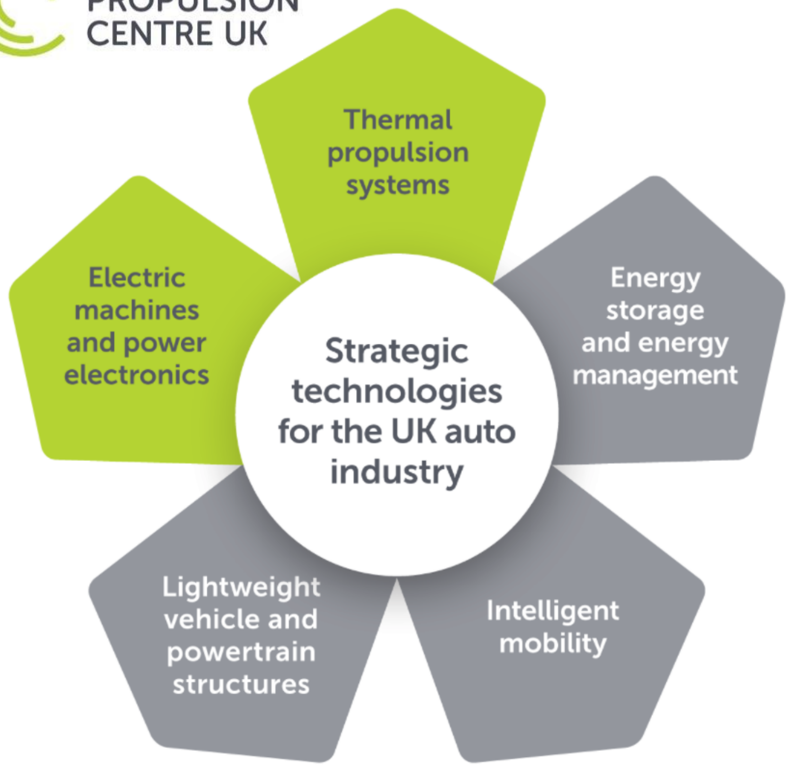
Air Handling capabilities has a significant impact on overall FC system efficiency and performance, and a system level optimisation is required

Building on experience in from turbocharging Diesel engines

- Independence of Air flow/operating pressure in fuel cell stack
  - More flexibility in matching and broader set of architectures to consider
  - Likely to change map width requirements (particularly with respect to surge)
- Steady flow but low exergy turbine inlet conditions
  - Still turbine appears to have considerable impact on overall system efficiency and compressor e-machine power
- Thermal considerations of FC stack are important
  - In particular during transients

APC Trident

Corporate slide on APC Trident programme



DECARBONISING HEAVY DUTY POWERTRAINS

Project Highlights

- Development of a highly efficient e-machine for energy recovery.
- Advance the adoption of decarbonising heavy duty applications through meeting their extreme demands of cost-performance, operational availability, design life and reliability.
- Build the UK supply chain for the next generation of heavy duty turbochargers.
- Utilising Bath Universities (IAAPS) system modelling capability across a multitude of existing powertrains, fuel cells, hybrids and alternative fuels.
- Total project value £20 million, with £10 million funded through the APC.

Project Consortium

- Cummins Turbo Technologies Ltd
- University of Bath
- Holtex Ltd
- Aeristech

With thanks to our funders

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