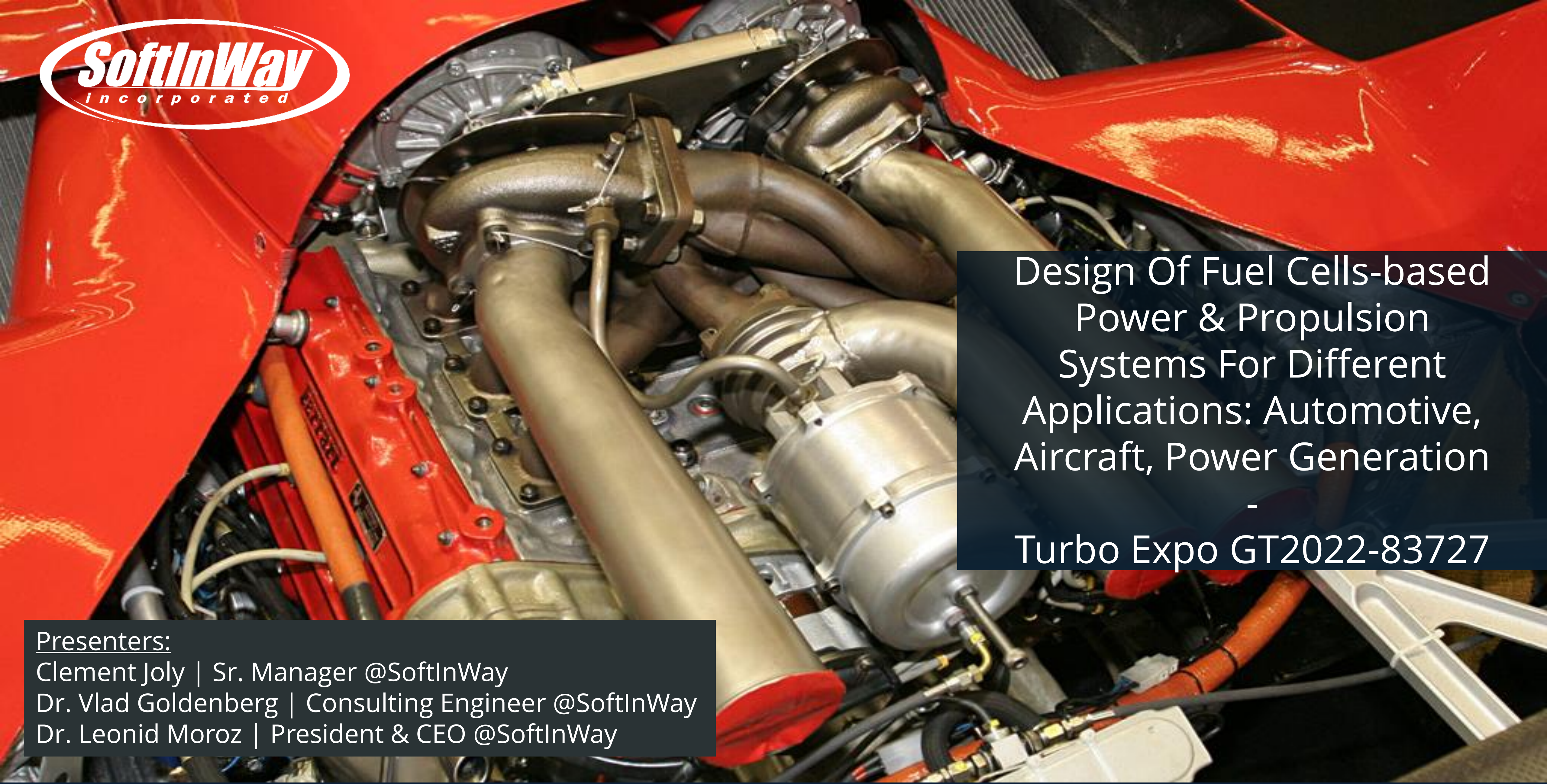


Design Of Fuel Cells-based Power & Propulsion Systems For Different Applications: Automotive, Aircraft, Power Generation

-

Turbo Expo GT2022-83727

Presenters:
Clement Joly | Sr. Manager @SoftInWay
Dr. Vlad Goldenberg | Consulting Engineer @SoftInWay
Dr. Leonid Moroz | President & CEO @SoftInWay

TUTORIAL DESCRIPTION

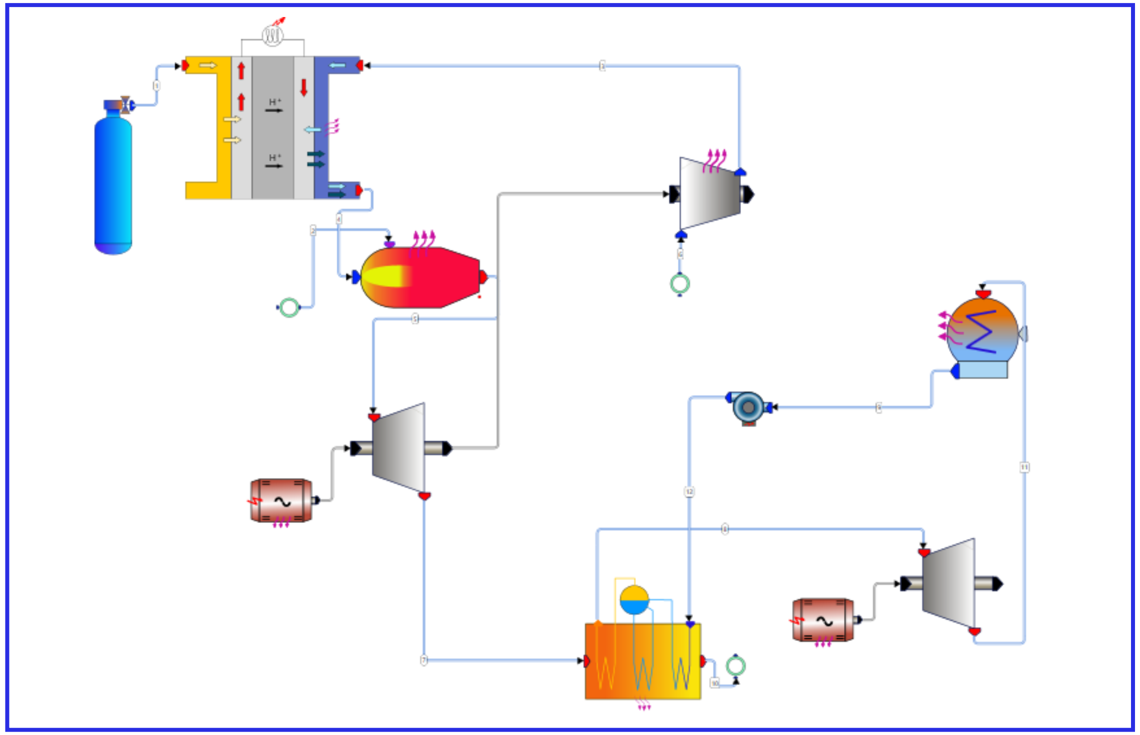
- Motivation: Fuel cells (FC) are a hot topic thanks to emergence of hydrogen as a means to reduce pollution across multiple industries
- FCs act as a middle ground between internal combustion engines and batteries
  - Quick Hydrogen fill-up, light compared to batteries, power density closer incumbent power train technologies
  - FC systems rely on turbomachinery to provide required flow streams and extract full energy potential from system.

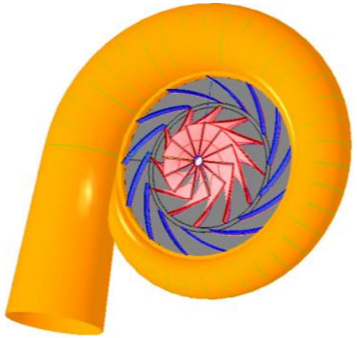
- Relatively newer fuel cell technologies often have very different operating regimes that engineers and operators should know to effectively design and operate such systems.

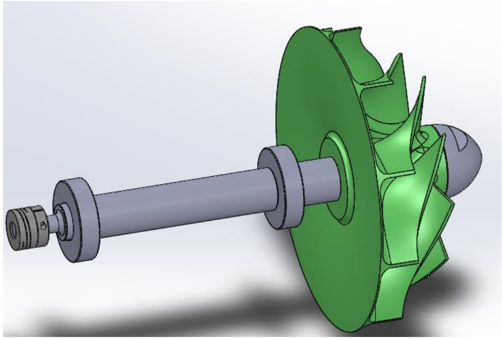
- Goal: Introduce the unique aspects of fuel cell technologies that enable both theoretical researchers and practitioners of these systems to maximally utilize their design experience.

- Learning objectives:
  - Understand and describe key system-level parameters pertinent in design of FC power trains.
  - Specify main system and component parameters for FC systems, including the turbomachinery

SOFTINWAY EXPERIENCE IN FUEL CELL-BASED POWER GENERATION AND PROPULSION







- Thermodynamic cycle calculation
  - Steady state
  - Transient
- Compressor/pump design
- Turbine/expander design
- Power train rotor dynamics analysis
- Bearing design

- Piping, valves and fittings
- Fuel & air supply systems
- Energy and fluid storage
- Secondary flows and lubrication
- Thermal management systems (incl. WHR)
  - Fuel cell thermal management
  - Electrical motor and generator cooling

AGENDA

1. <u>Introduction</u>
    1. Fuel cells in context with existing systems
    2. System architectures

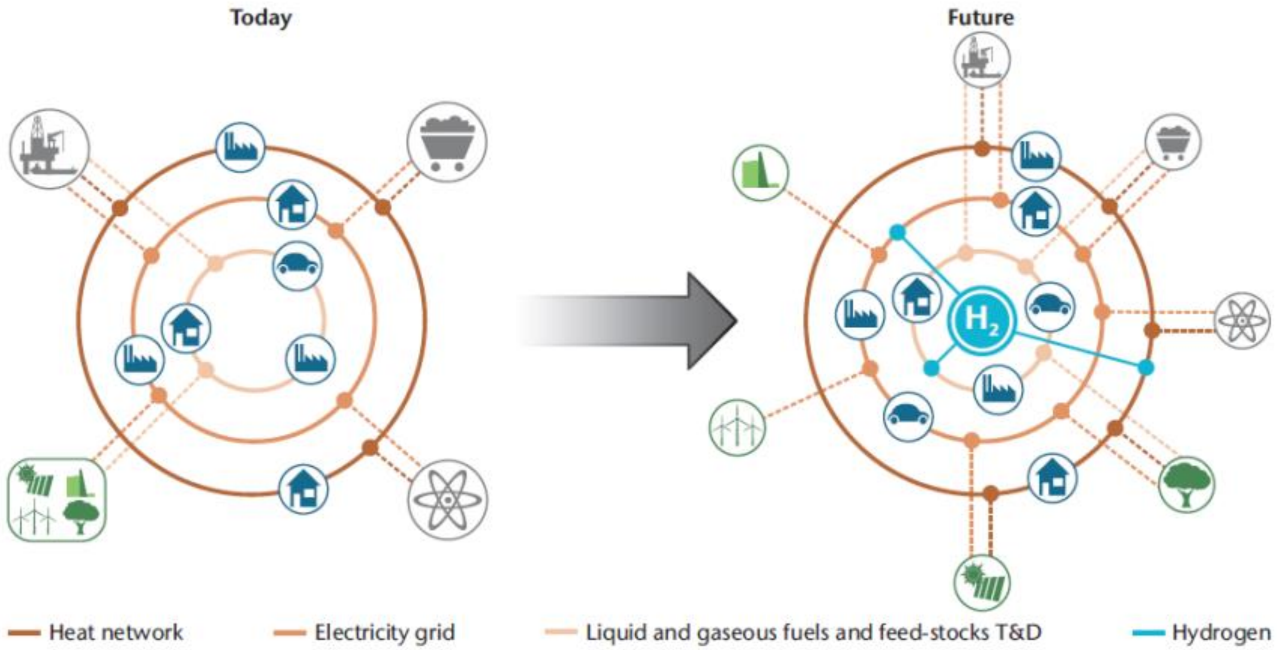
2. <u>Fundamentals</u>
    1. *Fuel Cells*
        1. Types of fuel cells
        2. Electrochemistry considerations
        3. Thermofluid considerations
        4. Model development
        5. System modelling
    2. *Turbomachinery*

3. <u>Applications & Examples (from literature)</u>
    1. General system architectures
    2. Stationary power generation
    3. Automotive and transportation
    4. Aerospace

1. Introduction

ENERGY SYSTEMS OF TODAY AND TOMORROW

- Hydrogen: Flexible energy carrier that can be produced from any regionally prevalent primary energy source
- Can be effectively transformed into any form of energy for diverse end-use applications

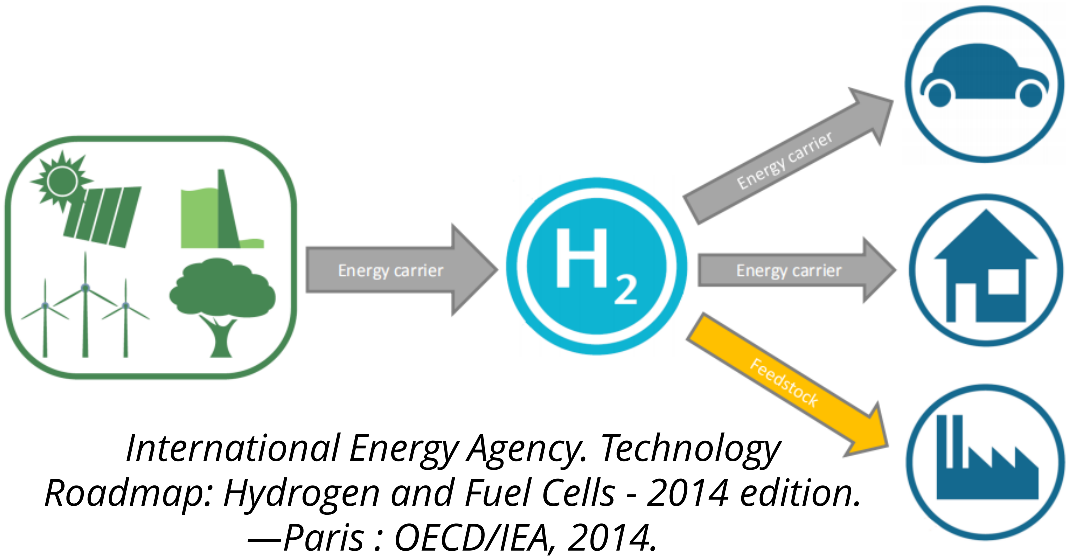


1. Hydrogen energy technologies: Materials of the seminar of the laboratory of VET JIHT RAS: collection of articles. scientific. tr. / BEFORE. Dunikov. - M .: JIHT RAN, 2017. - Issue. 1. - 5-21s.

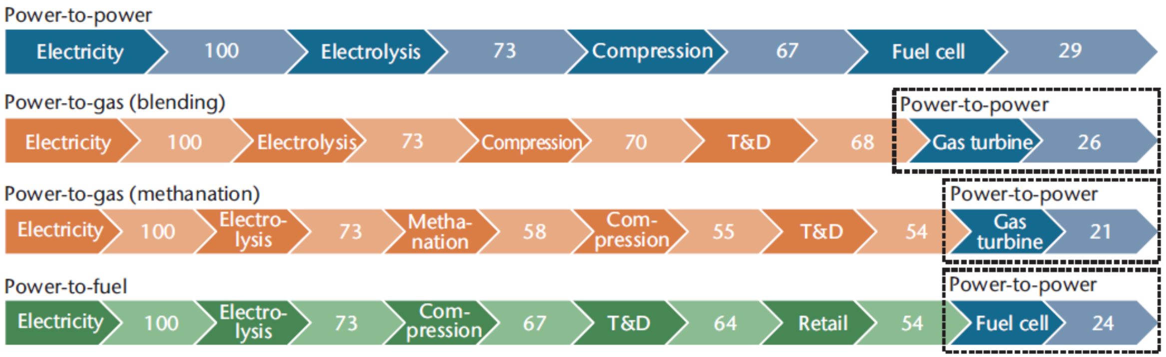
2. International Energy Agency. Technology Roadmap: Hydrogen and Fuell Cells - 2014 edition. —Paris : OECD/IEA, 2014.

BENEFITS OF HYDROGEN

- Clean and carbon-free fuel
- Considered a key element for energy transition.
  - Tool to reduce damaging effects of air pollution on human health and global warming (GHG)
- Renewable power generation by solar and wind is increasing, requiring flexible operation to balance the load on the energy grid with the ability to rapidly adjust the output.
  - Gas turbines with a combustion system for hydrogen operation offers a low carbon solution to support the stability of the energy grid. This provides a solution capturing the needs for energy storage, in the form of hydrogen, and flexible power generation.
- Fuel cell systems (FCS) represent an innovative technology that could potentially replace internal combustion engines.

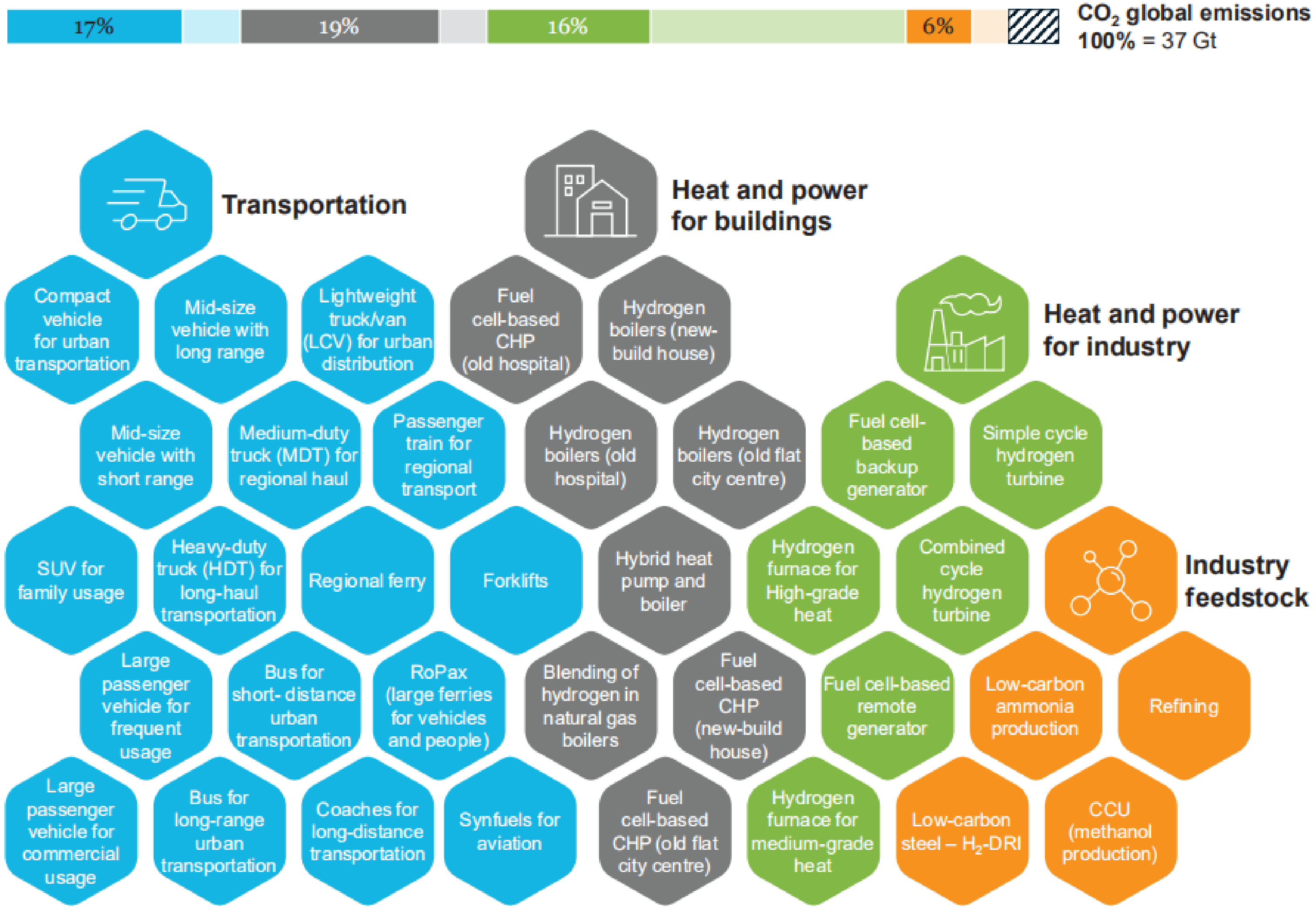


International Energy Agency. Technology Roadmap: Hydrogen and Fuel Cells - 2014 edition. —Paris : OECD/IEA, 2014.



Hydrogen – A key enabler for the energy transition. - Thijs Bouten, Jan Withag, Lars-Uno Axelsson, OPRA Turbines International B.V. Hengelo, The Netherlands. - 12 p.

OVERVIEW OF HYDROGEN APPLICATIONS



17% 19% 16% 6% ▨ CO_2 global emissions

100% = 37 Gt

Transportation

- Compact vehicle for urban transportation
- Mid-size vehicle with long range
- Lightweight truck/van (LCV) for urban distribution
- Mid-size vehicle with short range
- Medium-duty truck (MDT) for regional haul
- Passenger train for regional transport
- SUV for family usage
- Heavy-duty truck (HDT) for long-haul transportation
- Regional ferry
- Forklifts
- Large passenger vehicle for frequent usage
- Bus for short- distance urban transportation
- RoPax (large ferries for vehicles and people)
- Large passenger vehicle for commercial usage
- Bus for long-range urban transportation
- Coaches for long-distance transportation
- Synfuels for aviation

Heat and power for buildings

- Fuel cell-based CHP (old hospital)
- Hydrogen boilers (new-build house)
- Hydrogen boilers (old hospital)
- Hydrogen boilers (old flat city centre)
- Hybrid heat pump and boiler
- Blending of hydrogen in natural gas boilers
- Fuel cell-based CHP (new-build house)
- Fuel cell-based CHP (old flat city centre)

Heat and power for industry

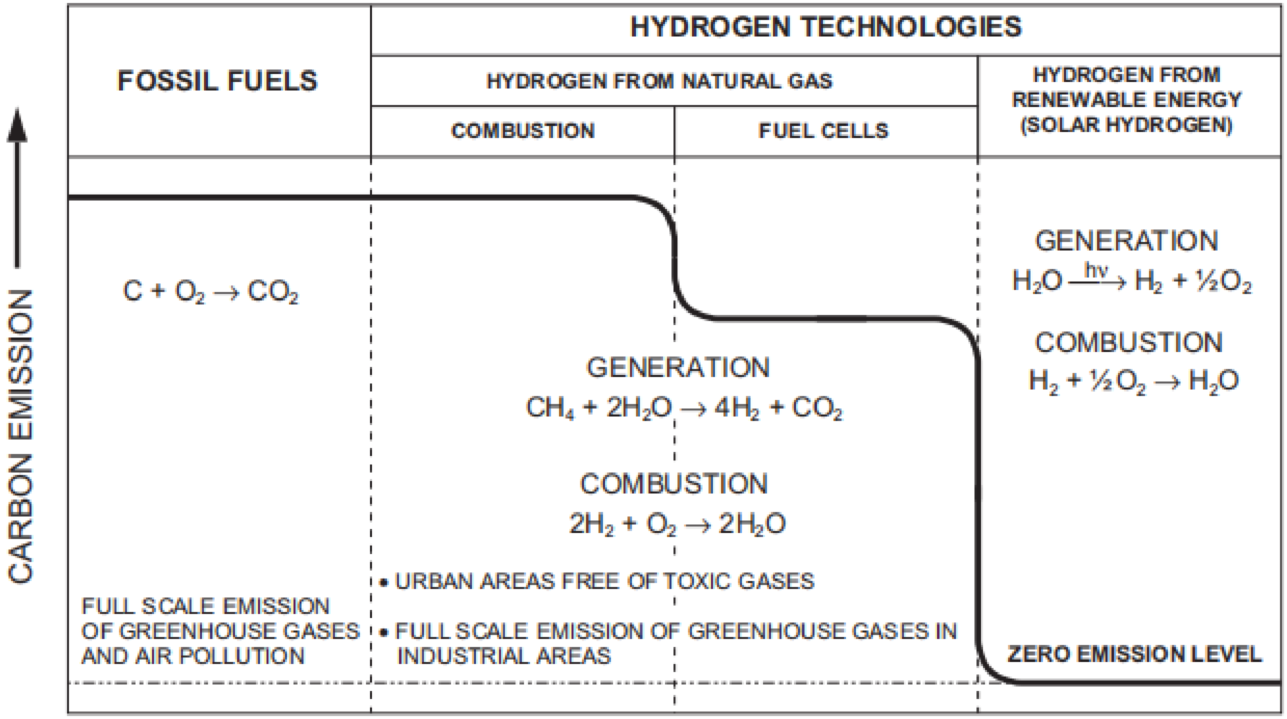
- Fuel cell-based backup generator
- Simple cycle hydrogen turbine
- Hydrogen furnace for High-grade heat
- Combined cycle hydrogen turbine
- Fuel cell-based remote generator
- Hydrogen furnace for medium-grade heat

Industry feedstock

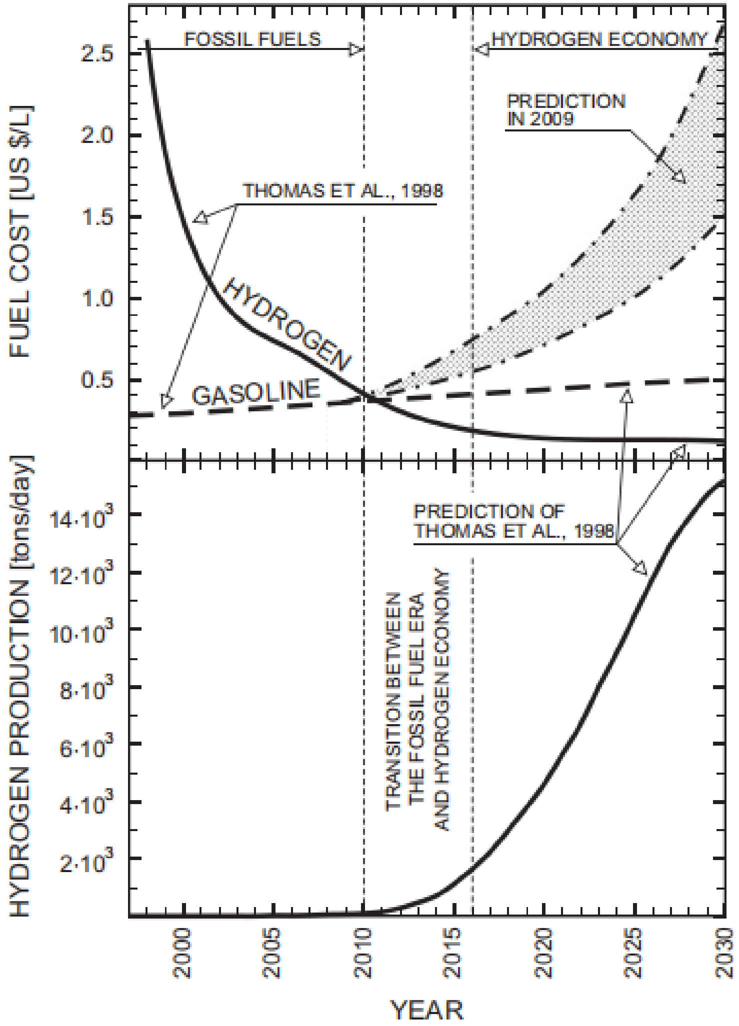
- Low-carbon ammonia production
- Refining
- Low-carbon steel – H_2-DRI
- CCU (methanol production)

Path to hydrogen competitiveness. -88p. 20 January 2020-https://hydrogencouncil.com

HYDROGEN ENERGY PROSPECTS



Effect of hydrogen generation and combustion on carbon emission



Costs of gasoline and hydrogen (upper part) and the hydrogen production (lower part) predicted for the period until 2030 (the amount of hydrogen is in units equivalent to the same amount of oil).

Impact of hydrogen on the environment - Janusz Nowotny , T. Nejat Veziroglu.- international journal of hydrogen energy 36 (2011) 13218 e13224

HYDROGEN AND FUEL CELL TECHNOLOGIES

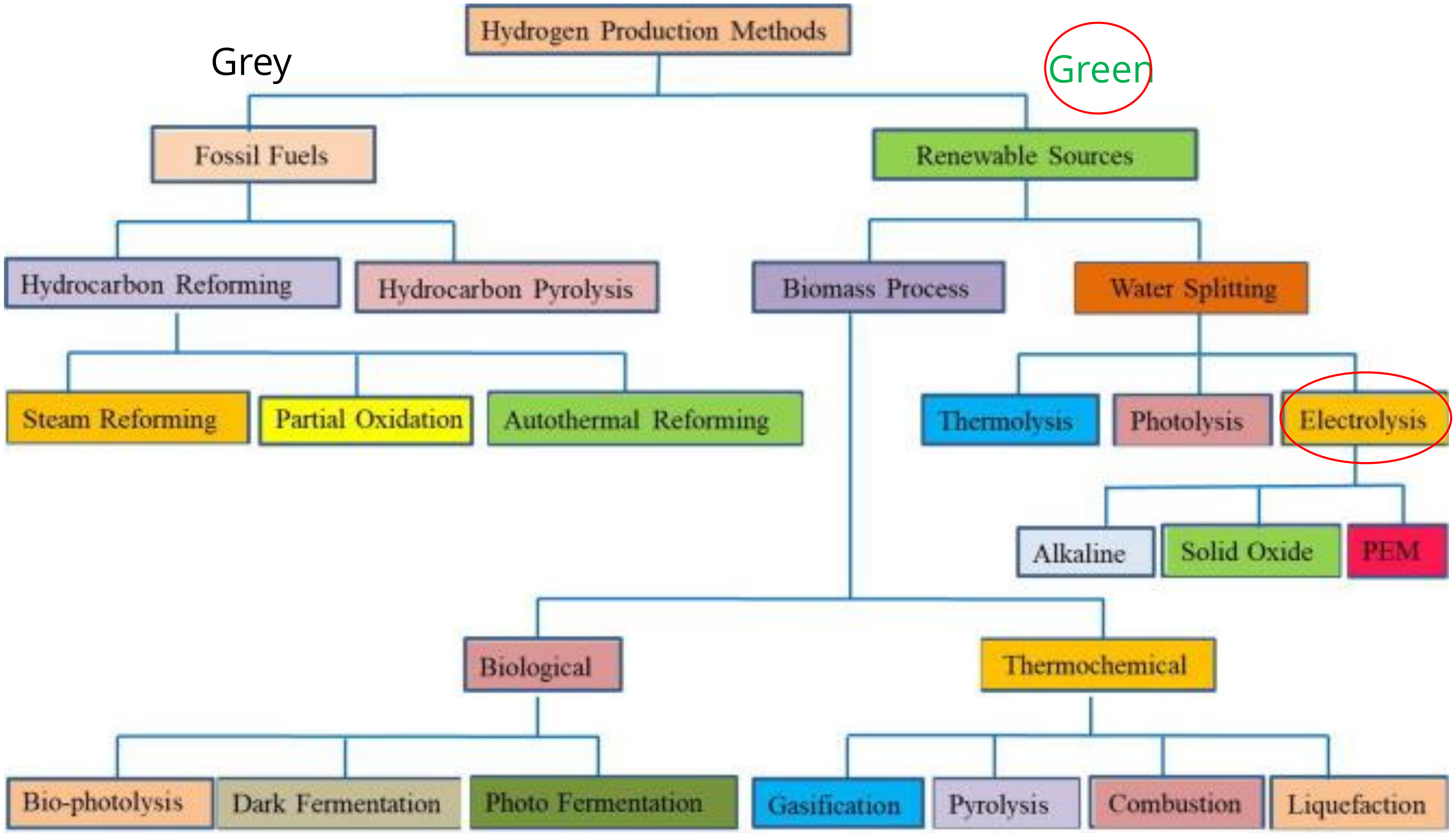
1. **Power-to-power**:
    - Electricity is transformed into hydrogen via **electrolysis**
    - Stored in an underground cavern or a pressurized tank and **re-electrified** when needed **using a fuel cell or a hydrogen gas turbine**

2. **Power-to-gas**:
    - Electricity is transformed into hydrogen via electrolysis
    - It is then blended in the natural gas grid (hydrogen-enriched natural gas – HENG) or transformed to synthetic methane in a subsequent methanation step. For methanation, a low-cost CO2 source is necessary

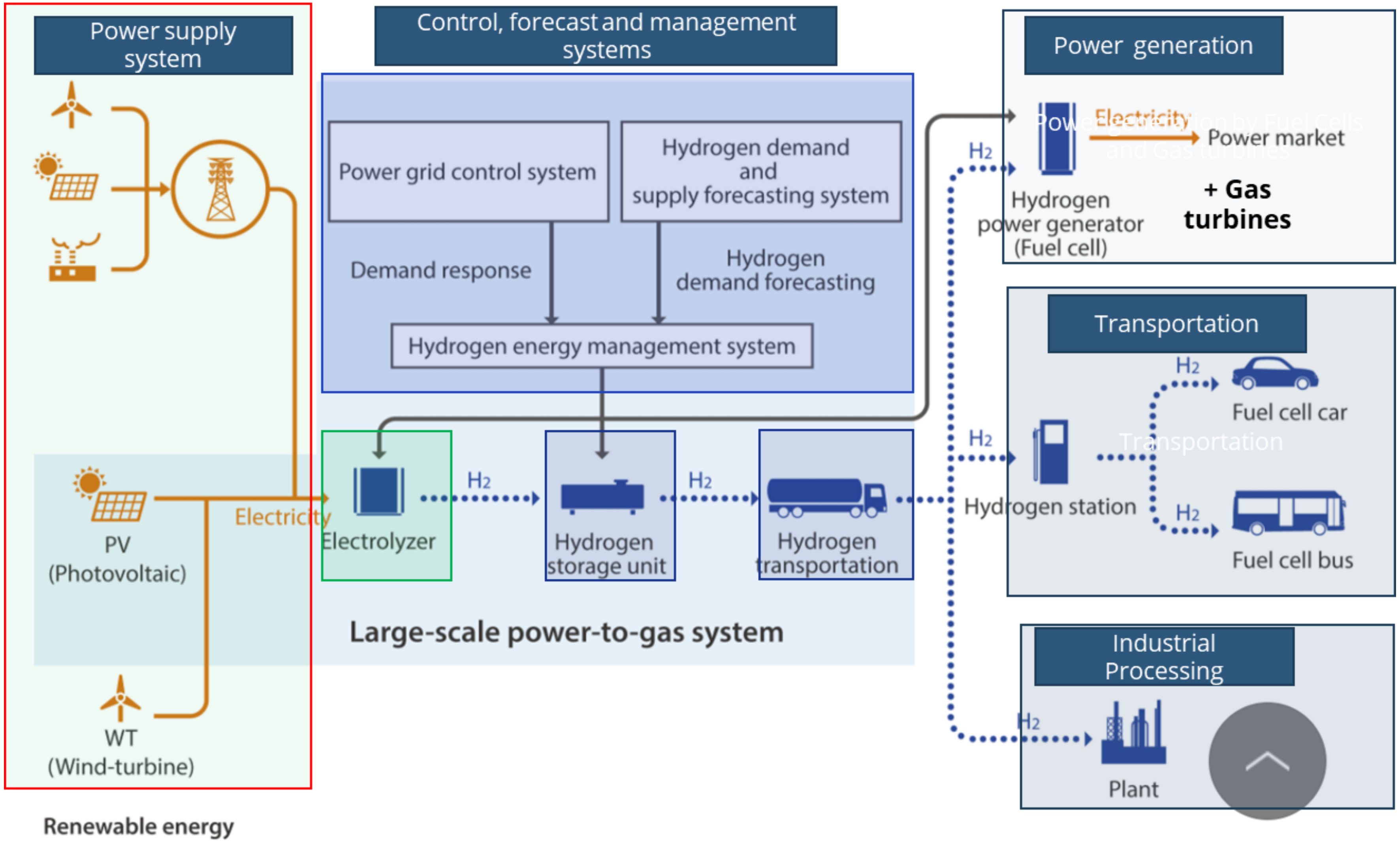
- **3. Power-to-fuel**:
    - Electricity is transformed into hydrogen and then **used as a fuel for FCEVs in the transport sector**.

- 4. **Power-to-feedstock**:
    - Electricity is transformed into hydrogen and then used as a feedstock, e.g. in the refining industry.

THE HYDROGEN RAINBOW



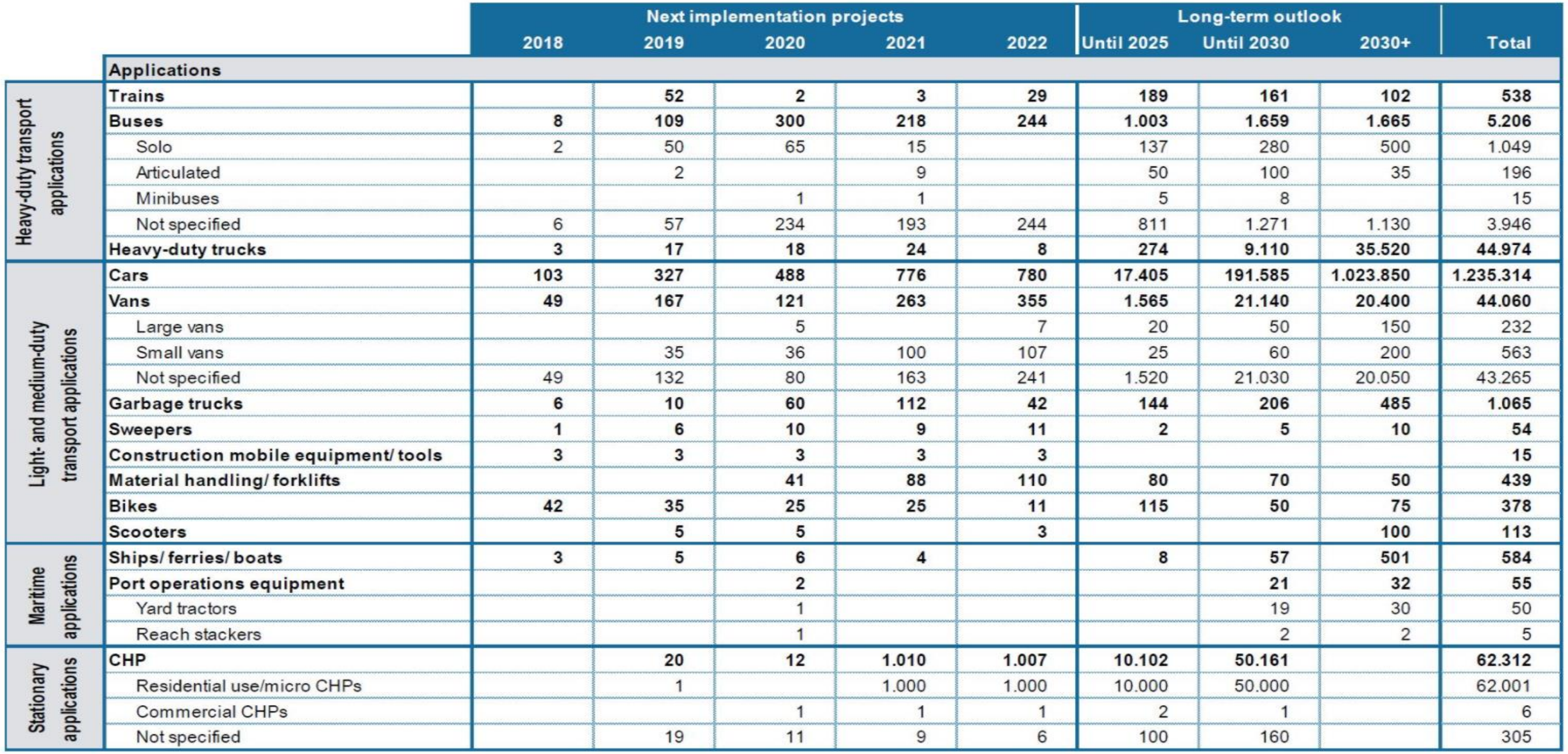
GREEN ENERGY SUBSYSTEMS



Example - Fukushima Hydrogen Energy Research Field (FH2R), a large-scale hydrogen energy system in Namie-cho, Fukushima Prefecture.

FUEL CELLS MARKET (2021)

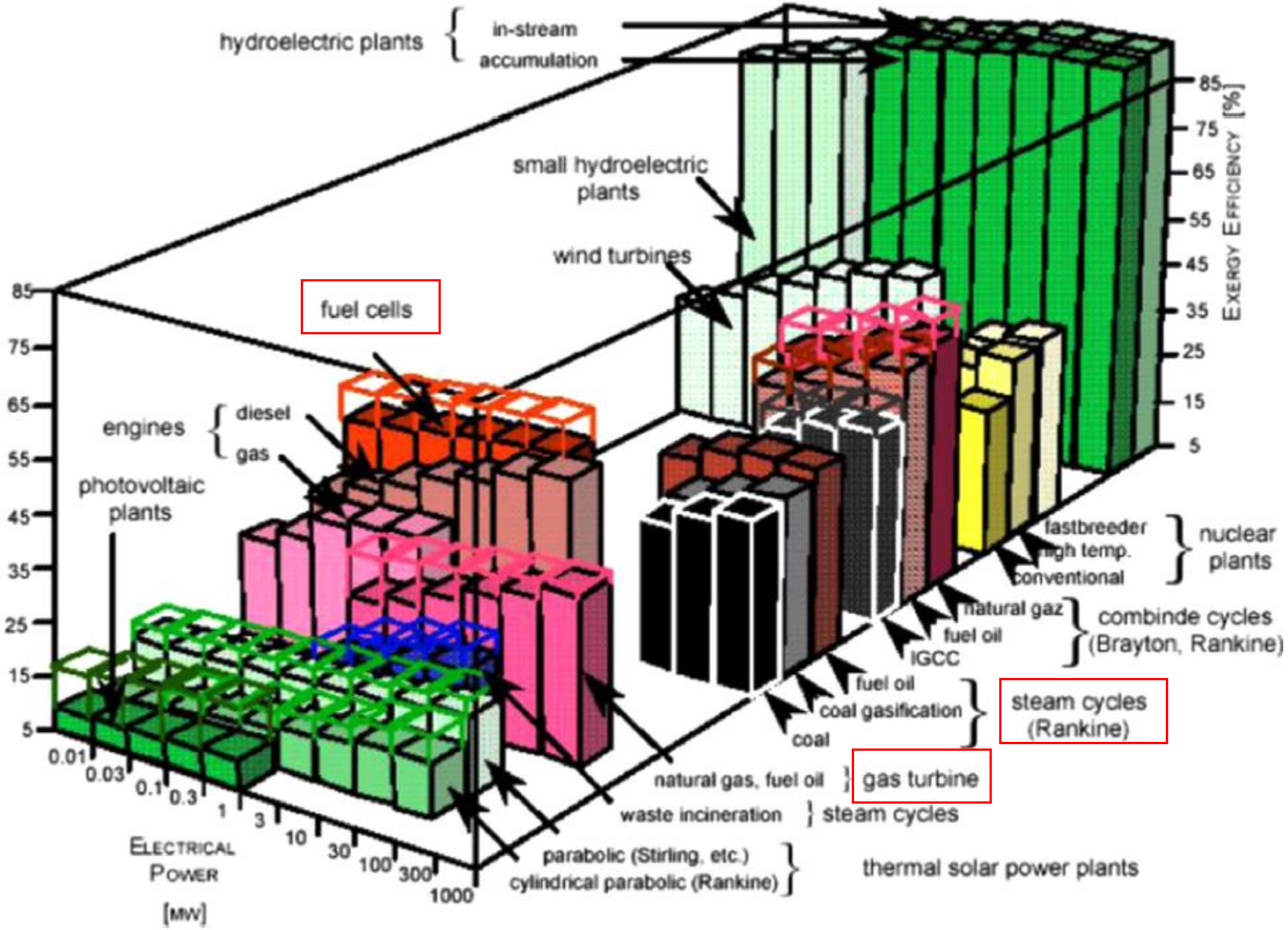
- Research projects and implementation initiatives in a wide array of transportation and stationary applications, including combined heat and power (CHP).



		Next implementation projects					Long-term outlook			
		2018	2019	2020	2021	2022	Until 2025	Until 2030	2030+	Total
	Applications									
Heavy-duty transport applications	**Trains**		**52**	**2**	**3**	**29**	**189**	**161**	**102**	**538**
	Buses	**8**	**109**	**300**	**218**	**244**	**1.003**	**1.659**	**1.665**	**5.206**
	Solo	2	50	65	15		137	280	500	1.049
	Articulated		2		9		50	100	35	196
	Minibuses			1	1		5	8		15
	Not specified	6	57	234	193	244	811	1.271	1.130	3.946
	Heavy-duty trucks	**3**	**17**	**18**	**24**	**8**	**274**	**9.110**	**35.520**	**44.974**
Light- and medium-duty transport applications	**Cars**	**103**	**327**	**488**	**776**	**780**	**17.405**	**191.585**	**1.023.850**	**1.235.314**
	Vans	**49**	**167**	**121**	**263**	**355**	**1.565**	**21.140**	**20.400**	**44.060**
	Large vans			5		7	20	50	150	232
	Small vans		35	36	100	107	25	60	200	563
	Not specified	49	132	80	163	241	1.520	21.030	20.050	43.265
	Garbage trucks	**6**	**10**	**60**	**112**	**42**	**144**	**206**	**485**	**1.065**
	Sweepers	**1**	**6**	**10**	**9**	**11**	**2**	**5**	**10**	**54**
	Construction mobile equipment/ tools	**3**	**3**	**3**	**3**	**3**				**15**
	Material handling/ forklifts			**41**	**88**	**110**	**80**	**70**	**50**	**439**
	Bikes	**42**	**35**	**25**	**25**	**11**	**115**	**50**	**75**	**378**
	Scooters		**5**	**5**		**3**			**100**	**113**
Maritime applications	**Ships/ ferries/ boats**	**3**	**5**	**6**	**4**		**8**	**57**	**501**	**584**
	Port operations equipment			**2**				**21**	**32**	**55**
	Yard tractors			1				19	30	50
	Reach stackers			1				2	2	5
Stationary applications	**CHP**		**20**	**12**	**1.010**	**1.007**	**10.102**	**50.161**		**62.312**
	Residential use/micro CHPs		1		1.000	1.000	10.000	50.000		62.001
	Commercial CHPs			1	1	1	2	1		6
	Not specified		19	11	9	6	100	160		305

Recent development of hydrogen and fuel cell technologies: A review Lixin Fan a , Zhengkai Tu a,∗ , Siew Hwa Chan b a School of Energy and Power Engineering, Huazhong University of Science and Technology, China b Energy Research Institute at Nanyang Technological University (ERI@N)

ENERGY CONVERSION DEVICE EXERGY EFFICIENCIES



Exergy efficiencies of main energy conversion devices - O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

FUEL CELLS VS. HEAT ENGINES

Fuel Cells	Heat Engines
Typically use a hydrogen-based fluid and atmospheric air as the fuel and oxidant, respectively	
Combine fuel oxidant **electrochemically**	Combine fuel oxidant via **combustion**
Produce electrical work **directly** from chemical energy	Electricity production is a **multi-step process**: thermal energy from internal fuel chemical energy (combustion), then mechanical energy, and finally electrical energy (if needed) through generator
Fewer-to-zero pollutants and have higher theoretical and practical efficiencies	Limited by Carnot efficiency between their low and the high working temperatures and are responsible for a significant portion of the world’s pollution
Static devices that operate with **almost no noise or vibrations**	**Many dynamic components** (e.g., pistons and gears) that produce a lot of noise and vibrations, thus limiting their applications

FUEL CELLS POLLUTION

- When hydrogen supplied to FC is pure (i.e.,not reformation-based hydrogen which is always contaminated with COx), the durability and reliability of the fuel cell significantly improve in comparison to when we run the fuel cell on reformation-based hydrogen.
  - One of the most important advantages of fuel cells in comparison to heat engines,

- FCs are inherently clean energy converters that ideally run on pure hydrogen.

- For **non-renewable energy-based water electrolysis**, the emissions and energy used for the electrolysis process make it **more harmful to the environment than conventional combustion heat engines**. Moreover, it is **economically unfeasible** since any fossil energy used for hydrogen production is going to be always more than the energy content of hydrogen.

FUEL CELLS VS. BATTERIES

Fuel Cells	Batteries
Electrochemical cells that consist of an electrolyte sandwiched between two electrodes	
Use internal oxidation–reduction reactions to **convert** the **chemical energy** content of a fuel to **DC electricity**	
Electrodes (i.e., catalyst layer and gas diffusion layer) typically consist of a proton-conducting media, carbon-supported catalyst, and electron-conducting fibers	Electrodes are typically **metals** (e.g., zinc, lead, or lithium) **immersed in mild acids**
Used for **energy conversion only**	Used as **energy storage and conversion devices**
Reactants are supplied from a separate storage device and the internal components are not used up in the electrochemical reactions. Thus, theoretically, a fuel cell can keep running as long as the reactants are sufficiently supplied and the products are properly removed. As a result, an operational fuel cell system requires a fuel storage mechanism and an oxidant supply mechanism to be incorporated within it	Uses the chemical energy stored in its electrodes to fuel the electrochemical reactions that give us electricity at a specified potential difference. Thus, a battery has a limited lifetime and can only function as long as the electrodes' material is not yet depleted. Upon depletion of the electrodes material, a battery must be either replaced (in case of a disposable battery) or recharged (by using an electric current to reform dissolved metals on the electrodes)
No loss of performance during idling	During idling, electrochemical reactions that deteriorate the battery occur very slowly, reducing the lifetime of the battery
No leakage or corrosion	Prone to leakage or corrosion

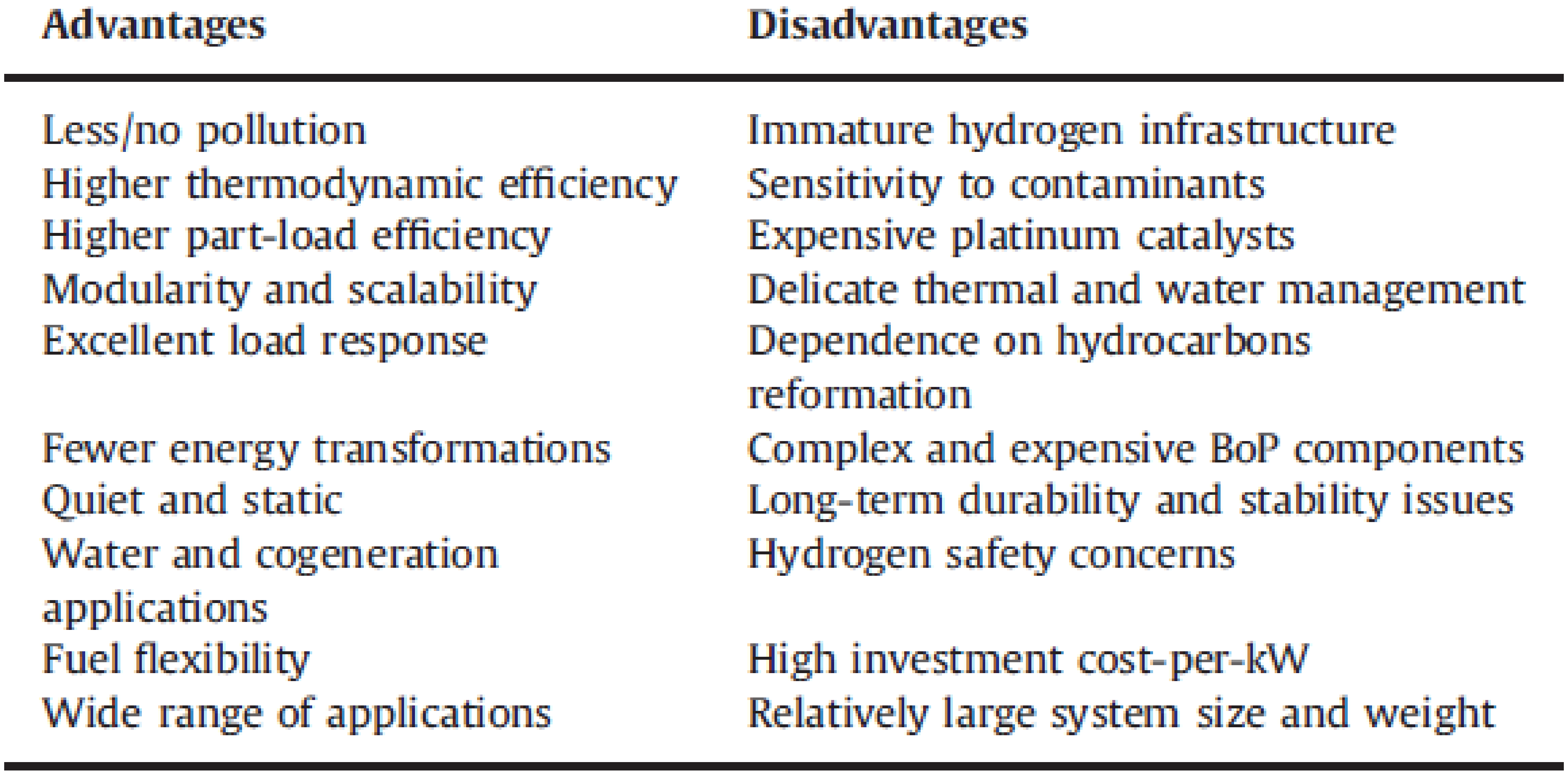
FUEL CELL CHALLENGES

- Cost
  - FCs are expensive - **3 main reasons behind current high cost of FCs** are:
    - Dependence on platinum-based catalysts
    - Delicate membrane fabrication techniques
    - Coating and plate material of bipolar plates.
  - ~50% of FC system is **Balance of Power (BoP) components** (fuel supply and storage subsystems, pumps, blowers, power and control electronics, and compressors).
  - **Future benefit for economy of scale** (less demanding manufacturing and assembly vs. competing techs)
- Durability
  - **Need 5x current rates** (e.g., at least 60,000h (in 2014 review)) for stationary distributed generation sector to present a long-term reliable alternative to the current power generation technologies
  - Contamination mechanisms due to **air pollutants and fuel impurities** need to be carefully addressed to enhance durability
- Hydrogen infrastructure
  - In 2014, 96% of the world's hydrogen was produced from hydrocarbon reformation processes (not viable)
  - Hydrogen production from fossil fuels with use in FCs is economically disadvantageous since delivered cost-per-kWh from hydrogen generated from a fossil fuel is higher than cost-per-kWh if fossil fuel is used directly
  - Promoting renewable-based (green) hydrogen required (only viable solution)
  - Challenge in development of hydrogen storage mechanisms that provide high energy density per mass and volume whilst maintaining a reasonable cost
    - Safety concerns - very light and highly-flammable fuel.

FUEL CELL CHALLENGES (CONTINUED)

- Water balance
  - Water transport across all streams to keep membrane well-hydrated without causing water accumulation or blockage over different operating conditions and load requirements:
    - Water entering with inlet streams
    - Water generated by cathodic reaction
    - Water migration from one component to another
    - Water exiting with exit streams.
  - Improper water management leads to both performance loss and durability degradations due to permanent membrane damage, low membrane ionic conductivity, non- homogeneous current density distribution, delamination of components, and reactants starvation.
- Parasitic load
  - Load required to run auxiliary BoP components reduces overall system efficiency.
  - Improving aux. components (air compressors, coolant pumps, hydrogen circulation pumps, etc.) increases system performance
- Codes, standards, safety and public awareness
  - **Lack of internationally-accepted codes and standards for hydrogen systems** in general
    - Need general best-practices and consistent safety standards in the design, installation, operation, maintenance, and handling of hydrogen equipment were established.
  - FCs have a **negative reflection on public's acceptance** of hydrogen power solutions.
    - General public needs to be convinced that hydrogen is similar to conventional fuels in certain aspects and different in other aspects.

MAIN PROS AND CONS OF FUEL CELLS



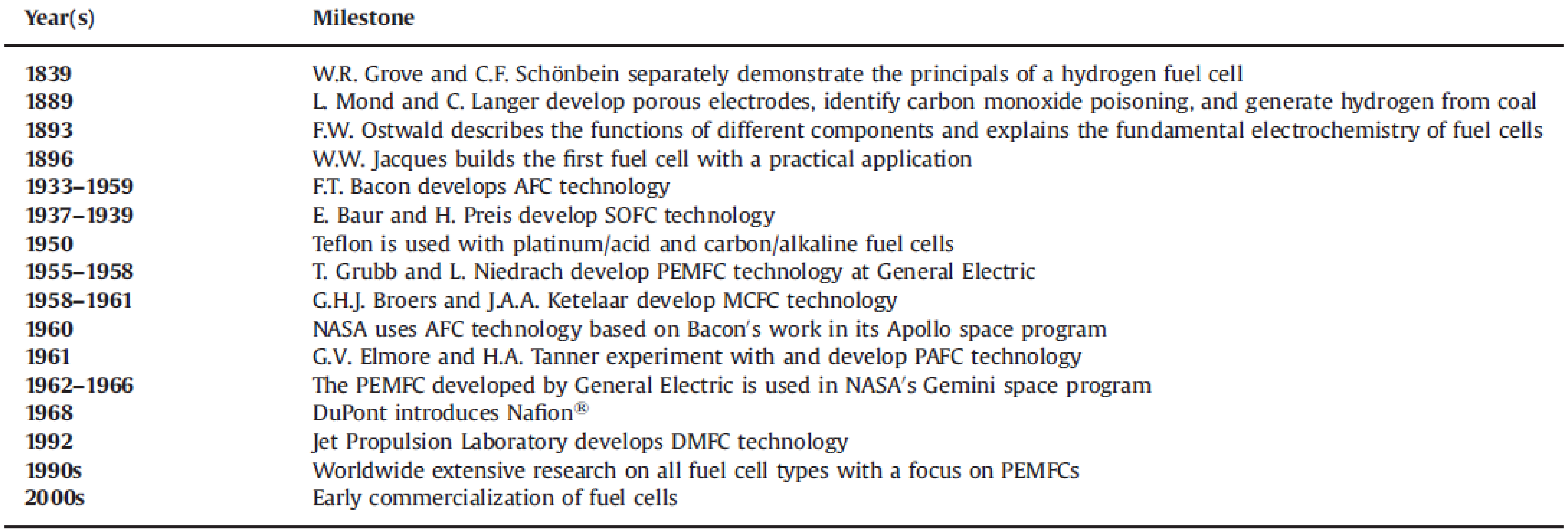
Advantages	Disadvantages
Less/no pollution	Immature hydrogen infrastructure
Higher thermodynamic efficiency	Sensitivity to contaminants
Higher part-load efficiency	Expensive platinum catalysts
Modularity and scalability	Delicate thermal and water management
Excellent load response	Dependence on hydrocarbons reformation
Fewer energy transformations	Complex and expensive BoP components
Quiet and static	Long-term durability and stability issues
Water and cogeneration applications	Hydrogen safety concerns
Fuel flexibility	High investment cost-per-kW
Wide range of applications	Relatively large system size and weight

Summary of the main advantages and disadvantages of fuel cells
O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

1.1 Fuel Cells in Context with Existing Systems

FUEL CELL HISTORY

- FC R&D goes back to early 1800s with Sir William Grove due to his famous water electrolyzer / fuel cell experimental demonstration.
  - Used electrolysis background to conceptualize and realize a reverse process to generate electricity.
  - Originally called a **gas battery**, now known as fuel cell.
- In 1959, Francis Thomas Bacon demonstrated the first fully-operational fuel cell
  - His work was licensed and adopted by NASA (including for use in the 1960s in Gemini and Apollo manned space programs).



Year(s)	Milestone
1839	W.R. Grove and C.F. Schönbein separately demonstrate the principals of a hydrogen fuel cell
1889	L. Mond and C. Langer develop porous electrodes, identify carbon monoxide poisoning, and generate hydrogen from coal
1893	F.W. Ostwald describes the functions of different components and explains the fundamental electrochemistry of fuel cells
1896	W.W. Jacques builds the first fuel cell with a practical application
1933–1959	F.T. Bacon develops AFC technology
1937–1939	E. Baur and H. Preis develop SOFC technology
1950	Teflon is used with platinum/acid and carbon/alkaline fuel cells
1955–1958	T. Grubb and L. Niedrach develop PEMFC technology at General Electric
1958–1961	G.H.J. Broers and J.A.A. Ketelaar develop MCFC technology
1960	NASA uses AFC technology based on Bacon's work in its Apollo space program
1961	G.V. Elmore and H.A. Tanner experiment with and develop PAFC technology
1962–1966	The PEMFC developed by General Electric is used in NASA's Gemini space program
1968	DuPont introduces Nafion®
1992	Jet Propulsion Laboratory develops DMFC technology
1990s	Worldwide extensive research on all fuel cell types with a focus on PEMFCs
2000s	Early commercialization of fuel cells

Main milestones in the history of fuel cells - O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

ADVANTAGES/CHARACTERISTICS

- FCs have an advantage in the number of energy transformations over heat engines when the desired output is electrical power. However, fuel cells are **on par** with batteries and heat engines in the number of energy transformations **when the desired output is mechanical work**.
- FCs have **excellent modularity**
  - **Changing number of cells-per-stack and/or stacks-per-system allows controlling power output**.
  - FC efficiency does not vary much with system size or load factor (FCs have higher efficiencies at part loads compared to full loads)
    - Particularly useful in large-scale fuel cell systems that would normally run on part-load instead of full- load.
- Wide diversity: From micro-fuel cells (<1W power outputs) to multi-MW prime power generation plants.
- **Very good dynamic load-following characteristics due to prompt nature of the electrochemical reactions involved.**
- **Static silent device**.
  - Promotes FC use for auxiliary power and distributed generation applications in addition to portable applications that require silent-operation.
  - Very few dynamic parts (and hence, almost no vibrations) making fuel cells design, manufacturing, assembly, operation, and analysis simpler than that of heat engines.

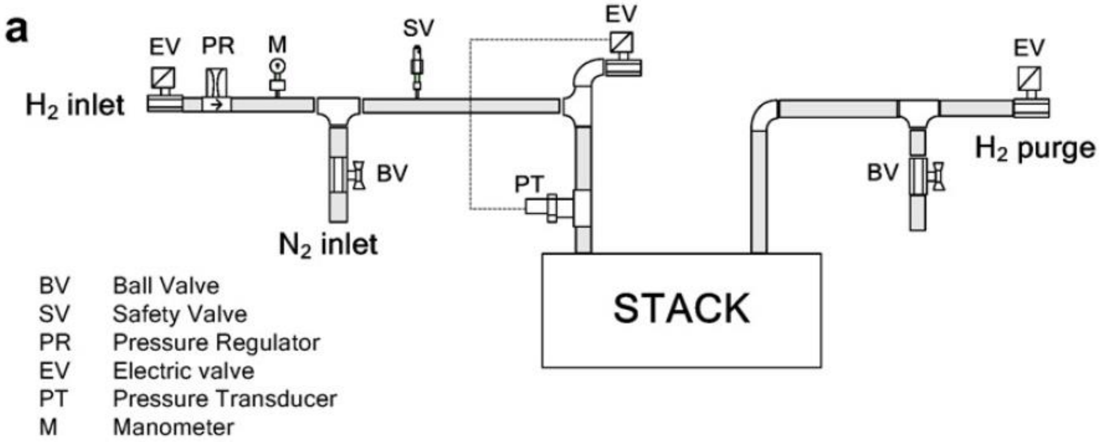
1.2 System Architectures

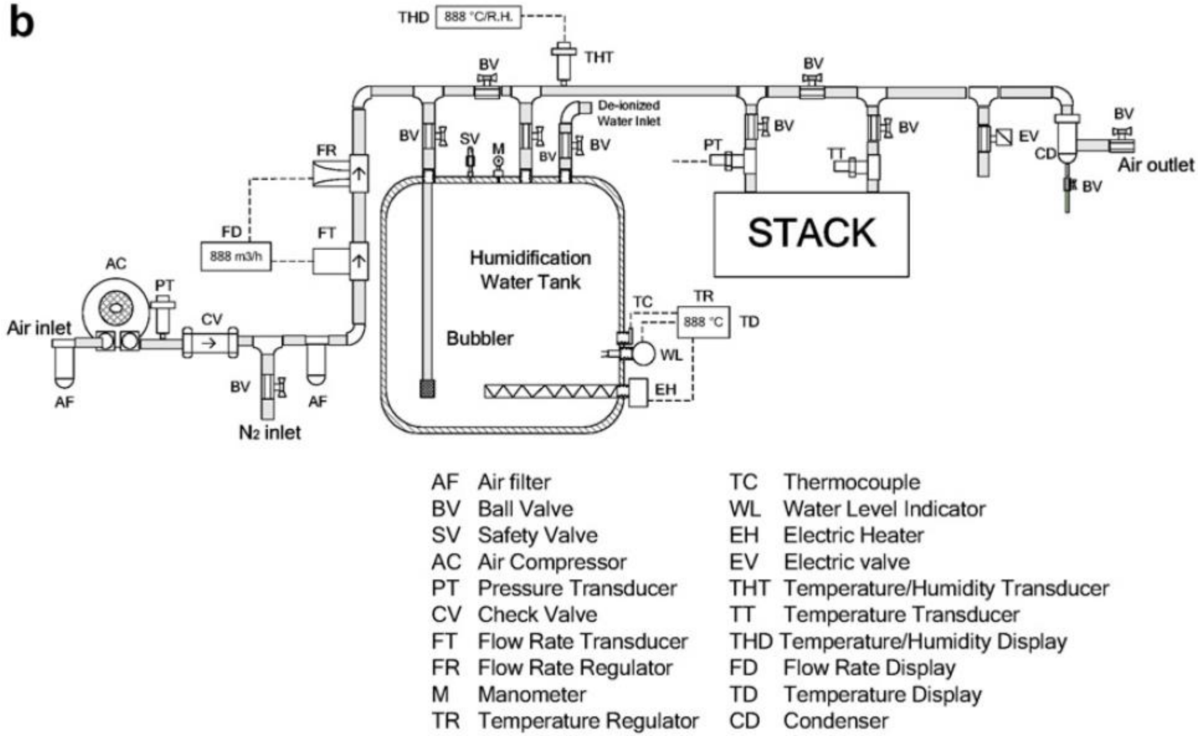
LOW VS. HIGH HEAT FUEL CELLS

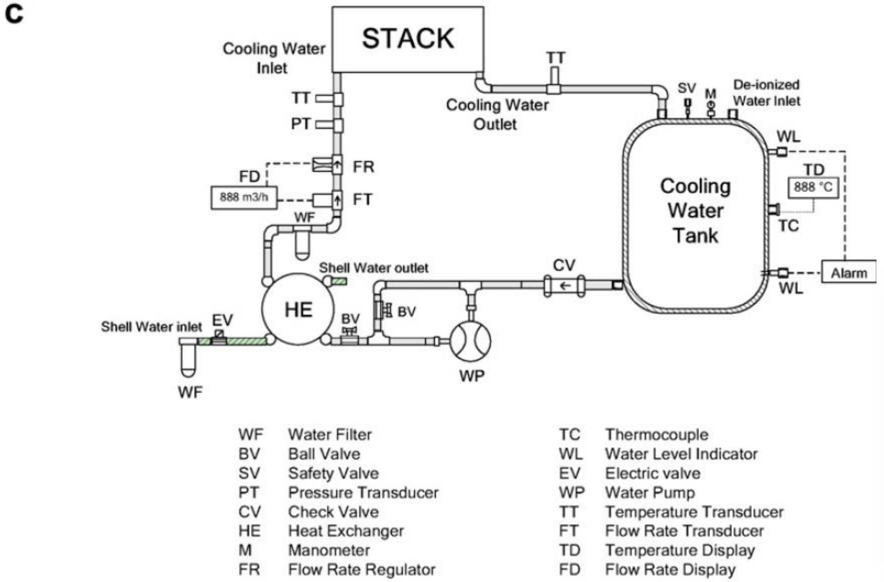
- Low-temperature FCs require short warm-up times
  - Important for portable and emergency power applications

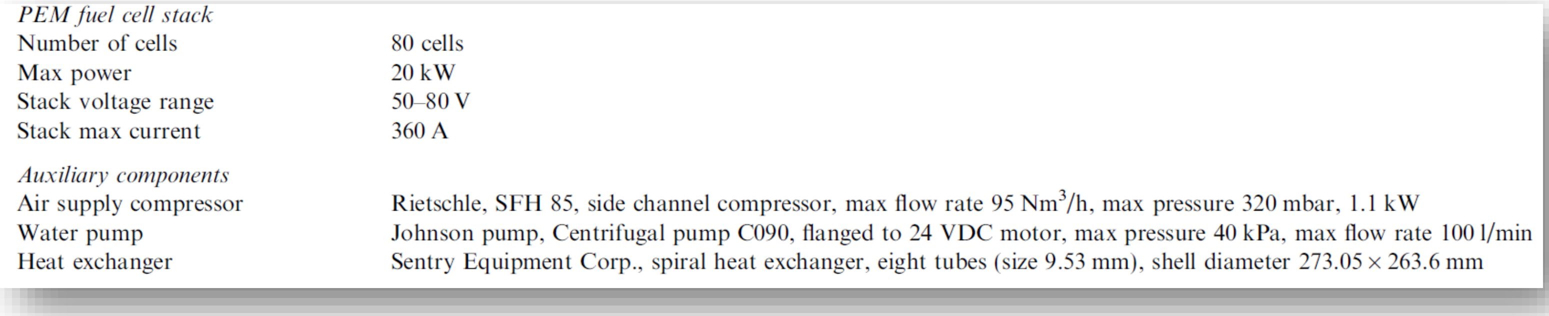
- Medium-to-high temperature FCs can benefit from waste heat recovery
  - Increases overall system efficiency
  - Provides additional form of power output useful for domestic hot water (DHW) and space heating residential applications or CHP industrial-level applications.

FUEL CELL SECTIONS









PEM fuel cell stack	
Number of cells	80 cells
Max power	20 kW
Stack voltage range	50–80 V
Stack max current	360 A
Auxiliary components	
Air supply compressor	Rietschle, SFH 85, side channel compressor, max flow rate 95 Nm^3/h, max pressure 320 mbar, 1.1 kW
Water pump	Johnson pump, Centrifugal pump C090, flanged to 24 VDC motor, max pressure 40 kPa, max flow rate 100 l/min
Heat exchanger	Sentry Equipment Corp., spiral heat exchanger, eight tubes (size 9.53 mm), shell diameter 273.05 × 263.6 mm

PEM fuel cell sections (for a given experimental setup) showing (a) hydrogen feeding, (b) air feeding and (c) stack cooling systems as well as used equipment and technical specifications (table)

2. Fundamentals

2.1 Fuel Cells

FUEL CELL

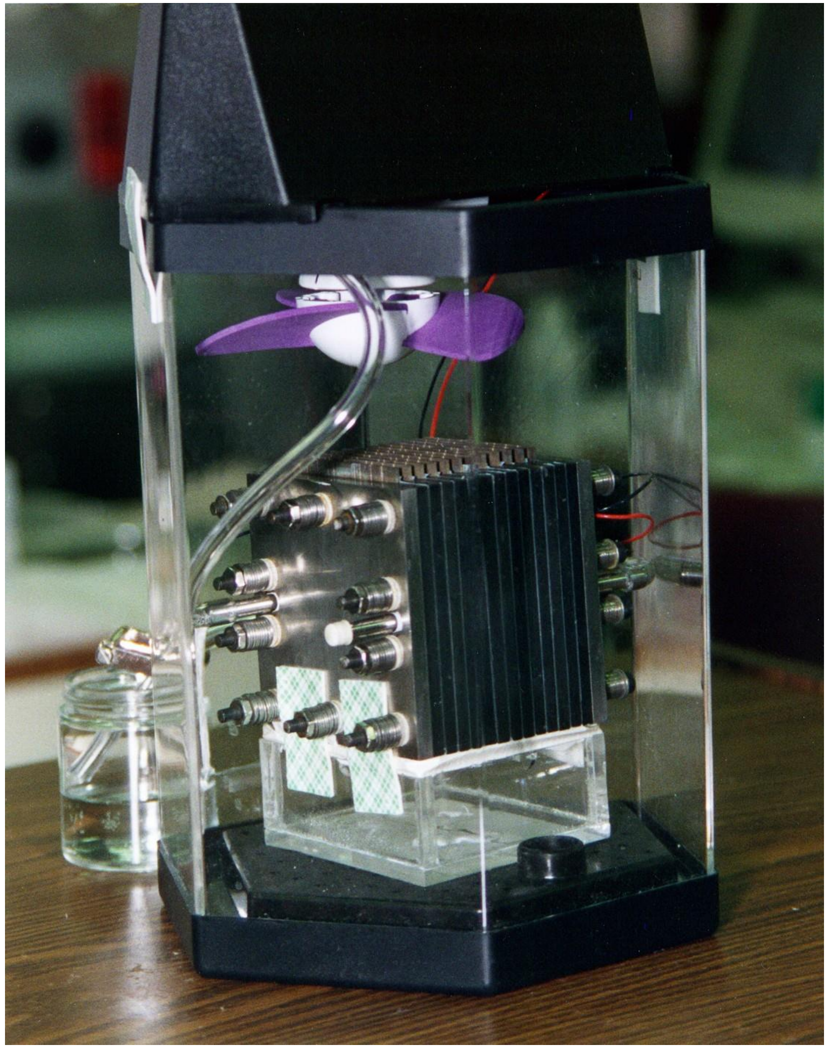
- **Electrochemical devices that convert fuel chemical energy directly to usable energy - electricity and heat - without combustion.**

- Fuel cells (like batteries) contain electrodes and electrolytic materials to produce electricity.

- Fuel cells do not store chemical energy, only convert it
  - No recharging but need fuel and oxidant supply.

- **Interdisciplinary system combining electrochemistry, thermodynamics, engineering economics, material science and engineering, and electrical engineering.**

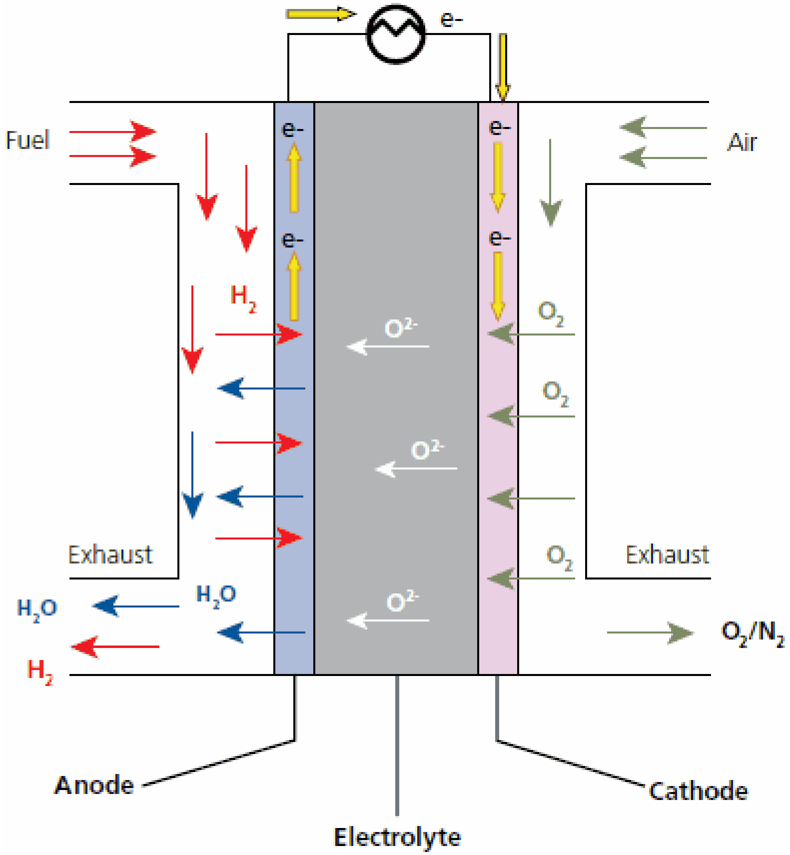
- FCs include **3 active components**:
  - Fuel electrode (anode | positive)
  - Oxidant electrode (cathode | negative)
  - Electrolyte sandwiched between them.
    - Electrodes consist of a porous material covered with a layer of catalyst (often platinum in PEMFCs). H_2 is delivered from a gas-flow stream to the anode where it reacts electrochemically.
    - The **hydrogen is oxidized to produce hydrogen ions and electrons**.



Fuel cell

FUEL CELL SCHEME

- Fuel is electrochemically oxidized on the anode surface and oxidant is electrochemically reduced on the cathode surface.
  - Ions created by the electrochemical reactions flow between anode and cathode through the electrolyte.
  - Electrons produced at the anode flow through an external load to the cathode completing an electric circuit.
- A **typical fuel cell** requires gaseous fuel and oxidant flows.
  - Hydrogen preferred fuel due to high reactivity (minimizes need for expensive catalysts) + H2 electro-oxidation leads only to H2O emission.
  - Hydrocarbon fuels can be supplied but typically require conversion to hydrogen or a hydrogen-rich mixture.
  - Ambient oxygen preferred oxidant due to availability.
- **Electrolyte serves as an ion conductor**.
  - **Ion transport direction depends on fuel cell type**, which determines the type of ion that is produced and transported across electrolyte between electrodes.
- FC building blocks are called the Membrane Electrode Assemblies (MEAs)



General schematic of a fuel cell

UNDERSTANDING FUEL CELLS

- **Operating temperature =** temperature needed for the chemical reactions to occur (based on FC type)
- **Catalyst =** substance that speeds up the chemical process by lowering the amount of energy needed to cause the reaction.
- **Ionization =** a compound separating into ions (e.g. $2H_2 \rightarrow 4H^+ + 4e^-$)
- **Anode =** electrode where the chemical reaction **produces positive ions**
  - Material itself can be a catalytic metal e.g. Palladium – Pd, or a mixture of substances to have the catalytic property to speed up the process
- **Cathode =** electrode where **negative ions are produced**
  - Can be a catalytic metal or a mixture
- **Electrolyte = permits only the appropriate ions to pass (positive or negative based on FC type)**,
  - Electrolyte does not react with the ions.
  - May consist of a liquid solution or a solid material.
  - Electrolyte is electron-insulated electrolyte and serves the vital function of ionic transfer.

MAIN FC EQUATIONS (PEMFC)

- **Hydrogen ions migrate through acidic electrolyte** while **electrons are forced through an external circuit** all the way to the cathode.

$$H_2 \Rightarrow 2H^+ + 2e^-$$

- At the cathode, **electrons and hydrogen ions react with the oxygen** supplied from an external gas-flow stream **to form water**

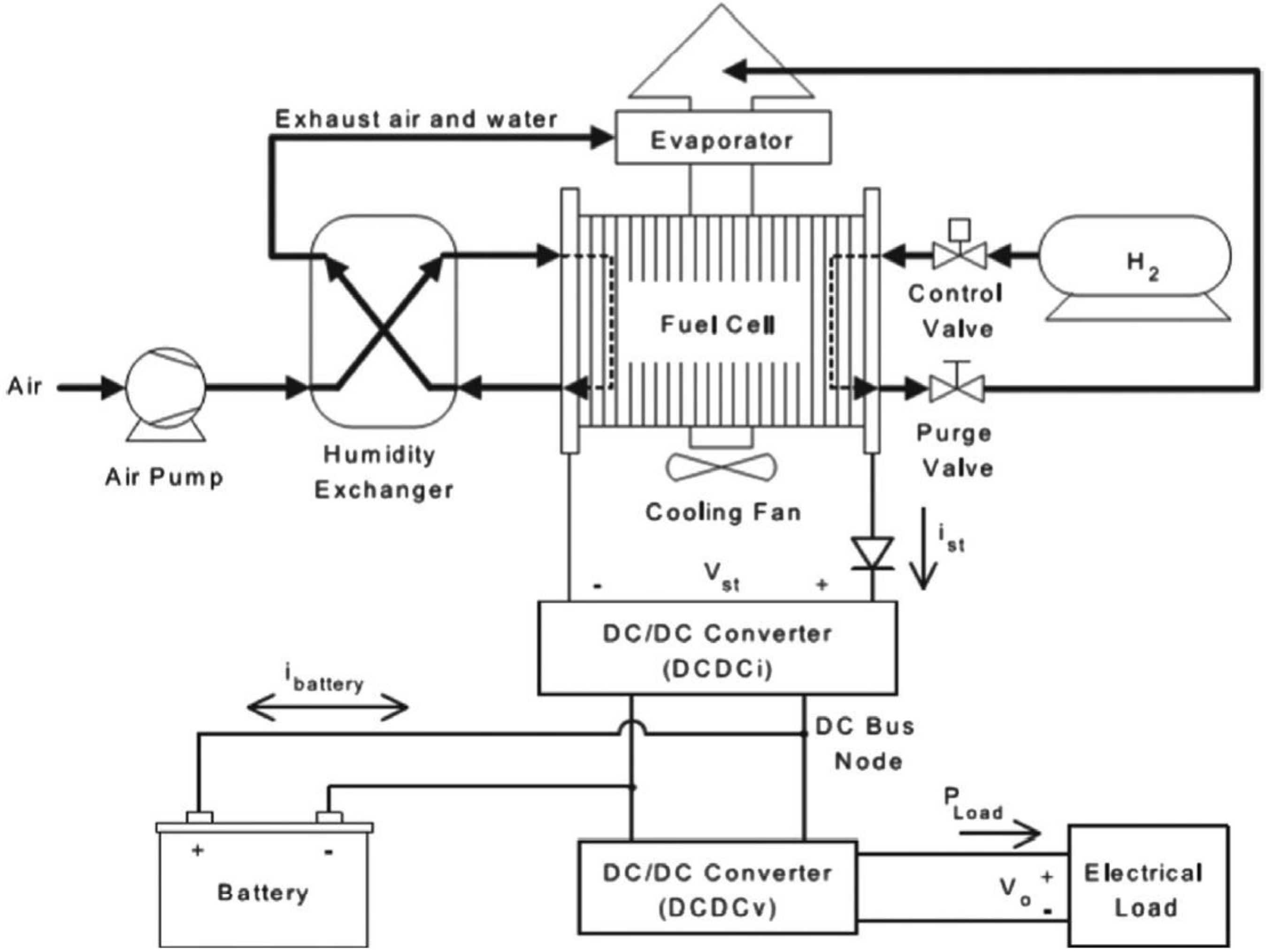
$$\frac{1}{2}O_2 + 2H^+ + 2e^- \Rightarrow H_2O$$

- The overall reaction in the fuel cell produces **water, heat, and electrical work** as follows:

$$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O + W_{ele} + Q_{heat}$$

- **Heat and water by-products must be continuously removed** to maintain continuous isothermal operation for ideal electric power generation.
  - Water and thermal management are key areas in the efficient design and operation of fuel cells.

COMPLETE HYDROGEN-AIR PEM FC SYSTEM

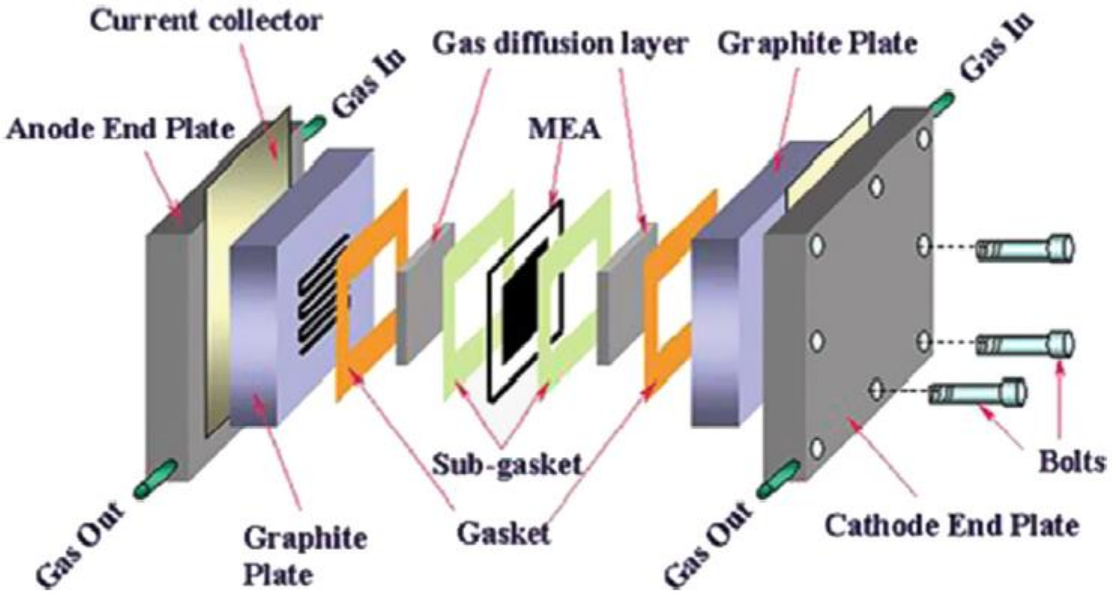


Schematic of complete hydrogen-air PEMFC system - Ramos-Paja CA, Romero A, Giral R, Calvente J, Martinez-Salamero L. Mathematical analysis of hybrid topologies efficiency for PEM fuel cell power systems design. Int J Electr Power Energy Syst 2010;32:1049–61.

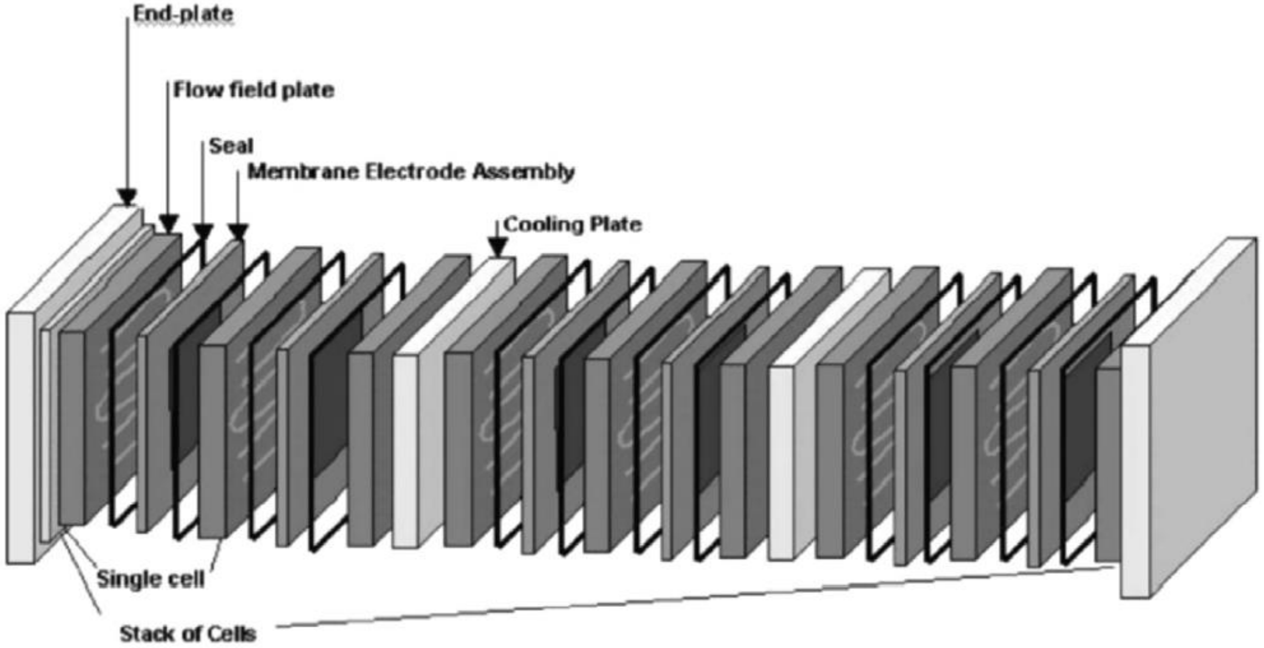
CELL, STACK AND SYSTEM

- The **unit cell** is the heart of a FC system **where basic electrochemical reactions take place**.
  - Each electrode is a thin electrocatalyst layer (usually platinum deposited on the surface of carbon-supported powder) attached to either the membrane or the gas diffusion layer. This microscopic catalyst electrode layer is where the fuel cell's electrochemical reactions take place.
- A **single fuel cell is only capable of producing about 0.5-0.8 V** - typical fuel cell designs link together **many individual cells to form a "stack"** that produces a more useful voltage.
  - FC stack can be configured with groups of cells in series/parallel connections to further tailor the voltage, current and power produced.
  - ~ >50 cells per stack
- FC stack significantly more complex than single unit cell due to the requirements for current collection, thermal management, water management, humidification of gases, cell and gas separation, structural support, and oxidant and fuel distribution.
- Usually, **the complexity of the overall fuel cell system increases with increasing fuel cell stack size as the temperature, pressure, water, and heat become more problematic and demanding.**

FUEL CELL STACKS



Single unit cell and a stack a cells - Farrington L. Fuel for thought on cars of the future. Sci Comput World 2003

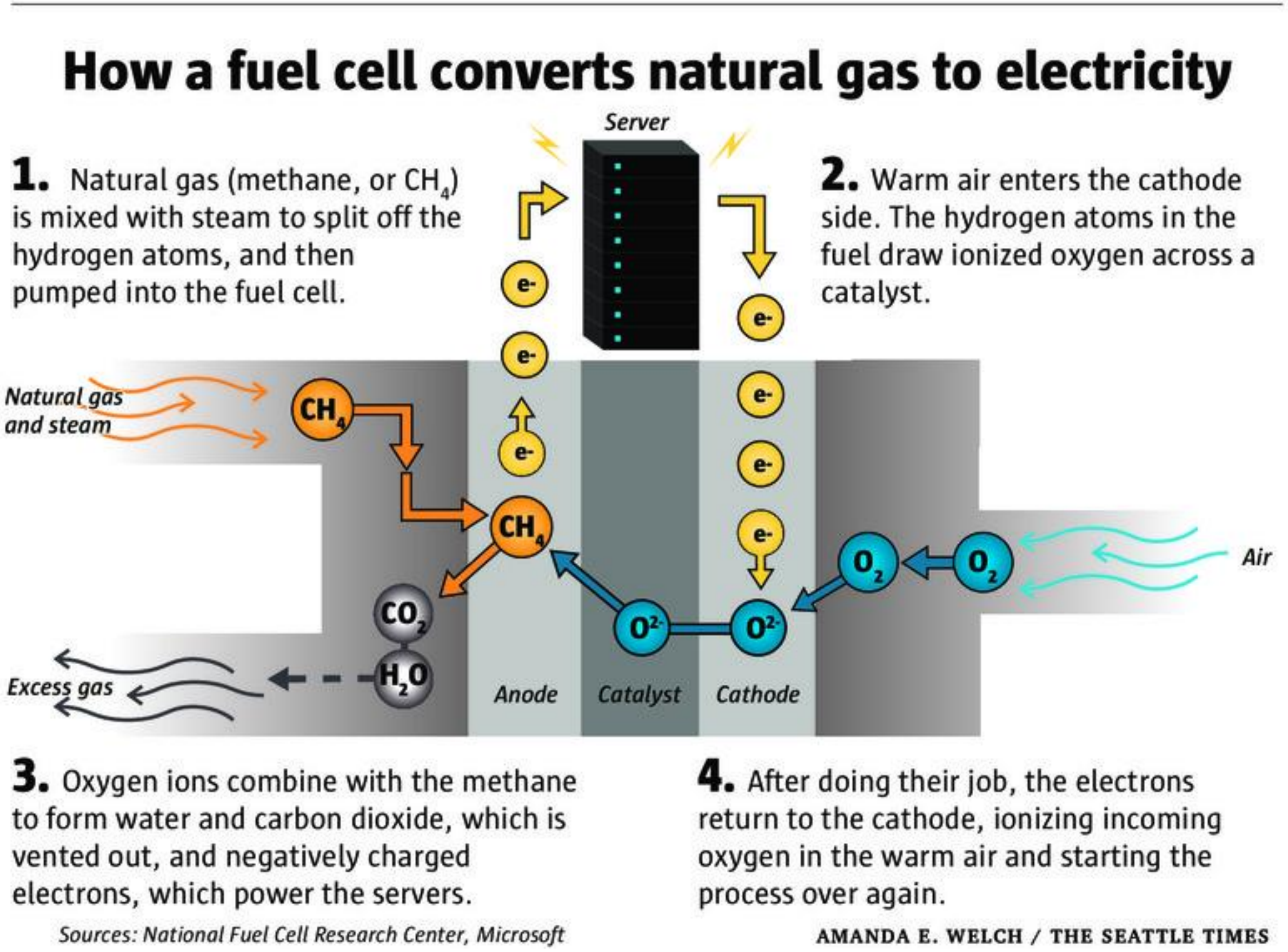


Main components in a fuel cell stack - Mehta V, Cooper JS. Review and analysis of PEM fuel cell design and manufacturing. J Power Sources 2003; 114:32–53

PEMFC BALANCE-OF-PLANT SUBSYSTEMS

Subsystem	Function
Water Management	Ensures all parts of the fuel cell are **sufficiently hydrated without flooding**.
	Humidifies incoming gases (especially to anode).
	Ensures proper **water removal from cathode**.
	Employs purge cycles and back pressure regulators for removal of accumulated liquid water from anode
Thermal Management	Uses *fans* for **active air cooling**.
	Uses *pumps* for **circulation of cooling liquid through cooling plates**.
	Provides **start-up heating in cold climates**, if required
Gases Management	Employs an appropriate **storage mechanism for hydrogen** with pressure-reducing regulators.
	Uses a fuel cell reformer in case of using hydrocarbons as hydrogen sources.
	Employs a *pump* for hydrogen recirculation.
	Employs a *fan, blower, or compressor* for **air supply**
Power Conditioning	**Converts variable low-DC voltage output to usable DC power** via a step-up DC–DC converter when required.
	Inverts the variable low-DC voltage output to usable AC power via a switch-mode DC–AC inverter when required.
	Employs a battery or an ultra capacitor to **meet power spike transients**.

FUEL TO ELECTRICITY CONVERSION (FROM NG)



How a fuel cell converts natural gas to electricity

1. Natural gas (methane, or CH_4) is mixed with steam to split off the hydrogen atoms, and then pumped into the fuel cell.

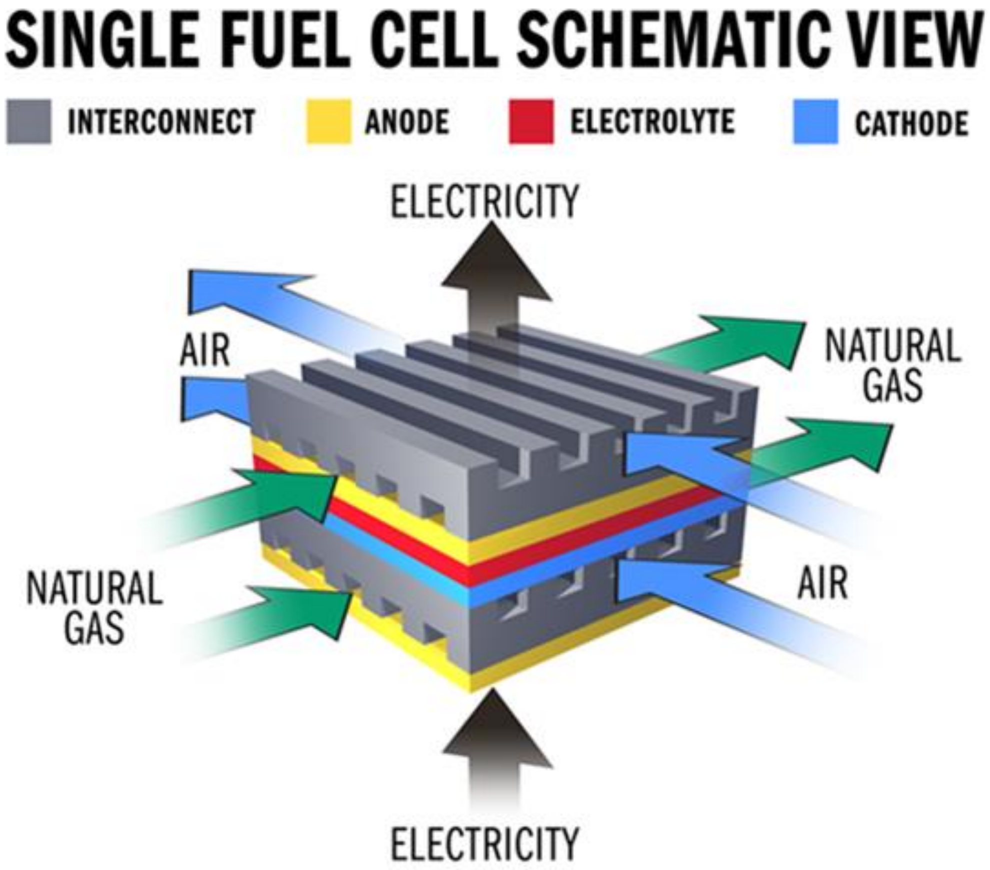
2. Warm air enters the cathode side. The hydrogen atoms in the fuel draw ionized oxygen across a catalyst.

3. Oxygen ions combine with the methane to form water and carbon dioxide, which is vented out, and negatively charged electrons, which power the servers.

4. After doing their job, the electrons return to the cathode, ionizing incoming oxygen in the warm air and starting the process over again.

Sources: National Fuel Cell Research Center, Microsoft

AMANDA E. WELCH / THE SEATTLE TIMES



SINGLE FUEL CELL SCHEMATIC VIEW

▨ INTERCONNECT 🟨 ANODE 🟥 ELECTROLYTE 🟦 CATHODE

2.1.1 Types of Fuel Cells

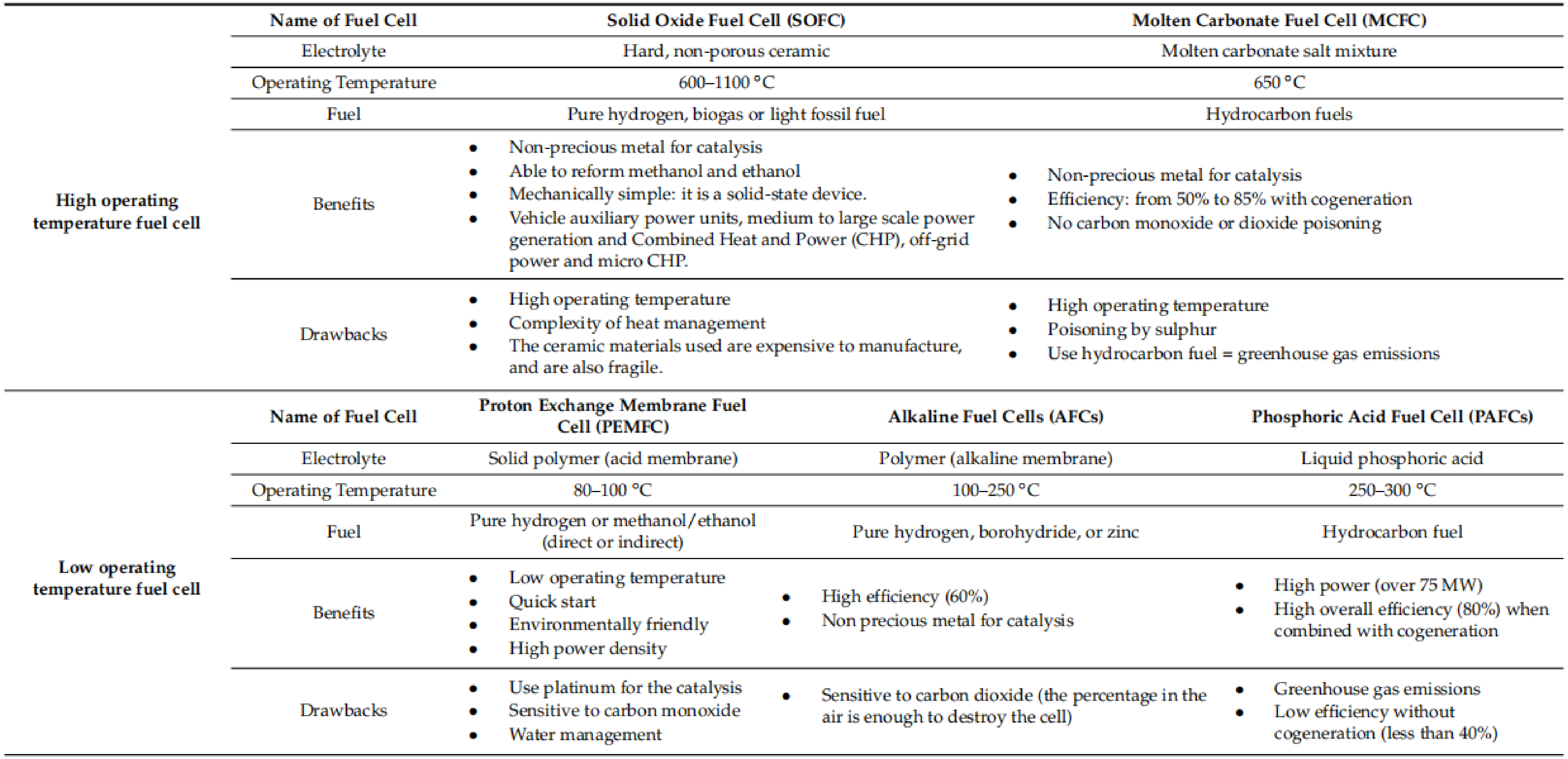
FUEL CELL TYPES

- Most common fuel cell types in order of operating temperature (ranging from 80 to 1000 deg. C):
  - 1. Proton exchange membrane fuel cells (PEMFC)
  - 2. Alkaline fuel cells (AFC)
  - 3. Phosphoric acid fuel cells (PAFC)
  - 4. Molten carbonate fuel cells (MCFC)
  - 5. Solid oxide fuel cells (SOFC)

FUEL CELL TYPES AND THEIR APPLICATIONS

- Fuel cells are conventionally categorized according to their electrolyte material.
  - Differ in their power outputs, operating temperatures, electrical efficiencies, and typical applications.
- <u>PEMFCs</u> have largest range of applications as they are extremely flexible.
  - Most promising candidates for **transport applications** due to their **high power density, fast start-up time, high efficiency, low operating temperature, and easy and safe handling**.
  - **Still too expensive** to be competitive or economically-feasible.
- <u>AFCs</u> have the best performance when operating on pure hydrogen and oxygen, yet their intolerance to impurities (especially carbon oxides) and short lifetimes hinder their role for terrestrial applications
  - Predominantly used for extraterrestrial purposes.
- <u>Phosphoric acid fuel cells (PAFCs)</u> are possibly the **most commercially-developed fuel cells** operating at intermediate temperatures.
  - Used for combined-heat-and-power (CHP) applications with high energy efficiencies.
- <u>Molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs)</u> are high-temperature fuel cells appropriate for **cogeneration and combined cycle systems**.
  - MCFCs have the highest energy efficiency attainable from methane-to- electricity conversion in 250kW-20MW range
  - SOFCs are best suited for base-load utility applications operating on coal-based gasses.

FUEL CELL TYPE CLASSIFICATION



	Name of Fuel Cell	Solid Oxide Fuel Cell (SOFC)	Molten Carbonate Fuel Cell (MCFC)
High operating temperature fuel cell	Electrolyte	Hard, non-porous ceramic	Molten carbonate salt mixture
	Operating Temperature	600–1100 °C	650 °C
	Fuel	Pure hydrogen, biogas or light fossil fuel	Hydrocarbon fuels
	Benefits	• Non-precious metal for catalysis • Able to reform methanol and ethanol • Mechanically simple: it is a solid-state device. • Vehicle auxiliary power units, medium to large scale power generation and Combined Heat and Power (CHP), off-grid power and micro CHP.	• Non-precious metal for catalysis • Efficiency: from 50% to 85% with cogeneration • No carbon monoxide or dioxide poisoning
	Drawbacks	• High operating temperature • Complexity of heat management • The ceramic materials used are expensive to manufacture, and are also fragile.	• High operating temperature • Poisoning by sulphur • Use hydrocarbon fuel = greenhouse gas emissions

	Name of Fuel Cell	Proton Exchange Membrane Fuel Cell (PEMFC)	Alkaline Fuel Cells (AFCs)	Phosphoric Acid Fuel Cell (PAFCs)
Low operating temperature fuel cell	Electrolyte	Solid polymer (acid membrane)	Polymer (alkaline membrane)	Liquid phosphoric acid
	Operating Temperature	80–100 °C	100–250 °C	250–300 °C
	Fuel	Pure hydrogen or methanol/ethanol (direct or indirect)	Pure hydrogen, borohydride, or zinc	Hydrocarbon fuel
	Benefits	• Low operating temperature • Quick start • Environmentally friendly • High power density	• High efficiency (60%) • Non precious metal for catalysis	• High power (over 75 MW) • High overall efficiency (80%) when combined with cogeneration
	Drawbacks	• Use platinum for the catalysis • Sensitive to carbon monoxide • Water management	• Sensitive to carbon dioxide (the percentage in the air is enough to destroy the cell)	• Greenhouse gas emissions • Low efficiency without cogeneration (less than 40%)

NOTE: Any one of the above fuel cell types can be integrated into a hybrid gas turbine fuel cell cycle, the advantages of integration are most prominent with the high temperature fuel cells (i.e., MCFC and SOFC). This is due to the fact that a gas turbine engine can more effectively utilize the heat produced at the higher operating temperatures of MCFC and SOFC technology than it can that produced by other fuel cell types. In a complementary fashion, the MCFC and SOFC technologies can directly benefit from the pressure and temperature conditions (higher pressure and preheating of reactants) that a gas turbine engine can produce in an integrated hybrid cycle.

FUEL CELL TYPES SUMMARY

	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide	Immobilized Liquid Phosphoric Acid	Immobilized Liquid Molten Carbonate	yttrium-stabilized zirconia
Operating Temperature	80°C	120°C -150°C	200°C	650°C	800-1000°C
Charge Carrier	H+	OH-	H+	CO3-2	O-2
External Reformer for CH4	Yes	Yes	Yes	No	No
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless-based	Ceramic
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Usable Rejected Heat Recovery	Negligible	Negligible	Yes	Yes	Yes
Gaseous/Liquid Water Formation	Cathode	Anode	Cathode	Anode	Anode
Fuel	Pure H2 (tolerates CO2)	Pure H2	Pure H2 (tolerates CO2, 1.5%CO)	H2, CO, CH4,other hydrocarbons (toleratesCO2)	H2, CO, CH4, other hydrocarbons (toleratesCO2)
Electrical Efficiency	35%	40-60%	40-50%	50-60%	50-65%

AFC - Alkaline Fuel Cell;
MCFC - Molten Carbonate Fuel Cell;
PAFC - Phosphoric Acid Fuel Cell;
PEMFC - Proton Exchange Membrane Fuel Cell;
SOFC - Solid Oxide Fuel Cell.

EXHAUSTIVE COMPARISON (1)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Low-temperature proton exchange membrane	Solid Nafion	Anode: Platinum supported on carbon Cathode: Platinum supported on carbon	Graphite	H_2	H^+	Carbon monoxide (CO) Hydrogen sulfide (H_2S)	60 - 80	**Highly modular for most applications** High power density Compact structure Rapid start-up due to low temperature operation Excellent dynamic response	**Complex water and thermal management** Low-grade heat High sensitivity to contaminants Expensive catalyst	40 - 60	4	H
High-temperature proton exchange membrane	Solid composite Nafions Polybenzimidazole (PBI) dopedin phosphoric acid	Anode: Platinum–Ruthenium supported on carbon Cathode: Platinum–Ruthenium supported on carbon	Graphite	H_2	H^+	Carbon monoxide (CO)	110 - 180	Simple water management Simple thermal management Accelerated reaction kinetics High-grade heat High tolerance to contaminants	Accelerated stack degradation Humidification issues Expensive catalyst	50 - 60	3	M
Solid Oxide	Solid yttria-stabilized zirconia(YSZ)	Anode: Nickel–YSZ composite Cathode: Strontium-doped lanthanum manganite (LSM)	Ceramics	Methane	O^{2-}	Sulfides	800 - 1000	**High electrical efficiencies** High-grade heat High tolerance to contaminants Possibility of internal reforming Eliminated electrolyte issues Fuel flexibility Inexpensive catalyst	**Slow start-up** Low power density Strict material requirements High thermal stresses Sealing issues Durability issues High manufacturing costs	55 - 65	3	H

EXHAUSTIVE COMPARISON (2)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Molten Carbonate	Liquidalkali carbonate (Li2CO3, Na2CO3, K2CO3) in Lithium aluminate (LiAlO2)	Anode: Nickel Chromium (NiCr) Cathode: Lithiated nickel oxide (NiO)	Stainless Steel	Methane	CO3,2-	Sulfides Halides	600 - 700	**High electrical efficiencies** High-grade heat High tolerance to contaminants Possibility of internal reforming Less strict material requirements Fuel flexibility Inexpensive catalyst	Slow start-up **Low power density** Electrolyte corrosion and evaporative losses Corrosion of metallic parts Air crossover Catalyst dissolution in electrolyte Cathode carbon dioxide (CO2)injection requirement	55 – 65	4	H
Phosphoric Acid	Concentrated liquidphosphoric acid (H3PO4) in silicon carbide(SiC)	Anode: Platinum supported on carbon Cathode: Platinum supported on carbon	Graphite	H2	H+	Carbon monoxide(CO) Siloxane Hydrogen sulfide (H2S)	160 - 220	**Technologically mature and reliable** Simple water management Good tolerance to contaminants High-grade heat	Relatively slow start-up Low power density High sensitivity to contaminants Expensive auxiliary systems Low electrical efficiencies Relatively large system size Electrolyte acid loss Expensive catalyst **High cost**	36 – 45	5	M

EXHAUSTIVE COMPARISON (3)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Alkaline	Potassium hydroxide(KOH) watersolution Anion exchange membrane (AEM)	Anode: Nickel Cathode: Silver supported on carbon	Metallic Wires	H2	OH-	CO2	Below zero - 230	High electric efficiency due to fast reduction reaction kinetics Wide range of operation temperature and pressure Inexpensive catalyst Catalyst flexibility **Relatively low costs**	**Extremely high sensitivity to contaminants** Pure hydrogen and oxygen required for operation Low power density Highly corrosive electrolyte leads to sealing issues Complex and expensive electrolyte management for mobile electrolyte systems	60 - 70	5	L
Direct Methanol	Solid Nafion	Anode: Platinum–Ruthenium supported on carbon Cathode: Platinum supported on carbon	Graphite	Liquid methanol–water solution	H+	CO	Ambient - 110	Compact size **Simple system** High fuel volumetric energy density Easy fuel storage and delivery Simple thermal management for liquid methanol systems	**Low cell voltage and efficiency due to poor anode kinetics** **Low power density** Lack of efficient catalysts for direct oxidation of methanol Fuel and water crossover Complex water management High catalyst loading High cost Carbon dioxide (CO2) removal system Fuel toxicity	35 - 60	3	H

EXHAUSTIVE COMPARISON (4)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Direct Ethanol	Solid Nafion Alkaline media Alkaline-Acidmedia	Anode: Platinum–Ruthenium supported on carbon Cathode: Platinum supported on carbon	Graphite	Liquid ethanol–water solution	H+	CO	Ambient - 120	Compact size Environmentally-friendly fuel High fuel volumetric energy density Relatively low fuel toxicity Relatively higher gravimetric energy density Easy fuel storage and delivery Simple thermal management	Low power density High sensitivity to carbon monoxide (CO) Low cell voltage and efficiency due to poor anode kinetics Lack of efficient catalysts for direct oxidation of ethanol High cost Fuel and water crossover	20 - 40	2	L
Directethylene glycol	Solid Nafions Anion exchange membrane (AEM)	Anode: Platinum supported on carbon Cathode: Platinum supported on carbon	Graphite	Liquid ethylene glycol	H+	CO	Ambient - 130	Compact size High fuel volumetric energy density Low volatility due to low vapor pressure and high boiling point Easy fuel storage and delivery Simple thermal management Simple water management Existence of distribution infrastructure	Low power density Low cell voltage and efficiency due to poor anode kinetics Lack of efficient catalysts for direct oxidation of ethylene glycol Low fuel gravimetric energy density Durability issues High cost Fuel crossover	20 - 40	2	L

EXHAUSTIVE COMPARISON (4)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Microbial	Ion exchange membrane	Anode: Biocatalyst supported on carbon Cathode: Platinum supported on carbon	N/A	Anyorganic matter (e.g., glucose, acetate, waste-water)	H+	Bacterial contamination of cathode	20 - 60	Fuel flexibility Biocatalyst flexibility No need for enzymatic catalysts isolation, extraction,and preparation Relatively higher lifetime for biocatalysts Capacity for self-regeneration of enzymes	Electron transfer mechanisms from the metabolism in the micro organisms to the fuel cell anode is problematic Relatively lower energy density due to using some of the energy for the micro organisms activity Very low power density Low columbic yield Inflexible operation conditions	15 - 65	1	M
Direct Carbon	Solid yttria-stabilized zirconia(YSZ) Moltencarbonate Moltenhydroxide	Anode: Graphite or carbon-based material Cathode: Strontium-doped lanthanum manganite (LSM)	N/A	Solidcarbon (e.g., coal, coke, biomass)	O2-	Ash Sulfur	600 - 1000	High electrical efficiency High volumetric energy density Fuel flexibility NoPM, NOx, or SOx emissions Structural simplicity High capacity for carbon sequestration	Carbon dioxide (CO2) emissions Rapid material corrosion and degradation Durability issues Sensitivity to fuel impurities Low power density	70 - 90	2	L

EXHAUSTIVE COMPARISON (5)

Fuel Cell Type	Typical Electrolyte	Typical Anode / Cathode Catalysts	Typical Interconnect Material	Typical Fuel	Charge Carrier	Major Contaminants	Operating Temp. (C)	Specific Advantages	Specific Disadvantages	Electrical Efficiency (%)	Technolog. Maturity	Research Activity
Direct Borohydride	Solid Nafion Anion exchange membrane (AEM)	Anode: Gold, silver,nickel,or platinum supported on carbon Cathode: Platinum supported on carbon	Graphite	Sodium borohydride (NaBH4)	Na+	N/A	20 - 85	Compact size High fuel utilization efficiency High fuel gravimetric hydrogen content No carbon dioxide (CO2) emissions Low toxicity and environmentally-friendly operation	Fuel crossover High cost Low power density Lack of analytical modeling techniques due to unknown borohydride oxidation reaction mechanisms Expensive catalyst Chemical instability of membrane and catalyst Ineffcient cathodic reduction reaction Ineffcient anodic oxidation reaction due to hydrogen evolution from hydrolysis of borohydride and partial release of fuel electrons	40 - 50	2	M
Direct Formicacid	Solid Nafion	Anode: Palladiumor platinum supported on carbon Cathode: platinum supported on carbon	N/A	Liquid formic acid (HCOOH)	H+	CO	30 - 60	Improved anodic oxidation reaction kinetics High fuel utilization efficiency Limited fuel crossover Easy fuel storage and delivery High power density No water required at the anode for oxidation reaction Compact size and structural simplicity	Fuel toxicity Components corrosion issues Low fuel gravimetric and volumetric energy density High fuel cost Low temperature operation	30 - 50	1	L

2.1.1.1 PEM

PEM FC

- **Proton exchange membrane fuel cells (PEMFC)** AKA Solid Polymer Fuel Cells operate at ~80°C
  - Capability of bringing the cell to its operating temperature quickly.
  - Electrolyte prevents gas crossover like SOFCs.

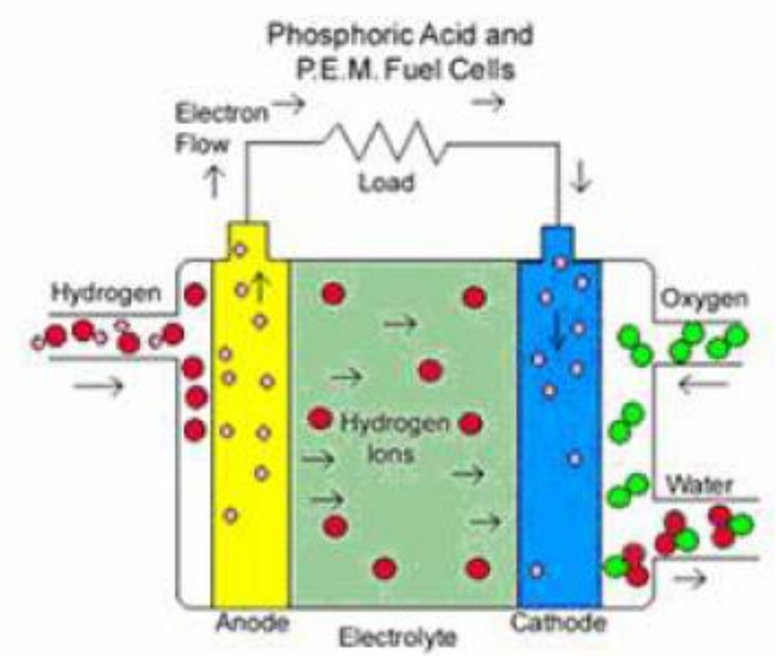
- Suited for quickly meeting shifts in power demand for applications that vary in output.

- **Due to membrane hydration requirement, FC must operate under conditions where the byproduct water does not evaporate faster than it is produced (usually <120°C)**
  - Membrane water management critical for efficient performance.

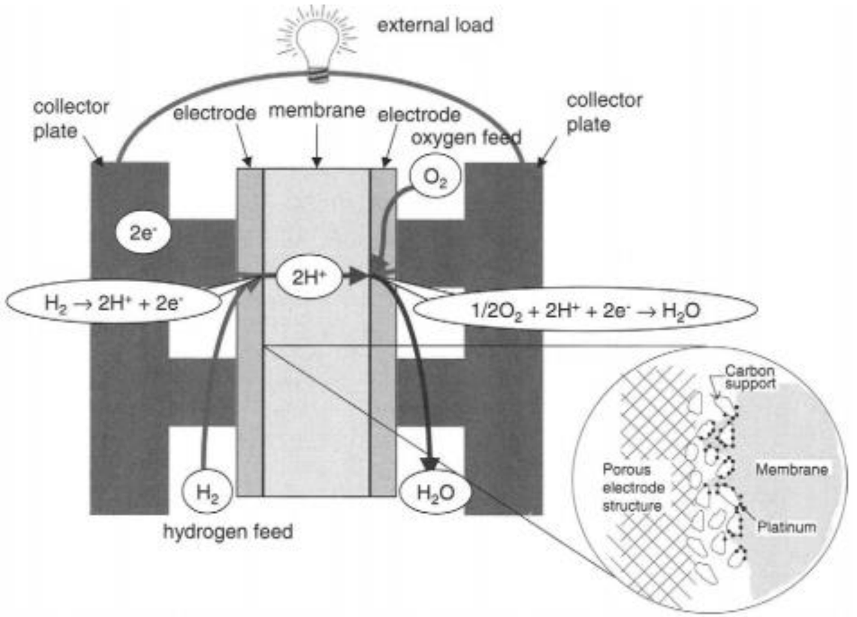
- PEM fuel cells also **require very pure hydrogen** with minimal or no CO (a poison at low temperature) which puts heavy demands on the fuel processing unit.

PRINCIPE OF OPERATION OF PEMFC

- Basic process:
  - Hydrogen decomposes into electrons and protons on the membrane
  - Protons pass through membrane
  - Electrons run along the wires and create an electric current



The basic principle of operation of a PEM fuel cell - https://users.encs.concordia.ca/~pillay/fuel-cells.html



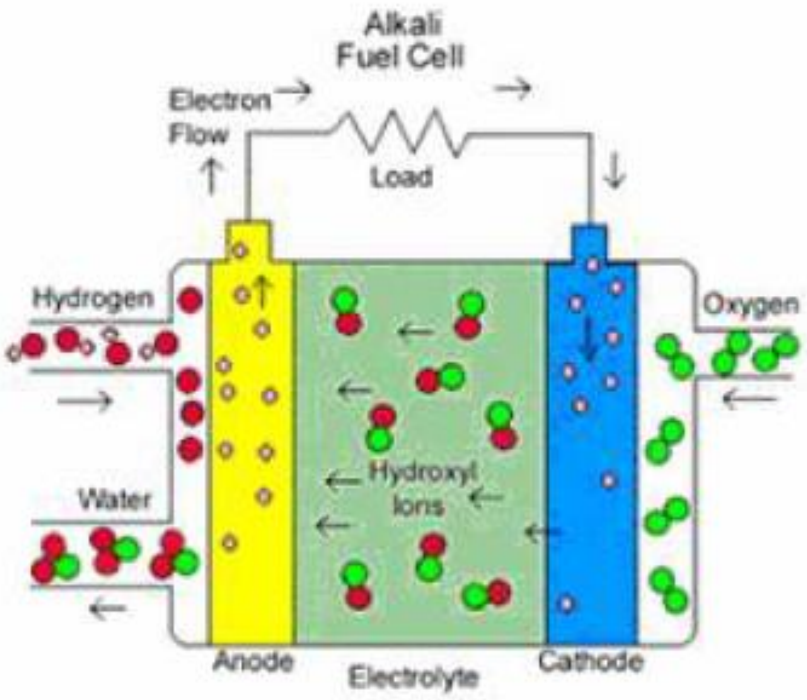
The basic principle of operation of a PEM fuel cell - Barbir F. PEM Fuel Cells. Theory and Practice / F. Barbir / 2nd Edition. – Academic Press, 2012. – 444 p.

2.1.1.2 Alkaline Fuel Cells (AFC)

ALKALINE FUEL CELLS (AFC)

- **Alkaline fuel cells (AFC)** operate around 120°C to 150°C using an aqueous solution of potassium hydroxide (KOH) as the electrolyte.
- **High performance compared to other fuel cells and its flexibility to use a wide range of electrocatalysts.**
- AFCs are **intolerant to CO_2** which reacts with the KOH and effectively degrades the cell performance.
  - **Requires use of pure hydrogen and pure oxygen, not air**

- <u>Operation:</u> Hydrogen is fed to the anode and ionized into $4H^+$ ion and $4e^-$. These hydrogen ions are not free moving ions and will be held in the receptive state at the anode. At the cathode, oxygen O_2 and water $2H_2O$ plus returning electrons from the circuit form hydroxide ions $4(OH^-)$.
- The free moving hydroxyl ions conduct through the potassium hydroxide (KOH) and combine with the hydrogen ions at the anode forming water.



The basic principle of operation of a AFC fuel cell - https://users.encs.concordia.ca/~pillay/fuel-cells.html

2.1.1.3 Phosphoric Acid Fuel Cells (PAFC)

PHOSPHORIC ACID FUEL CELLS (PAFC)

- **Phosphoric acid fuel cells (PAFC)** operate at 200°C using liquid concentrated phosphoric acid (H_3PO_4) as the electrolyte.
  - High relative stability of concentrated phosphoric acid allows operating on high end of acid temperature range of 200°C.
- PAFCs advantages include **tolerance to some impurities in fuel stream** broadening the choice of fuels they can use
  - Requires that hydrocarbon fuels be reformed.
- **Rejected heat from the cell is high enough in temperature to be used for heating**.
  - PAFC electrochemical environment at operating temperature is highly corrosive and can best be avoided by special operating procedures.
- **Unlike PEMFCs, a PAFC operates at near-ambient pressures and does not require the use of a compressor**.

- <u>Operation:</u> Same chemical process as the PEM fuel cell. Hydrogen gas, $2H_2$ is fed to the anode and ionized into 4H+ ion and 4e-. These hydrogen ions are the free moving ions and will conduct through the phosphoric acid electrolyte. At the cathode, a reaction causes O_2 molecules, the returning electrons, and hydrogen protons to combine producing water molecules, $2H_2O$.

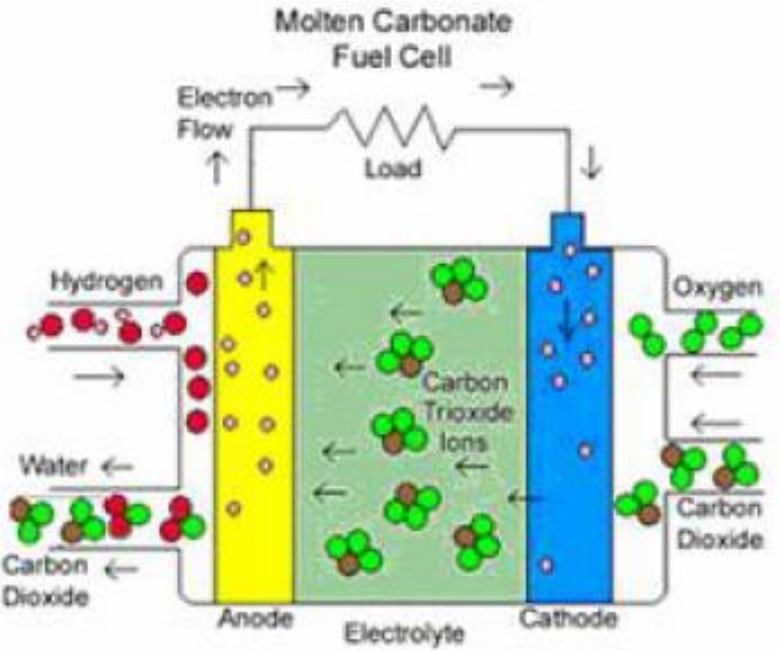
2.1.1.4 Molten Carbonate Fuel Cell (MCFC)

MOLTEN CARBONATE FUEL CELLS (MCFC)

- **Molten carbonate fuel cells (MCFC)** typically use a mixture of alkali carbonates (Li_2CO_3 and K_2CO_3) retained in a ceramic matrix, for an electrolyte.

- **High operating temp. (650°C) needed to achieve sufficient electrolyte conductivity** is beneficial:
  - **CHP capability** - rejected heat can be recovered and used
  - Flexibility in the electrocatalyst used
  - Internal reformation where anode poisoning by CO and, to a certain degre
    impurities is no longer an issue

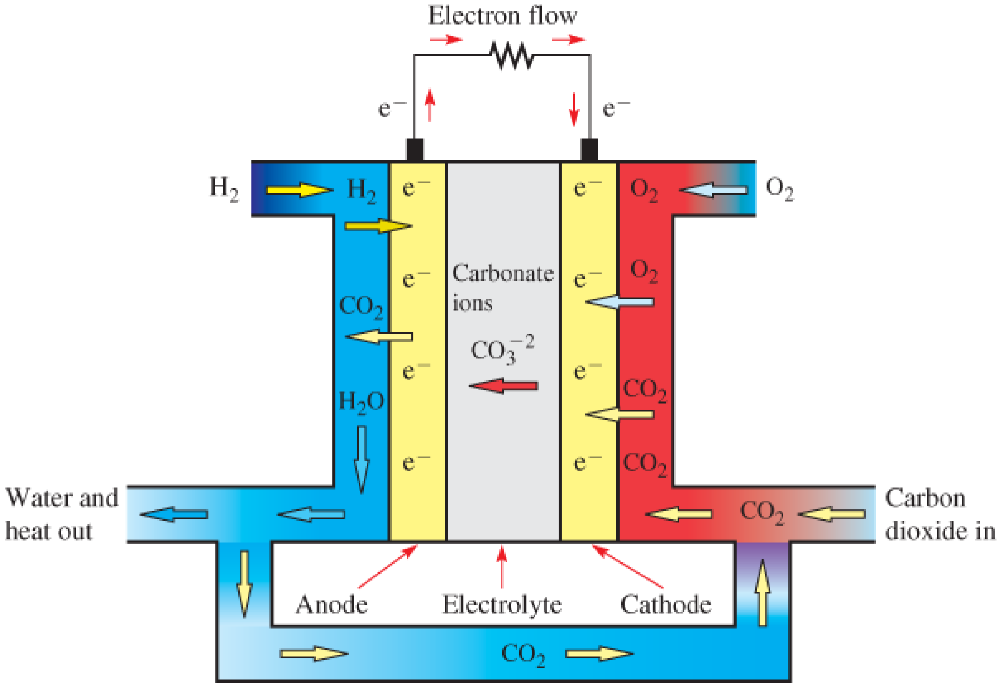
- **High-temperature corrosion is a major problem**
  - Requires use of expensive materials and protective layers.



The basic principle of operation of a MCFC fuel cell - https://users.encs.concordia.ca/~pillay/fuel-cells.html

MCFC OPERATION

- Operation: Formation of water will also occurs at anode.
- The hydrogen gas fed to the anode ionizes into 4H+ ion and 4e-.
  - H^+ produced at anode will not conduct through electrolyte.
- Cathode combines O_2 and $2CO_2$ from oxidant stream with electrons entering the cathode to produce carbonate ions $2CO_3^{2-}$ which enter the electrolyte.
- Free moving carbonate ions conduct through the electrolyte and combine with the hydrogen ions at the anode forming water $2H_2O$ and carbon dioxide $2CO_2$.
- **No extra carbon dioxide produced**.



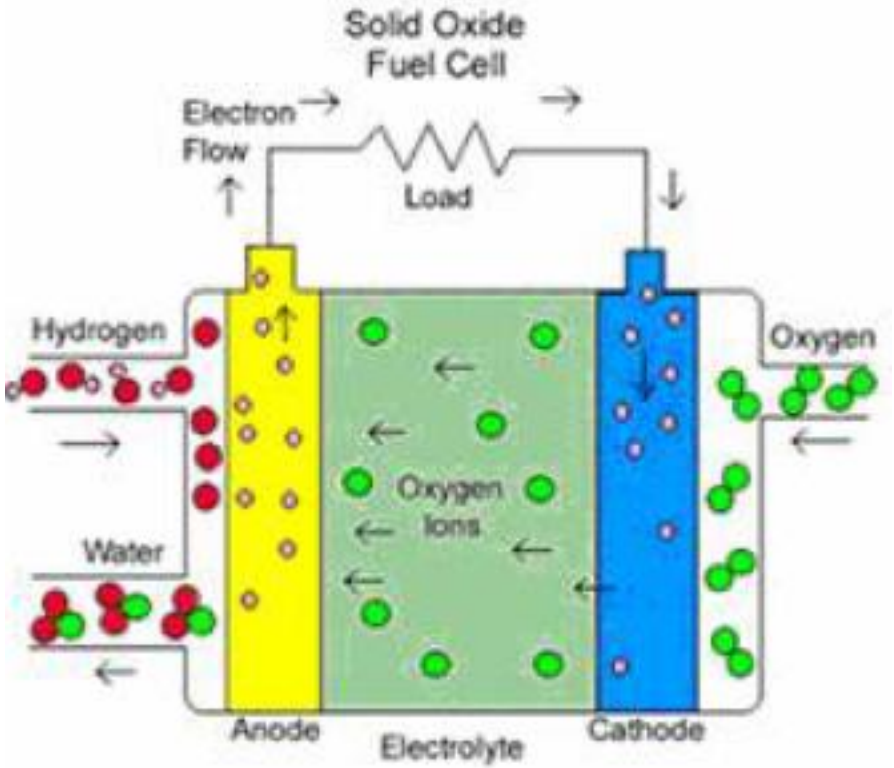
2.1.1.5 Solid Oxide Fuel Cell (SOFC)

SOLID OXIDE FUEL CELLS (SOFC)

- **Solid oxide fuel cells (SOFC)** offer same pros and cons of high temperature operation as MCFC.
  - Electrolyte comprised of a hard ceramic material of solid zirconium oxide and ytrria (yttrium-stabilized zirconia - YSZ), allowing operating temperatures to reach 1000°C.

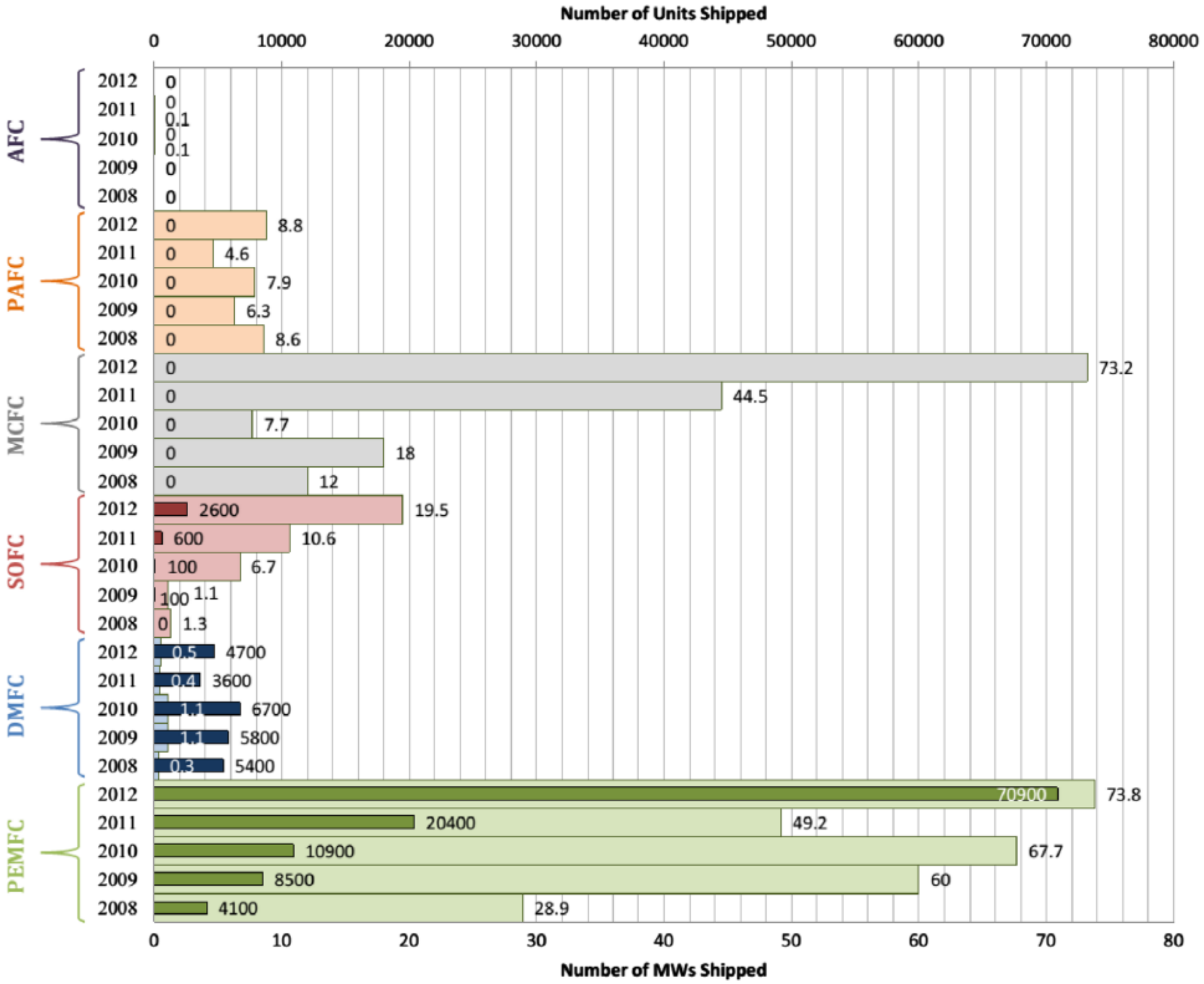
- Capable of generating enough power for **use in high-power applications**.

- Operation: Formation of water at the anode.
- Hydrogen gas is fed to the anode and ionized into $4H^+$ ion and $4e^-$.
  - Hydrogen ions are not free moving ions and will be held in the receptive state at anode.
- Cathode process with electrons entering the cathode forms oxygen ions $2O^{2-}$.
  - Free moving oxygen ions conduct through electrolyte and combine with the H^+ at anode to form water $2H_2O$.



The basic principle of operation of a SOFC fuel cell - https://users.encs.concordia.ca/~pillay/fuel-cells.html

FUEL CELL INDUSTRY GROWTH PER FC TYPE



Annual growth of the fuel cell industry between 2008 and 2012 by fuel cell type | Small bars represent unit; Large bars represent MWh

2.1.2 Electrochemistry Considerations

2.1.2.1 Reactions – Kinetics and Thermodynamics

ENTHALPY & ENTROPY OF FORMATION

- **Enthalpy of overall FC chemical reaction** = Difference between enthalpies of formation of products and reactants.
  - Enthalpy of formation represents amount of heat energy produced from complete fuel combustion

$$\Delta H_f = (h_f)_{H_2O} - (h_f)_{H_2} - (h_f)_{O_2}$$

- Enthalpy of formation of elements such as oxygen and hydrogen is zero by definition while enthalpy of formation of water can be calculated at different temperatures
  - Use of HHV if produced water is liquid vs. LHV if water is in vapor form.
- Since <u>no</u> combustion oxidation occur within a FC, it only serves to indicate amount of fuel energy input.
- **Gibbs free energy of formation** (on a mole basis) is used to determine max. portion of energy input that could be converted into useful electric work:

$$\Delta G_f = \Delta H_f - T\Delta S_f$$

- **Reaction entropy of formation** can be determined similarly $\Delta S_f = (s_f)_{H_2O} - (s_f)_{H_2} - (s_f)_{O_2}$
  - ΔSf term grows faster than the ΔHf term with an increase in temperature.
    - ΔGf decreases in magnitude as temperature is increased.

VOLTAGE EFFICIENCY

- To define a max. efficiency concept, the max. amount of energy available to do useful work (Gibbs free energy of formation) is compared to the energy input (enthalpy of formation) to FC system.
- Reversible max. FC efficiency definition: $\eta_{rev} = \frac{\Delta G_f}{\Delta H_f}$
- Electrical work is defined as the product of charge and potential: $W_{ele} = qE$
  - Total charge transferred with electrons in a fuel cell per every mole of H_2 is: $q = n\, N_{avg}\, q_{el}$
  - where n = number of electrons per molecule of H_2 involved in reaction , N_{avg} = Avogadro's number, and q_{el} = charge of an electron
- Gibbs free energy of formation is equal to electric work produced in FC system without irreversibilities.
  - Reversible cell voltage in FC can therefore be expressed as: $E_{rev} = -\frac{\Delta G_f}{nF}$
- **E_{rev} is the highest theoretically attainable voltage from an isothermal fuel cell**: Nernst voltage.
- FC voltage efficiency (with E the operating voltage) is: $\eta_{vol} = \frac{E}{E_{rev}}$

GIBBS FREE ENERGY OF FORMATION

- Gibbs free energy of formation is in reality not just a function of temperature but also pressure as:

$$\Delta G_f = \Delta G_f^0 - RT \ln \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right)$$

  - where the 0 superscript indicates standard conditions and the P are the gases partial pressures (proportional to the molar fractions in a mixture and assuming all species are in gaseous form).

- Therefore leading to

$$E_{rev} = E_{rev}^0 + \frac{RT}{nF} \ln \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right)$$

  - Where E_{rev}^0 is the reversible Nernst voltage at standard conditions

- **Effect of changing pressure (from P1 to P2) or concentration of hydrogen** can be expressed as:

$$\Delta E_{rev} = \frac{RT}{nF} \ln \frac{(P_{H_2})_2}{(P_{H_2})_1}$$

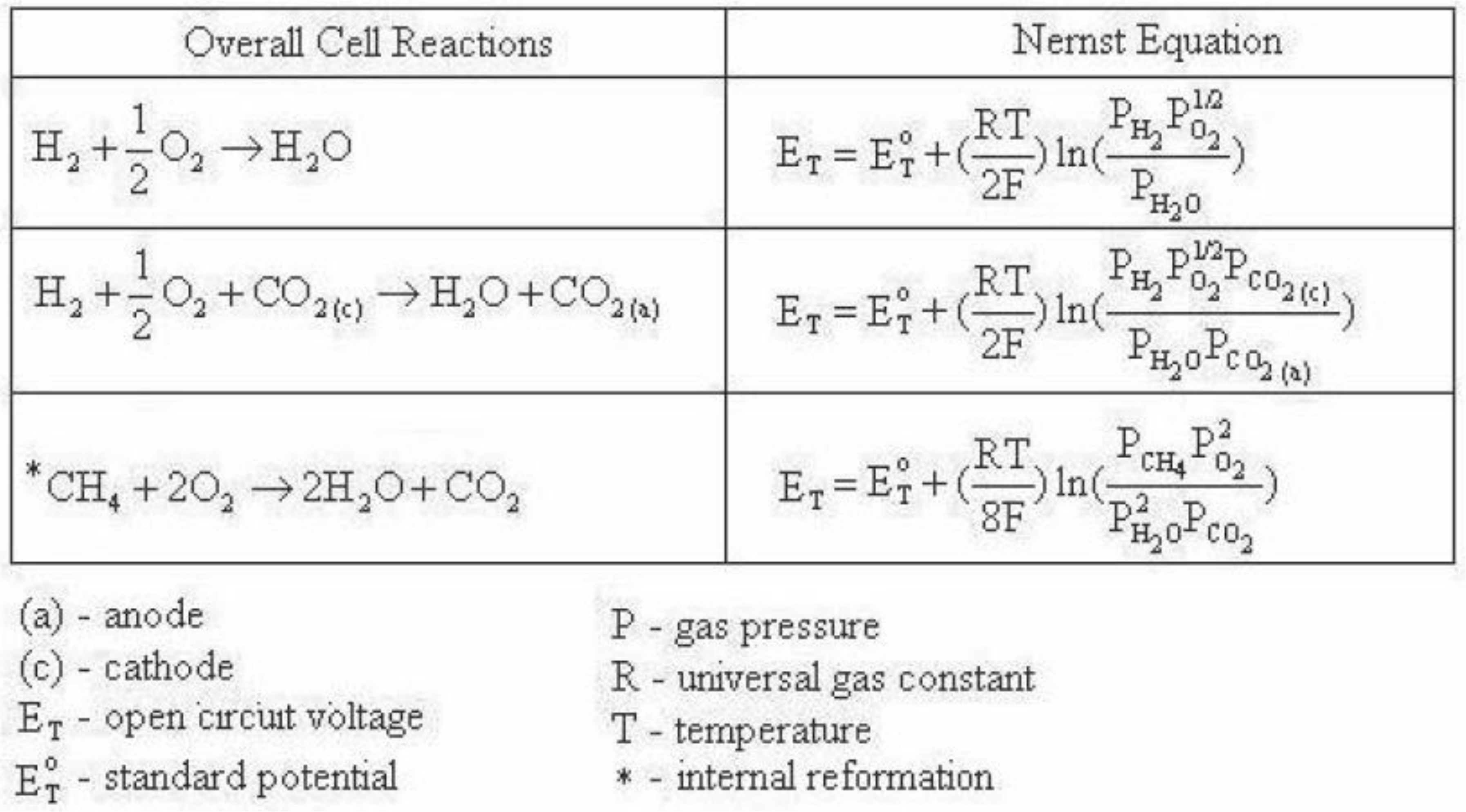
FUEL CELL POTENTIAL (GENERAL NERNST EQ.)

- **Open circuit voltage** = max. operating voltage (when no current is flowing) of FC
  - Determined based on chemical thermodynamics of overall cell reaction.
- The **Nernst equation** provides a relationship between the standard potential for the cell reaction and the open circuit voltage.
  - = Once standard potential is known for desired temperature, open circuit voltage can be determined at other partial pressures of reactants and products at that temperature.

- **General form of the Nernst equation for the overall cell reaction can be used to determine the open circuit voltage of any fuel cell**:
  - where: E_T= open circuit voltage
  - Eº_T= standard potential of the reaction
  - F =Faraday's number, 96487 C/equiv
  - R = universal gas constant, 8.314 J/ °K-mol
  - T = absolute temperature of cell, °K
  - PI = partial pressures or activity of the species involved
  - n = the number of electrons involved (equiv/mol)
  - x, y = stoichiometric coefficients

$$E_T = E_T^{\circ} + \left(\frac{RT}{nF}\right)\ln\frac{\prod[(P_{\text{reactants}})^x]}{\prod[(P_{\text{products}})^y]}$$

NERNST EQUATIONS



Overall Cell Reactions	Nernst Equation
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	$E_T = E_T^\circ + (\frac{RT}{2F})\ln(\frac{P_{H_2}P_{O_2}^{1/2}}{P_{H_2O}})$
$H_2 + \frac{1}{2}O_2 + CO_{2(c)} \rightarrow H_2O + CO_{2(a)}$	$E_T = E_T^\circ + (\frac{RT}{2F})\ln(\frac{P_{H_2}P_{O_2}^{1/2}P_{CO_{2(c)}}}{P_{H_2O}P_{CO_{2(a)}}})$
$^*CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$	$E_T = E_T^\circ + (\frac{RT}{8F})\ln(\frac{P_{CH_4}P_{O_2}^2}{P_{H_2O}^2P_{CO_2}})$

(a) - anode
(c) - cathode
E_T - open circuit voltage
E_T° - standard potential

P - gas pressure
R - universal gas constant
T - temperature
* - internal reformation

WATER FLOW RATE

- **Hydrogen and oxygen consumption rate in FC = f(stack current)**
- Faraday's law determines relation between required flow rates of reactants for a specified current, where: It = nzF where I, t, n, z, and F are current in A, time in seconds, number of moles, number of electrons in the reaction, and Faraday's constant, respectively, the molar flow rates of the reactants can be calculated as follows:
  - where $\dot{n}$ is the molar flow rate in mols.

$$\dot{n}_{hydrogen} = \frac{I}{2F} \qquad \dot{n}_{oxygen} = \frac{I}{4F} = \frac{\dot{n}_{hydrogen}}{2}$$

- Taking into account stoichiometric ratios, number of cells per stack, and the generalized case where the fuel and oxidant are not pure, the **equation** becomes:

$$\dot{n}_{fuel} = \frac{IS_{H_2}N_{cell}}{2Fr_{H_2}} \qquad \dot{n}_{oxidant} = \frac{IS_{O_2}N_{cell}}{4Fr_{O_2}}$$

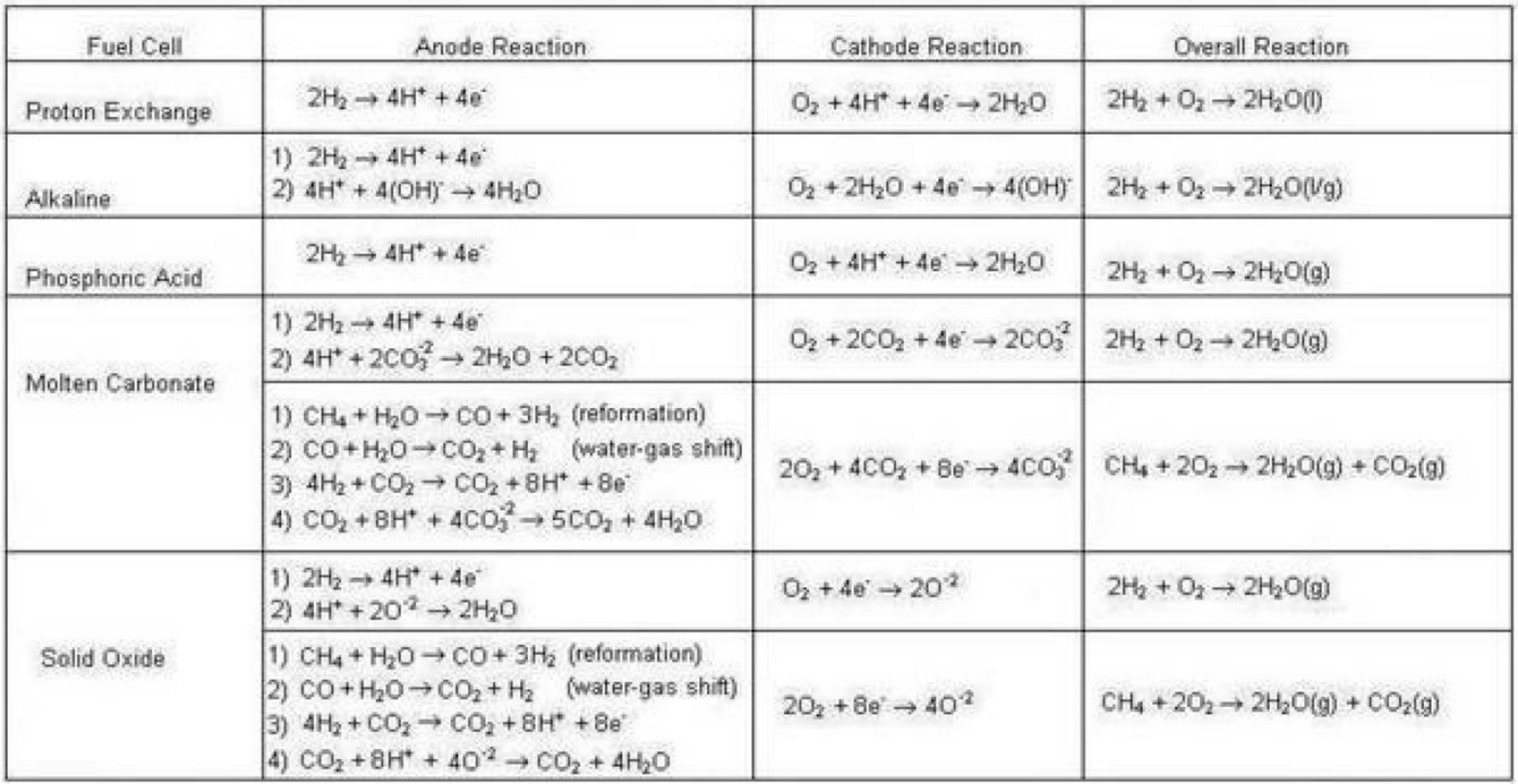
  - where Ncell is the number of unit cells, S is the stoichiometric ratio, and r is the volume/molar fraction.
- **Water molar flow rate in fuel exhaust** = water content in fuel inlet + water transported from cathode to anode as a result of back diffusion, less water transported from anode to cathode due to electroosmotic drag.

$$(\dot{n}_{H_2O})_{fuel,\ out} = (\dot{n}_{H_2O})_{fuel,\ in} + (\dot{n}_{H_2O})_{BD} - (\dot{n}_{H_2O})_{ED}$$

- Similar for **molar flow rate of water content in the oxidant exhaust**

$$(\dot{n}_{H_2O})_{oxidant,\ out} = (\dot{n}_{H_2O})_{oxidant,\ in} + (\dot{n}_{H_2O})_{gen} + (\dot{n}_{H_2O})_{ED} - (\dot{n}_{H_2O})_{BD}$$

ELECTROCHEMICAL REACTIONS IN FUEL CELLS



Fuel Cell	Anode Reaction	Cathode Reaction	Overall Reaction
Proton Exchange	$2H_2 \rightarrow 4H^+ + 4e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	$2H_2 + O_2 \rightarrow 2H_2O(l)$
Alkaline	1) $2H_2 \rightarrow 4H^+ + 4e^-$ 2) $4H^+ + 4(OH)^- \rightarrow 4H_2O$	$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$	$2H_2 + O_2 \rightarrow 2H_2O(l/g)$
Phosphoric Acid	$2H_2 \rightarrow 4H^+ + 4e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	$2H_2 + O_2 \rightarrow 2H_2O(g)$
Molten Carbonate	1) $2H_2 \rightarrow 4H^+ + 4e^-$ 2) $4H^+ + 2CO_3^{-2} \rightarrow 2H_2O + 2CO_2$	$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{-2}$	$2H_2 + O_2 \rightarrow 2H_2O(g)$
	1) $CH_4 + H_2O \rightarrow CO + 3H_2$ (reformation) 2) $CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift) 3) $4H_2 + CO_2 \rightarrow CO_2 + 8H^+ + 8e^-$ 4) $CO_2 + 8H^+ + 4CO_3^{-2} \rightarrow 5CO_2 + 4H_2O$	$2O_2 + 4CO_2 + 8e^- \rightarrow 4CO_3^{-2}$	$CH_4 + 2O_2 \rightarrow 2H_2O(g) + CO_2(g)$
Solid Oxide	1) $2H_2 \rightarrow 4H^+ + 4e^-$ 2) $4H^+ + 2O^{-2} \rightarrow 2H_2O$	$O_2 + 4e^- \rightarrow 2O^{-2}$	$2H_2 + O_2 \rightarrow 2H_2O(g)$
	1) $CH_4 + H_2O \rightarrow CO + 3H_2$ (reformation) 2) $CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift) 3) $4H_2 + CO_2 \rightarrow CO_2 + 8H^+ + 8e^-$ 4) $CO_2 + 8H^+ + 4O^{-2} \rightarrow CO_2 + 4H_2O$	$2O_2 + 8e^- \rightarrow 4O^{-2}$	$CH_4 + 2O_2 \rightarrow 2H_2O(g) + CO_2(g)$

2.1.2.2 FC Losses

TERMINAL VOLTAGE DUE TO LOSSES

- Output voltage V_T < open circuit voltage E_T when current is drawn from FC terminals by some load due to losses.
- Terminal voltage determined by subtracting losses from open circuit voltage. FC stack output voltage at terminals can be approximated by:

$$V_T = N \cdot (E_T - L)$$

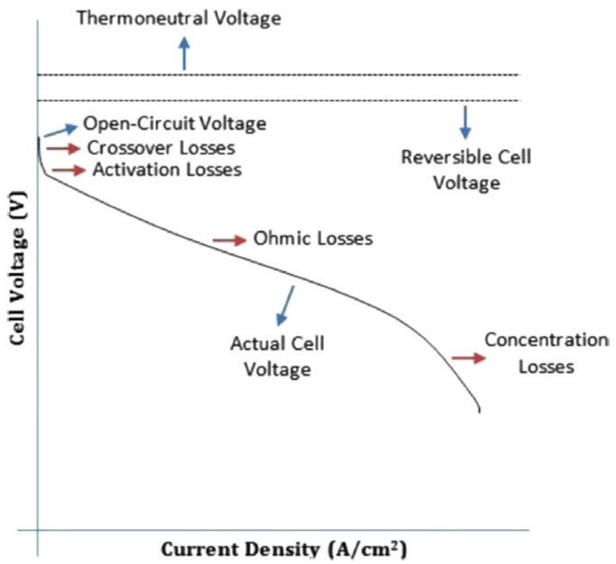
  - Where N = number of cells in stack, L = voltage losses (activation, impedance and concentration losses)
- Voltage loss can be approximated by:

$$L = (ZI + n_{act} + n_{conc}) = ZI + \frac{RT}{\alpha nF} \ln\left(\frac{I}{I_0}\right) + \frac{RT}{nF} \ln\left(\frac{I_{lim}}{I_{lim} - I}\right)$$

  - Where I = load current, I_0= exchange current related to activation losses, I_{lim} = limiting current related to concentration losses, Z = fuel cell impedance

POLARIZATION CURVE

- Several **irreversibilities exist within a fuel cell** that cause the actual cell voltage to be less than the reversible cell voltage determined by the Gibbs free energy equation.
  - Known as cell polarizations
- **Polarization curve** and equation represent a zero-dimensional steady-state model for a hydrogen fuel cell under the assumption that only a single gaseous phase is present.
  - One of the simplest and most common tools for evaluation of FC performance.
  - More detailed multi-dimensional and multi-phase models exist for better numerical modelling.

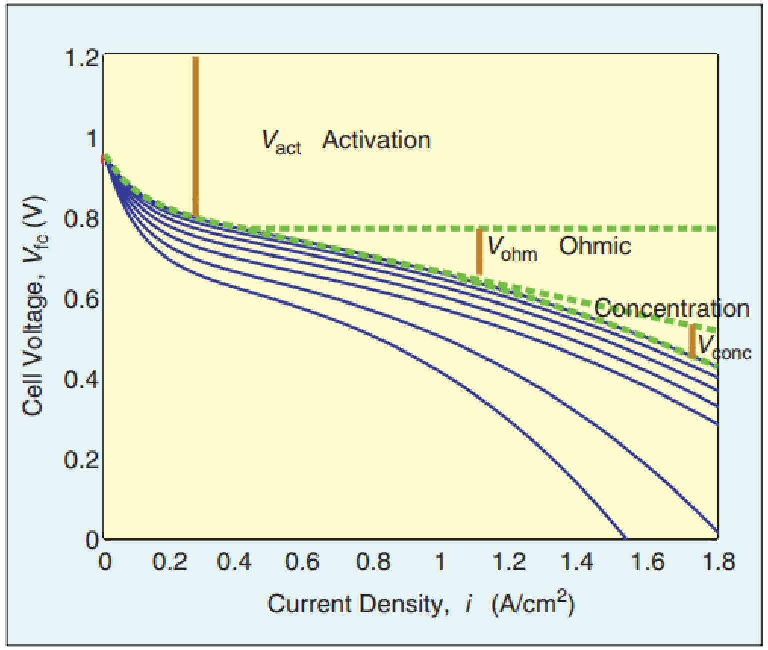


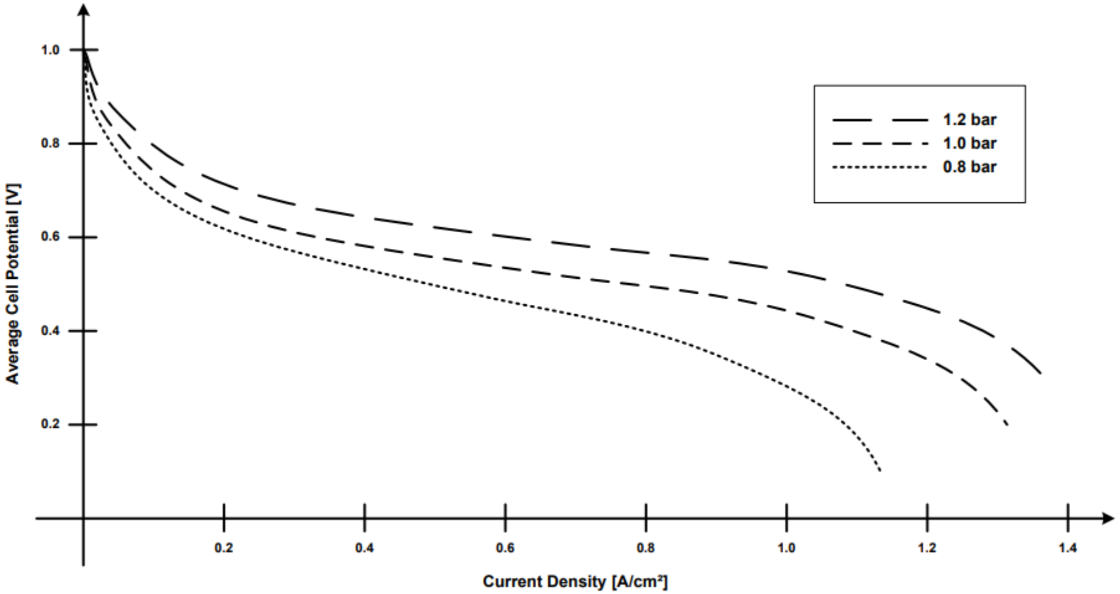
Typical polarization curve with voltage losses - O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

LOSSES IN FUEL CELL

- FC polarization curves for different oxygen partial pressures.
- Cell voltage drops with current density.
- Steady-state voltages depend on the **activation**, **ohmic**, and **concentration losses**.
  - Losses increase when the partial pressure of oxygen in the cathode decreases.

- **Losses:**
  - **Activation losses** = energy used to perform the electrochemical reactions.
    - Major loss at low current density.
  - **Ohmic (Impedance) losses** = result of protons flow through electrolyte and also electronic resistance of bipolar plates and various interconnections.
    - Mainly affect the nominal operating region.
    - Linear function of current
  - **Concentration losses** = bulk phase diffusion resistance which reduces the electrode partial pressures compared to the gas inlet ones.
    - Largely influence the high current density zone.





POLARIZATION CURVES

- Polarization curves for a particular PEM stack depend on (due to thermodynamic and kinetic effects):
  - Stack temperature
  - Reactant pressure
  - Air/fuel ratio
- For correct operation, a PEMFC needs some auxiliary components (including air compressor for oxidant supply and thermal and water management systems for stack temperature control and membrane humidification)
  - Critical to ensure proper FC humidification for electrolyte membrane operation without flooding cathode side with excess of water.
    - Water management is a delicate balance between these two conditions

ACTIVATION POLARIZATION

- Main cause of voltage drop at low current densities
- Caused by sluggish oxidation and/or reduction kinetics at the electrodes surface.
- **Initiating electrochemical reactions requires energy** that is reflected in the activation voltage drop.

- **Higher values of exchange current density = lower activation losses**
- **Can be achieved through**:
  - Selecting an active electrode catalyst
  - Increasing operation temperature or pressure
  - Increasing roughness of electrodes surface area to increase the active reaction sites
  - Increasing catalyst loading
  - Increasing reactants concentration to increase the active spots on the electrodes surface area.
- Other factors that increase the activation losses due to catalyst degradation include:
  - Presence of catalyst contaminants in reactants
  - Prolonged loading cycles

- Note: Even though we saw that at higher temperatures the reversible cell voltage is lower; this is not the case for the actual cell voltage.
  - The fact that activation losses decrease as temperature increases (as a result of the increased exchange current density) causes the actual cell voltage to actually increase with increased temperature.

CROSSOVER & IONIC POLARIZATIONS

- Crossover polarization: main cause of voltage loss at open-circuit conditions and is due to two reasons:
    - Direct hydrogen fuel diffusion from anode to cathode through electrolyte without anodic reaction taking place (even though the membrane is practically impermeable to the hydrogen fuel)
    - Internal passing of electrons through electrolyte rather than through external circuit (even though the membrane is practically impermeable to electrons)
- Crossover polarization is usually noticeable when the operation temperature is low and we are at or near the open- circuit conditions.

- Ionic and electric resistance of the stack's components to the flow of charge results in ohmic polarization.
    - Electrolyte, catalyst layer, flow field plates, current collectors, interfacial contacts between the components, and the terminal connections all contribute to these ohmic voltage losses.
    - **Electric resistivity** is due to resistivity of the electrically-conductive cell components to the electrons flow
    - **Ionic resistivity** is due to the resistivity of the membrane to the ions flow.
    - Usually, ionic resistivity >> ohmic voltage losses.
- Ohmic losses are dominant at the middle of the polarization curve and affect all types of fuel cells.
- To minimize ohmic losses, it is important to design the stack from materials with high conductivities, components with minimum thicknesses, and interconnects with minimum contact resistances through the optimization of the stack's compression pressure.

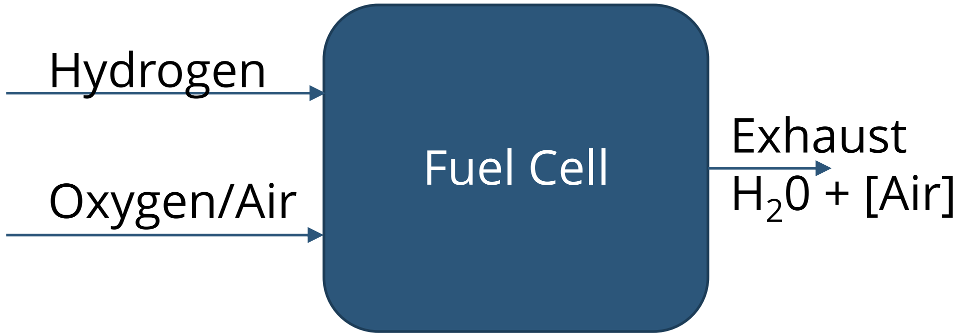
CONCENTRATION POLARIZATION

- Dominant at high current densities
- **Occurs when the electrode reactions are hindered by reduced reactants availability (i.e., concentration) at reaction sites**, resulting in partial pressure reduction
- **Can be due to**:
  - Limited hydrogen fuel supply
  - Limited diffusion rate of the fuel and oxidant from flow field channels to the catalyst layer
  - Poor air circulation at cathode which leads to nitrogen (or any other non-participating inert gases) build-up
  - Water accumulation and flooding at cathode and anode (especially for PEMFCs)
  - Impurities adsorption on electrode reaction areas.
- Cathode's concentration polarization usually dominates due to water accumulation, nitrogen build-up, and much lower diffusion rate of oxygen vs. hydrogen.
- **Concentration voltage losses can be minimized through:**
  - Proper water management
  - Removal of impurities
  - Optimization of stoichiometric ratio
  - Optimization of thickness and porosity of the GDL.

2.1.3 Thermofluid Considerations

THERMAL AND FLUID CONSIDERATIONS

- Material Flow Concerns:
- Hydrogen pressurized to rated operating parameter
  - Protons are internal charge carriers and travel through membrane
- Oxygen or air needs to be pressurized to required level to generate appropriate cell voltage and needs to be supplied at correct mass flow
  - If pure oxygen, need to carefully meter to not waste oxygen
  - Oxidant stream pressure largely determined by exhaust pressure, minus cell pressure loss (only flow friction loss)
  - How to control exhaust pressure



- Thermal Concerns:
- Fuel cell operates best at specific temperature
  - For PEM, it is less than 180°C
- Fuel and oxidant release chemical energy, per mass consumed.
  - 40%-70% goes to electrical while the rest manifests as various losses which ultimately result in heat.
- Can the exhaust stream absorb all losses and maintain required cell temperature? This is optimum if maximum energy recovery is desirable in an expansion turbine.
  - All extra heat energy must be rejected via dedicated cooling system.

STOICHIOMETRY

- Consider PEM with Hydrogen Fuel:

$2\ H_2 + O_2 \rightarrow 2\ H_20$ = Stoichiometric reaction
H_2: 2 g/mol
O_2: 32 g/mol
H_2O: 18 g/mol

(2 mol)*(2 g/mol) + (1 mol)*(32 g/mol) → (2 mol)*(18 g/mol)
$4\ kg\ H_2 + 32\ kg\ O_2 \rightarrow 36\ kg\ H_20$

- For space applications, 8 times more mass of O_2 is consumed vs. H_2. How about air-breathing applications?

- Air ~21% (molar) O_2 and ~79% (molar) N_2. Thus:

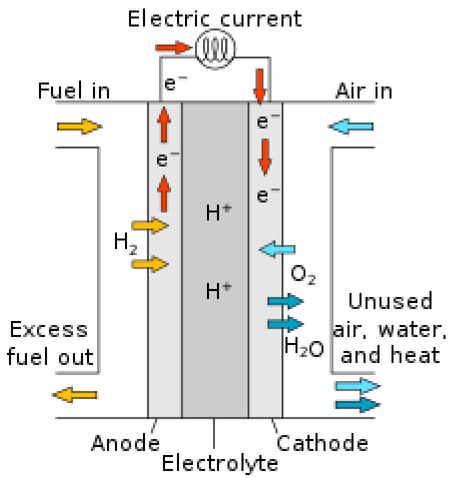
0.21*(32 g/mol) + 0.79*(28 g/mol) = 28.84 g Air
6.72 kg O_2 + 22.12 kg N_2 = 28.84 g Air
Or
1 kg O_2 + 3.29 kg N_2 = 4.29 kg Air

- Therefore, for air as oxidizer, stoichiometry is:

$4\ kg\ H_2 + 32\ kg\ O_2 + 105.3\ kg\ N_2 \rightarrow 36\ kg\ H_20 + 105.3\ kg\ N_2$
$\mathbf{4\ kg\ H_2 + 137.3\ kg\ Air \rightarrow 36\ kg\ H_20 + 105.3\ kg\ N_2}$

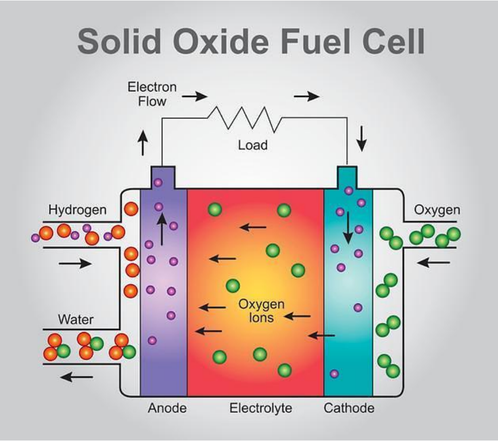
ENSURING PROPER THERMAL AND FLOW CONDITIONS

PEM



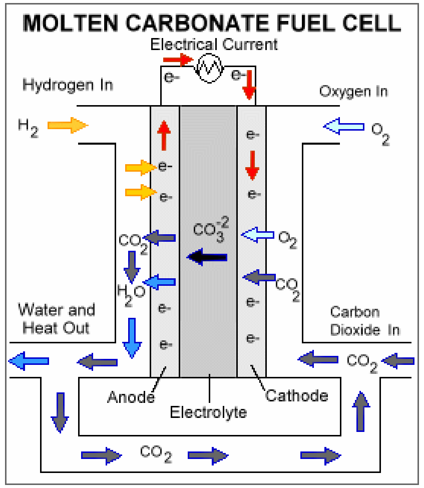
- Internal charge carriers (electrolyte) positive H^+
- Fuel may be completely consumed at anode
- Primary exhaust is at cathode/oxidant side
- Backpressure on exhaust determines partial pressure of oxygen at the cathode

SOFC



- Internal charge carriers (electrolyte) negative
- Oxygen can be completely consumed at cathode
- If air is used, balance of air needs to have vent
- Primary exhaust is at the anode/fuel side
- Backpressure on exhaust determines partial pressure of fuel (hydrogen)

MCFC

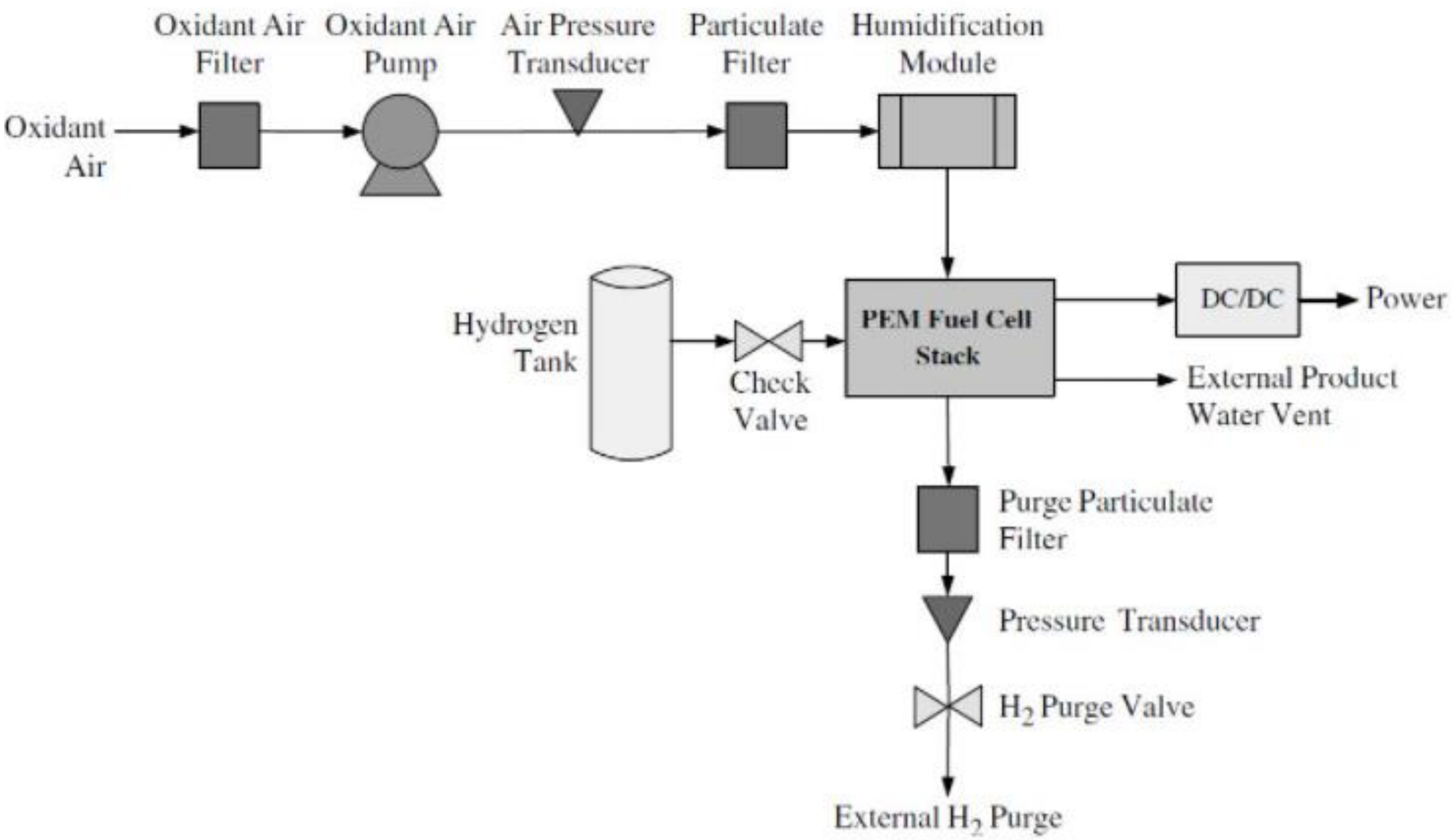


- Internal charge carriers (electrolyte) negative
- Oxygen can be completely consumed at cathode
- If air is used, balance of air needs to have vent
- Primary exhaust is at the anode/fuel side side
- Backpressure on exhaust determines partial pressure of fuel
- Exhaust needs partial recirculation to support electrolyte replenishment

- Fuel cell chemistry details are important to determine required auxiliaries to keep fuel cell happy and producing at optimum efficiency
- Supporting system is just as important as the fuel cell proper in ensuring power system production

2.1.4 Model Development

FUEL CELL SIMPLE SCHEME



Simple PEM Fuel Cell System (fuelcellstore.com)

SOME ASPECTS ASSOCIATED WITH FC MODELLING

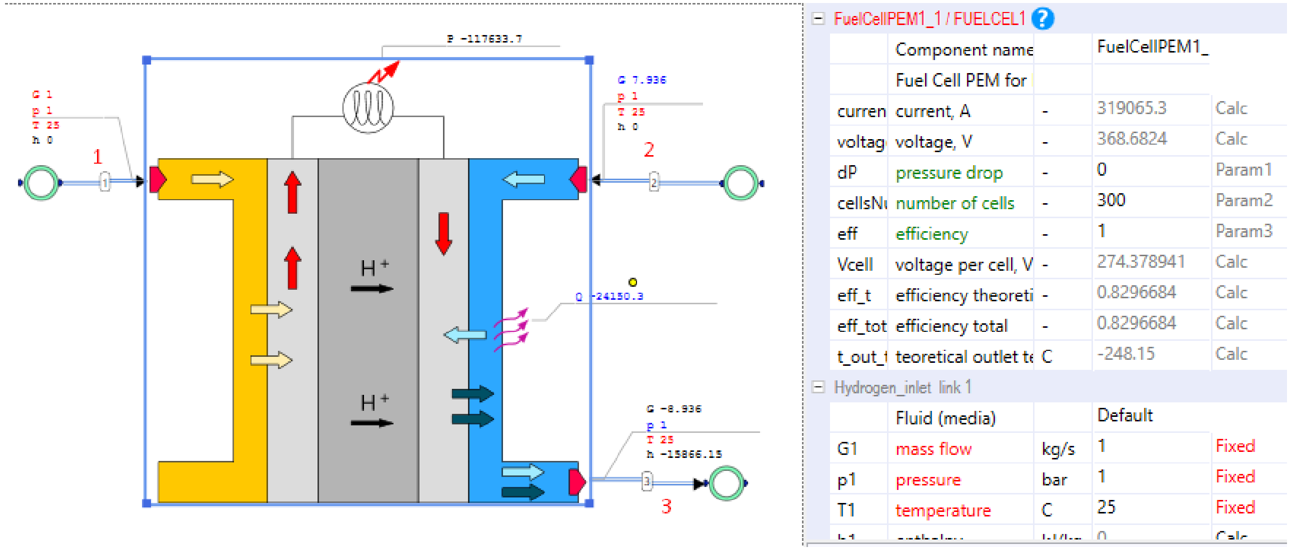
- FC Applications
- FC and the Hydrogen Economy
- Basic FC Chemistry and Thermodynamics
- FC Electrochemistry
- FC Charge Transport
- FC Mass Transport
- FC Heat Transport
- FC Modeling
- FC Materials
- FC Stack Components and Materials
- FC Stack Design
- FC System Design
- Fuel Types, Delivery, and Processing
- FC Operating Conditions
- FC Characterization

TYPICAL FUEL CELL PARAMETERS USED FOR MODELLING

- Parameters for FC stack:
    - Loss of pressure in oxygen-water channel
    - Number of cells connected in series by electric current
    - Efficiency - characterizes electrochemical losses in cell body. (Usually ~40-50 %)
- Results of calculation:
    - Cell power or fuel flow rate
    - Amount of heat that must be removed from the cell to maintain the set outlet temperature (or vice versa)
    - Amount of oxygen for complete oxidation of hydrogen
    - Cell voltage and current
    - Theoretical cell efficiency (efficiency depending only on thermodynamic parameters)
    - Overall cell efficiency, including both theoretical and electrochemical efficiency
    - Theoretical outlet temperature

PURE OXYGEN VS. AIR

- O_2 reaction creates water + electricity only
- With air it creates some residual air + formed water
    - Requires additional chemical terms to be accounted for
- The state of the water leaving the cell is determined depending on the parameters.

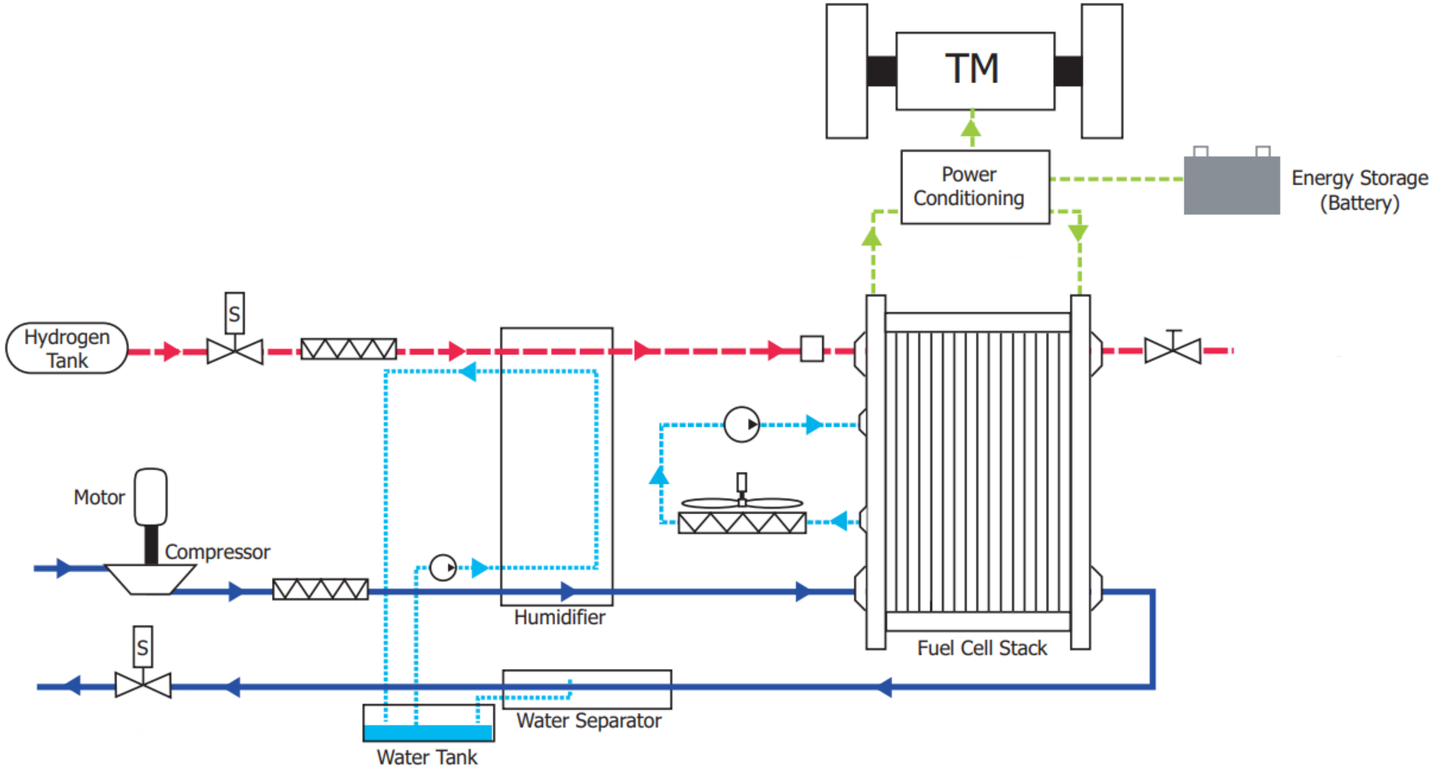


FuelCellPEM1_1 / FUELCEL1				
	Component name		FuelCellPEM1_	
	Fuel Cell PEM for			
curren	current, A	-	319065.3	Calc
voltag	voltage, V	-	368.6824	Calc
dP	pressure drop	-	0	Param1
cellsNı	number of cells	-	300	Param2
eff	efficiency	-	1	Param3
Vcell	voltage per cell, V	-	274.378941	Calc
eff_t	efficiency theoreti	-	0.8296684	Calc
eff_tot	efficiency total	-	0.8296684	Calc
t_out_t	teoretical outlet te	C	-248.15	Calc
Hydrogen_inlet link 1				
	Fluid (media)		Default	
G1	mass flow	kg/s	1	Fixed
p1	pressure	bar	1	Fixed
T1	temperature	C	25	Fixed

2.1.5 System Modelling (External Components)

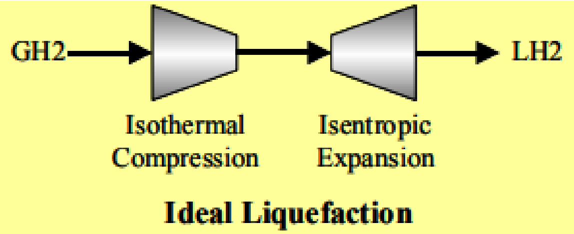
FUEL CELL STACK FLOW SYSTEMS

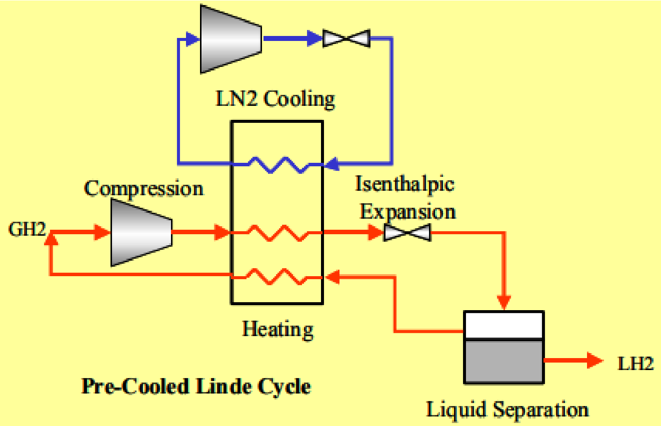
- **Fuel cell stack requires four flow systems:**
  - Hydrogen supply system to the anode;
  - Air supply system to the cathode;
  - De-ionized water supply system to the stack cooling channel;
  - De-ionized water supply system to the humidifier;



Overall scheme of automotive fuel cell system

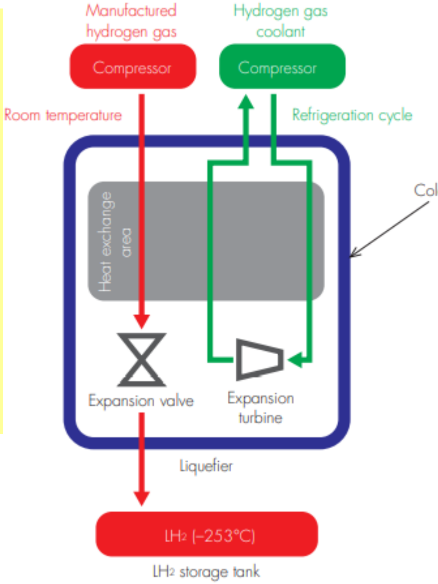
HYDROGEN LIQUEFACTION SYSTEMS



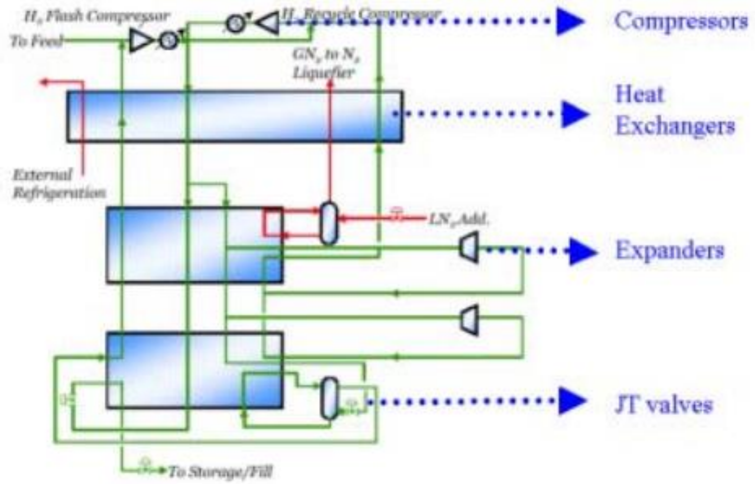


The ideal liquefaction process: gaseous hydrogen (GH2) is initially compressed and then expanded in a J-T valve resulting in the drop in its temperature, below its boiling point, forming liquid (LH2)

Hydrogen storage: state-of-the-art and future perspective e. Tzimas, c. Filiou, s.D. PETEVES and J.-B. VEYRET petten, the netherlands. -Isbn 92-894-6950-1.- European communities, 2003



Composition of hydrogen liquefaction system

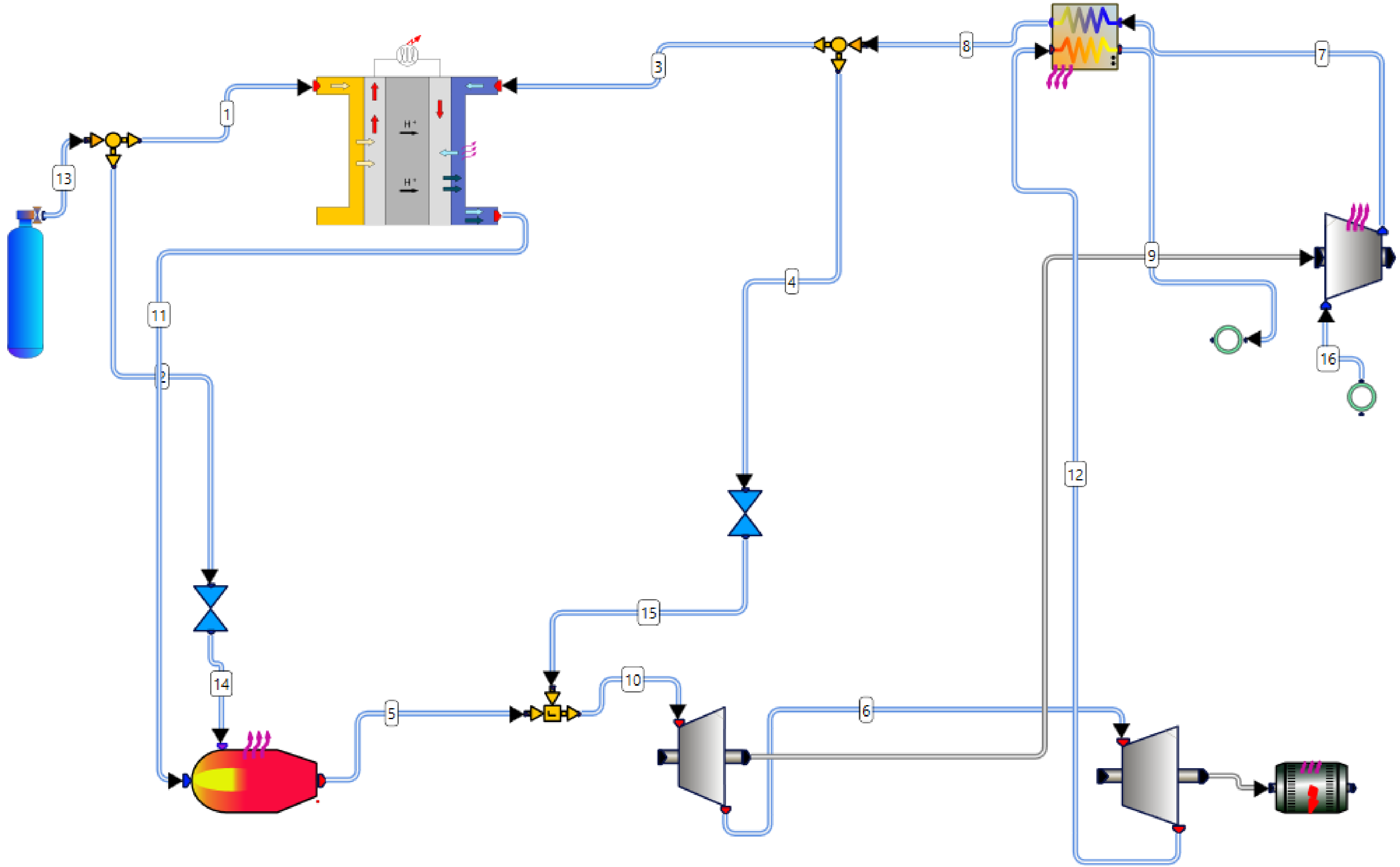


A schematic of the Claude cycle

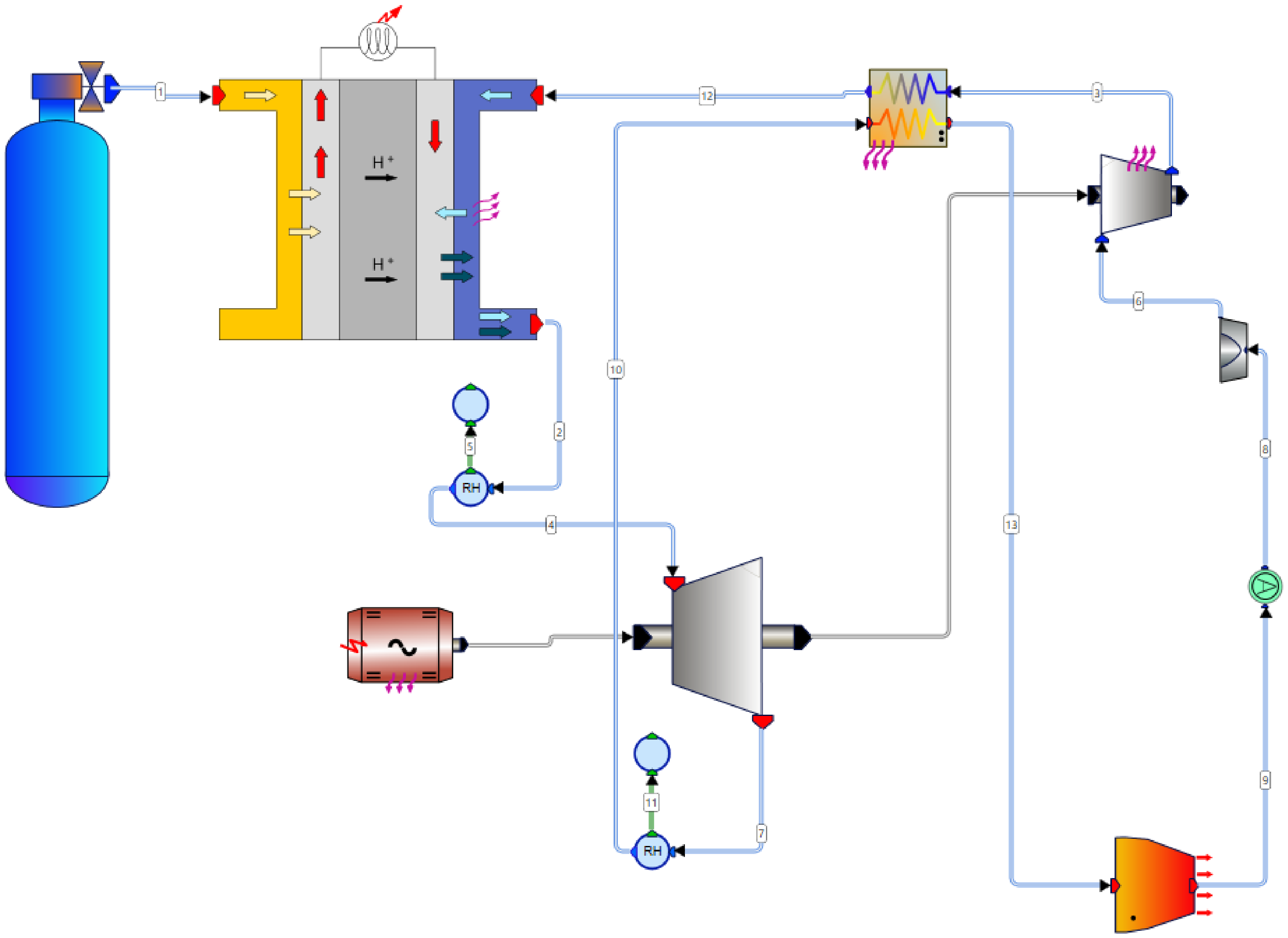
Technologies of hydrogen liquefaction, transport and storage — Paving the way to a hydrogen fueled future.- Shoji Kamiya,Kozo Isano,Daisuke Kariya,Toshihiro Komiya, Akira Yamaguchi,Yukichi Takaoka. -Technical Description.- p. 51-58

- The simplest liquefaction process is the pre-cooled Linde cycle, or Joule-Thomson cycle. Initially, the gas is compressed at ambient pressure and subsequently cooled to 80 K in a counter-flow heat exchanger using liquid nitrogen. Heat exchangers are used to lower the temperature even further, below its inversion temperature by transferring heat from the hydrogen stream to the returning cooled hydrogen. Ultimately, the cooled and compressed gas is forced to pass through a throttle valve or a mechanical expander where it undergoes an isenthalpic expansion to ambient pressure, producing some liquid. The liquid is removed and the cooled gas is returned to the compressor via the heat exchangers

EXAMPLES OF CYCLES USING PEM FUEL CELLS

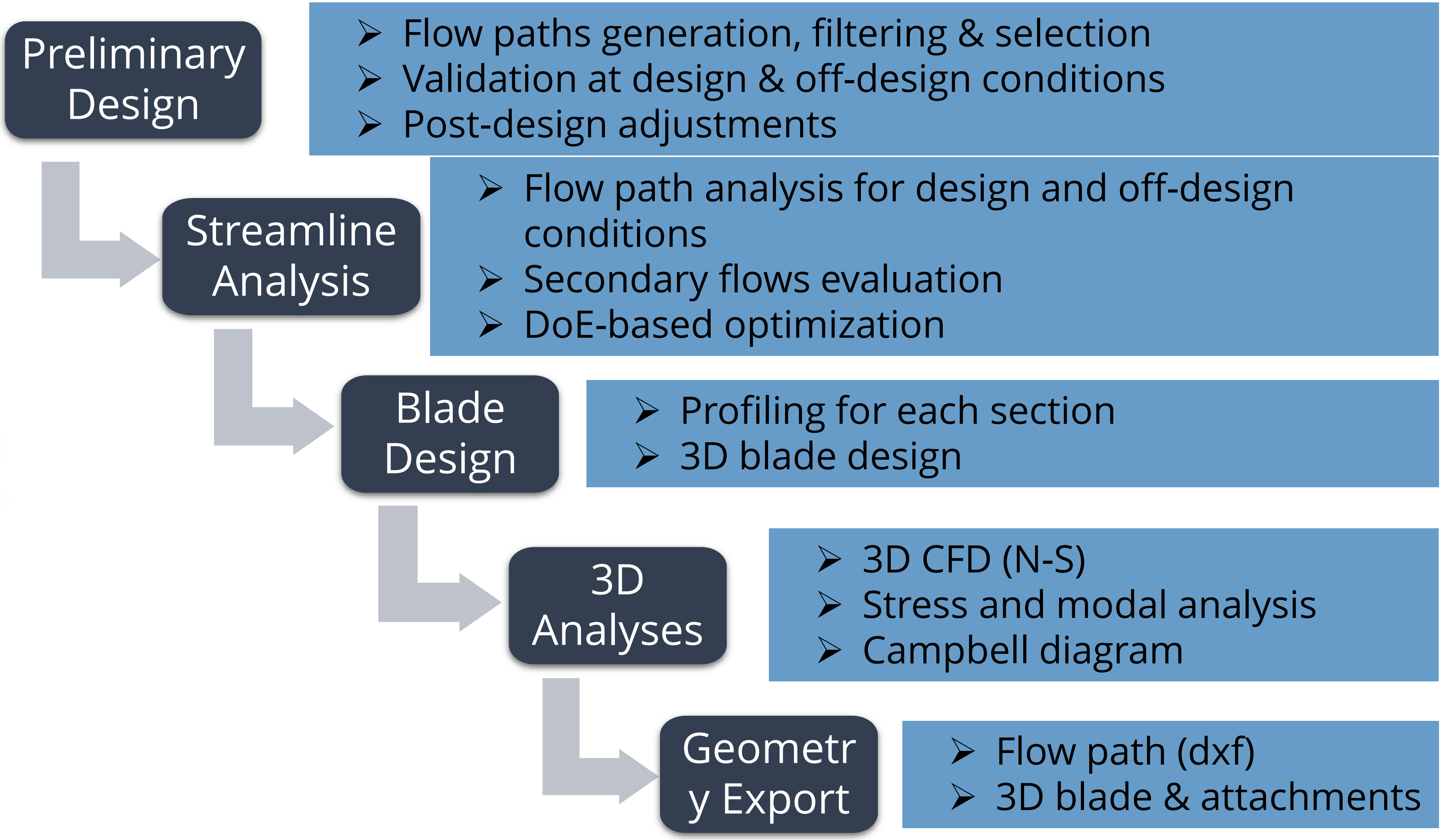


EXAMPLES OF CYCLES USING PEM FUEL CELLS



2.2 Turbomachinery

FLOW PATH DESIGN PROCESS



Preliminary Design

- Flow paths generation, filtering & selection
- Validation at design & off-design conditions
- Post-design adjustments

Streamline Analysis

- Flow path analysis for design and off-design conditions
- Secondary flows evaluation
- DoE-based optimization

Blade Design

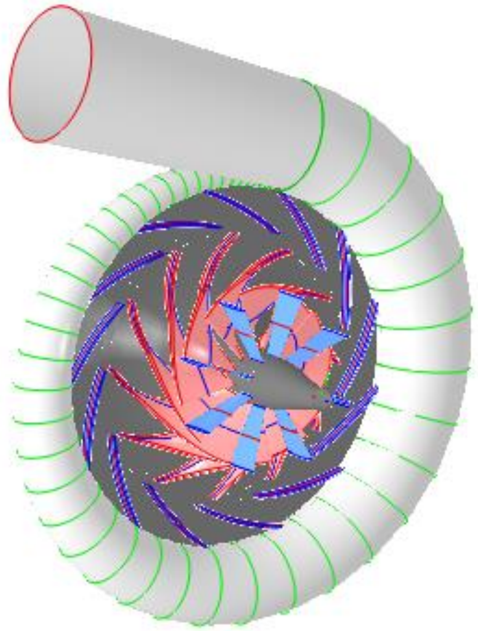
- Profiling for each section
- 3D blade design

3D Analyses

- 3D CFD (N-S)
- Stress and modal analysis
- Campbell diagram

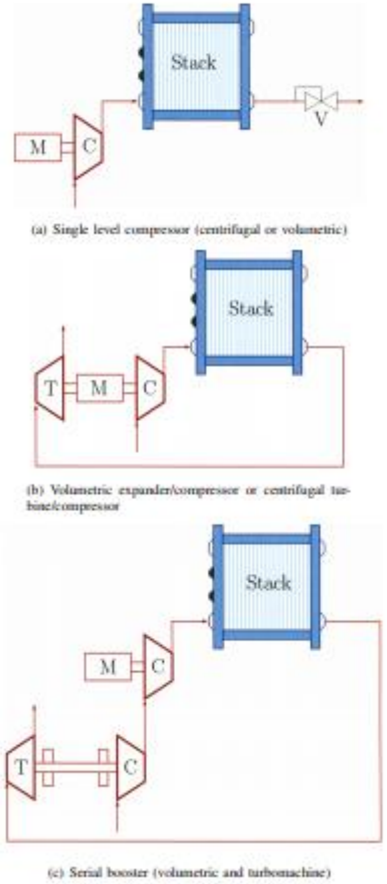
Geometry Export

- Flow path (dxf)
- 3D blade & attachments



TURBOMACHINES IN FUEL CELLS (COMPRESSOR OPTIONS)

Air compressors



(a) Single level compressor (centrifugal or volumetric)

(b) Volumetric expander/compressor or centrifugal turbine/compressor

(c) Serial booster (volumetric and turbomachine)

Three compression system topologies.
M=Motor, T=Turbine or Expander, C=Compressor

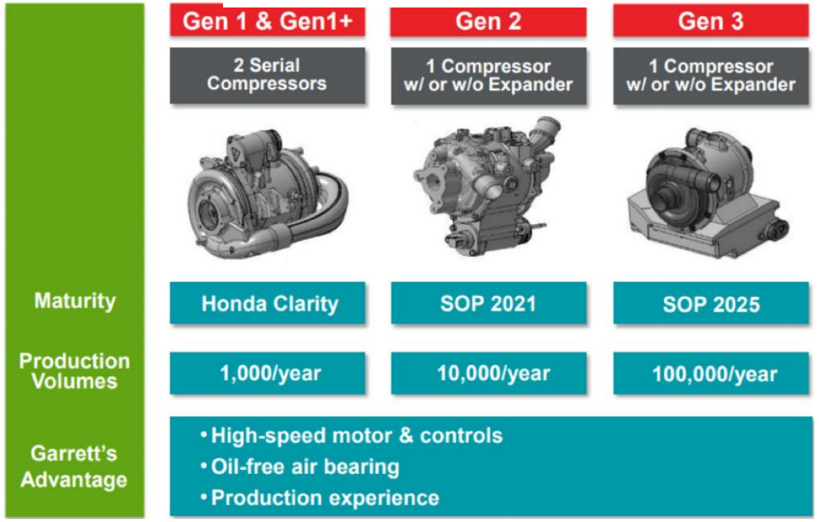
Air Management in PEM Fuel Cells: State-of-the-Art and Prospectives,- Benjamin BLUNIER Student Member, IEEE,
Abdellatif MIRAOUI Universite de Technologie de Belfort-Montbéliard (UTBM), Belfort CEDEX 90010, France

FUEL CELL COMPRESSORS

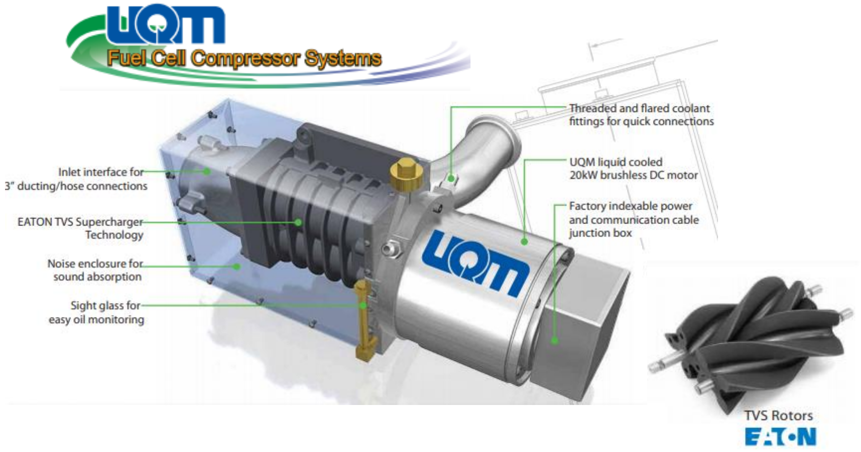
aeristech

ROTREX™

Garrett
ADVANCING MOTION



	Gen 1 & Gen1+	Gen 2	Gen 3
	2 Serial Compressors	1 Compressor w/ or w/o Expander	1 Compressor w/ or w/o Expander
Maturity	Honda Clarity	SOP 2021	SOP 2025
Production Volumes	1,000/year	10,000/year	100,000/year
Garrett's Advantage	• High-speed motor & controls • Oil-free air bearing • Production experience		



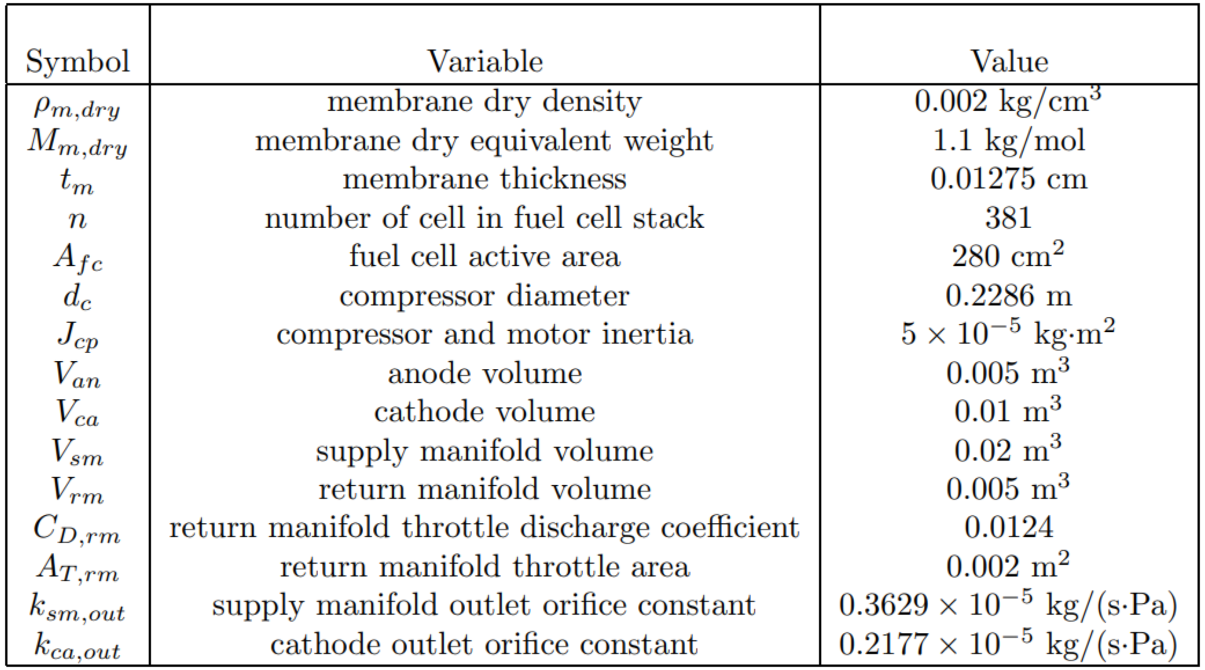
Celeroton

BOSCH
Invented for life

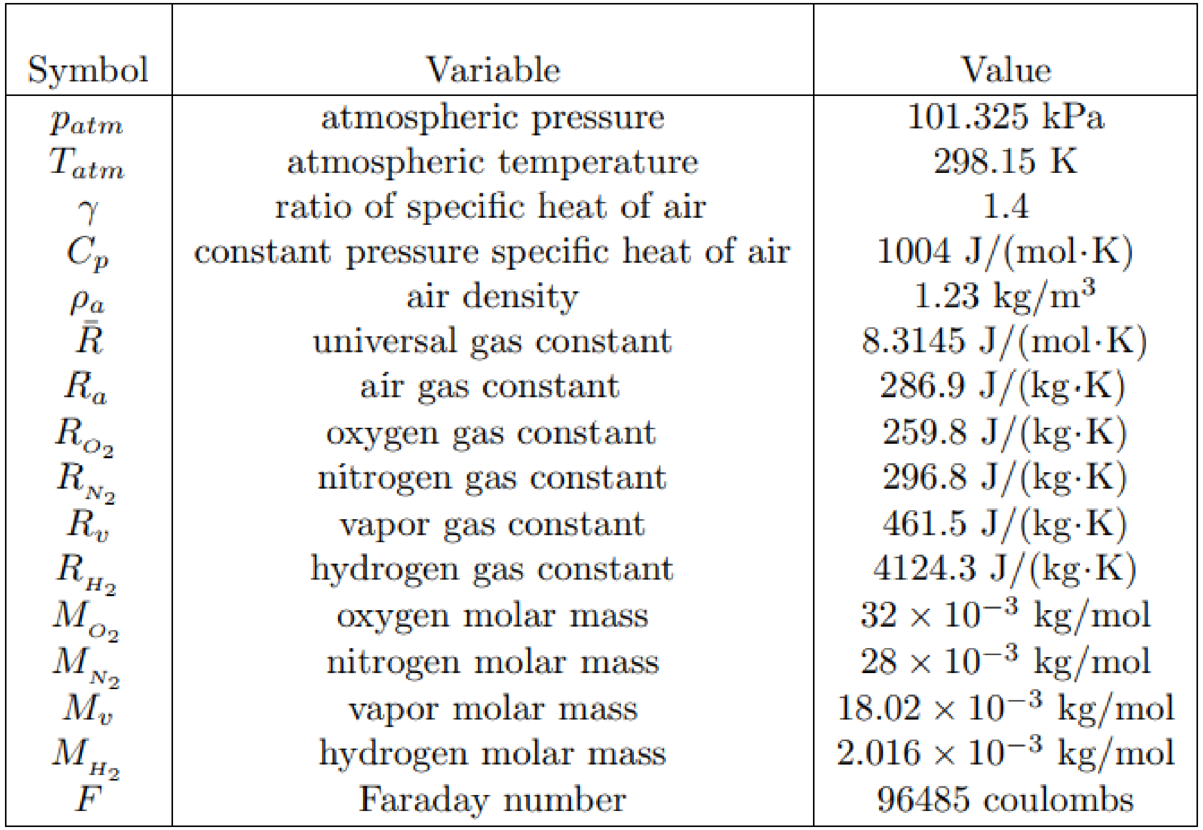
2.2.1 Compressors for Fuel Cells

FUEL CELL PROTOTYPE

- The fuel cell stack is based on the 75 kW stacks used in the FORD P2000 fuel cell prototype vehicle.



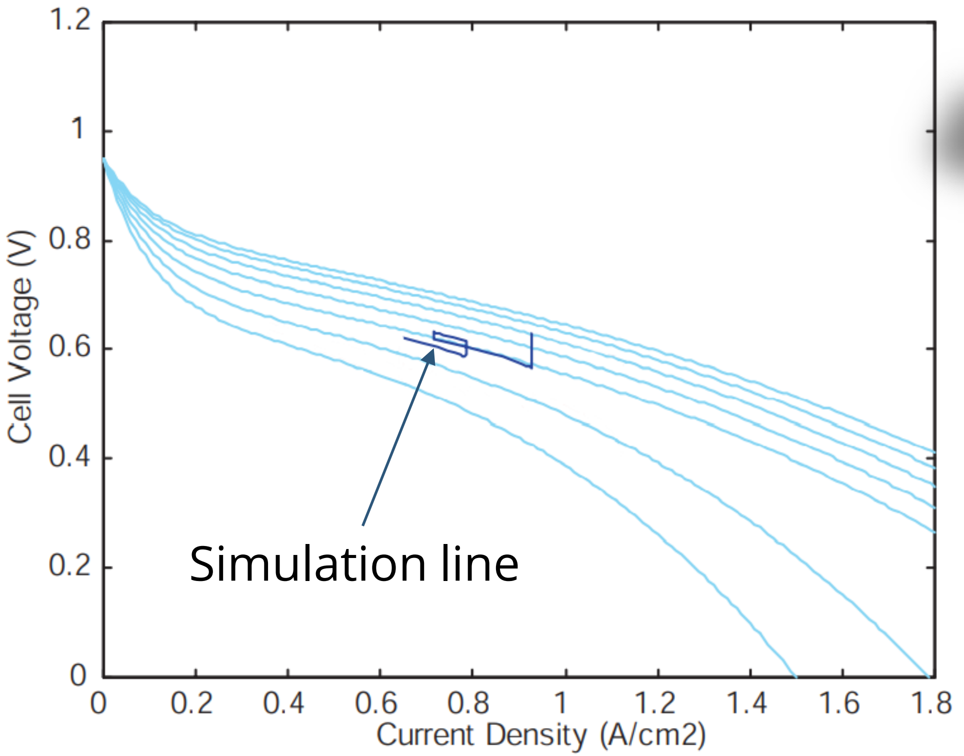
Symbol	Variable	Value
$\rho_{m,dry}$	membrane dry density	$0.002\ \mathrm{kg/cm^3}$
$M_{m,dry}$	membrane dry equivalent weight	$1.1\ \mathrm{kg/mol}$
t_m	membrane thickness	$0.01275\ \mathrm{cm}$
n	number of cell in fuel cell stack	381
A_{fc}	fuel cell active area	$280\ \mathrm{cm^2}$
d_c	compressor diameter	$0.2286\ \mathrm{m}$
J_{cp}	compressor and motor inertia	$5 \times 10^{-5}\ \mathrm{kg{\cdot}m^2}$
V_{an}	anode volume	$0.005\ \mathrm{m^3}$
V_{ca}	cathode volume	$0.01\ \mathrm{m^3}$
V_{sm}	supply manifold volume	$0.02\ \mathrm{m^3}$
V_{rm}	return manifold volume	$0.005\ \mathrm{m^3}$
$C_{D,rm}$	return manifold throttle discharge coefficient	0.0124
$A_{T,rm}$	return manifold throttle area	$0.002\ \mathrm{m^2}$
$k_{sm,out}$	supply manifold outlet orifice constant	$0.3629 \times 10^{-5}\ \mathrm{kg/(s{\cdot}Pa)}$
$k_{ca,out}$	cathode outlet orifice constant	$0.2177 \times 10^{-5}\ \mathrm{kg/(s{\cdot}Pa)}$



Symbol	Variable	Value
p_{atm}	atmospheric pressure	$101.325\ \mathrm{kPa}$
T_{atm}	atmospheric temperature	$298.15\ \mathrm{K}$
γ	ratio of specific heat of air	1.4
C_p	constant pressure specific heat of air	$1004\ \mathrm{J/(mol{\cdot}K)}$
ρ_a	air density	$1.23\ \mathrm{kg/m^3}$
$\bar{R}$	universal gas constant	$8.3145\ \mathrm{J/(mol{\cdot}K)}$
R_a	air gas constant	$286.9\ \mathrm{J/(kg{\cdot}K)}$
R_{O_2}	oxygen gas constant	$259.8\ \mathrm{J/(kg{\cdot}K)}$
R_{N_2}	nitrogen gas constant	$296.8\ \mathrm{J/(kg{\cdot}K)}$
R_v	vapor gas constant	$461.5\ \mathrm{J/(kg{\cdot}K)}$
R_{H_2}	hydrogen gas constant	$4124.3\ \mathrm{J/(kg{\cdot}K)}$
M_{O_2}	oxygen molar mass	$32 \times 10^{-3}\ \mathrm{kg/mol}$
M_{N_2}	nitrogen molar mass	$28 \times 10^{-3}\ \mathrm{kg/mol}$
M_v	vapor molar mass	$18.02 \times 10^{-3}\ \mathrm{kg/mol}$
M_{H_2}	hydrogen molar mass	$2.016 \times 10^{-3}\ \mathrm{kg/mol}$
F	Faraday number	96485 coulombs

Thermodynamic parameters used in simulation of fuel cell system

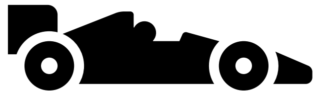
VEHICLE MOVEMENT



Current-voltage trajectories

Section 1-2: Increase power!

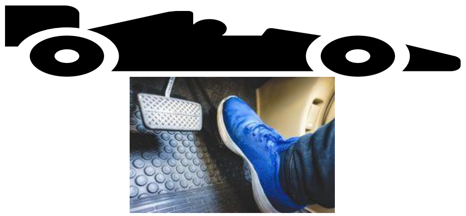
Section 2-3: Acceleration at constant power



Section 3-4: Decrease power

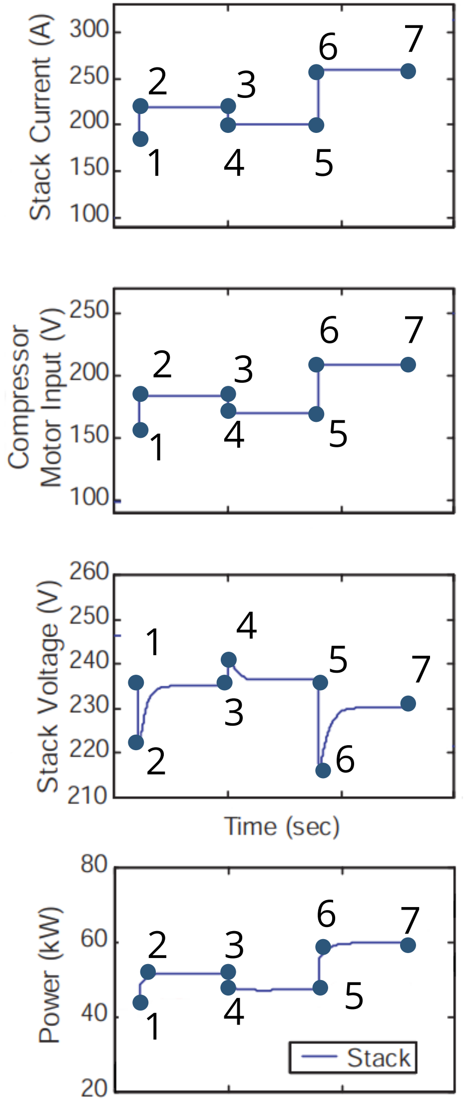
Section 4-5: Deceleration / cruise at constant power

Section 5-6: Increase power!



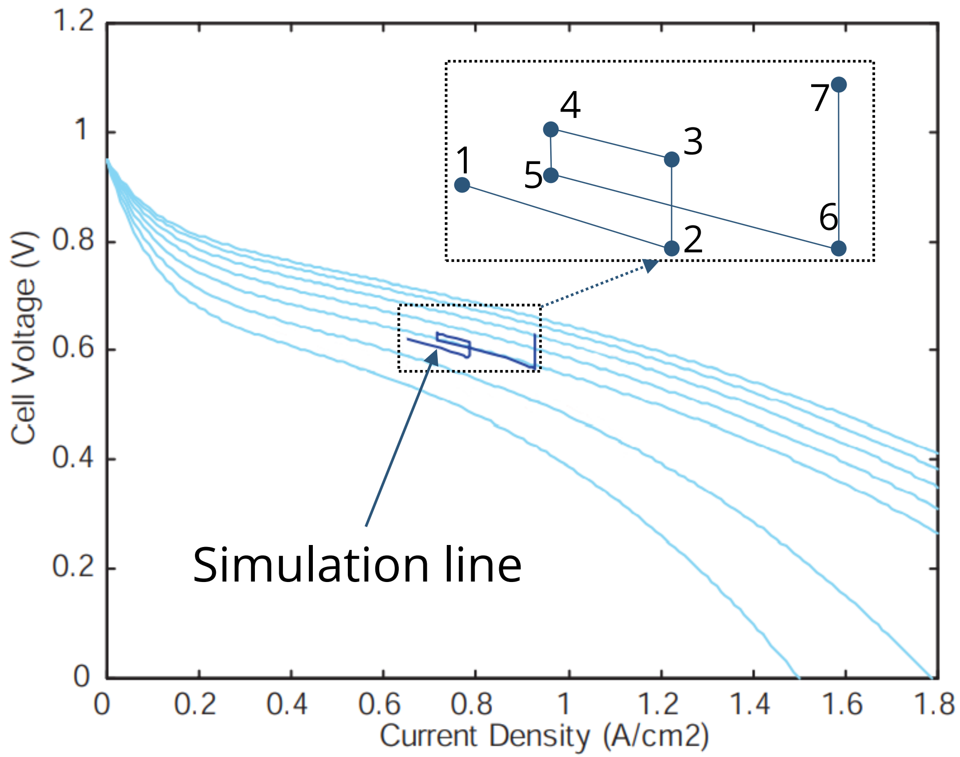
Section 6-7: acceleration at constant power

DESCRIPTION OF FUEL CELL SIMULATION AND PERFORMANCE MAP

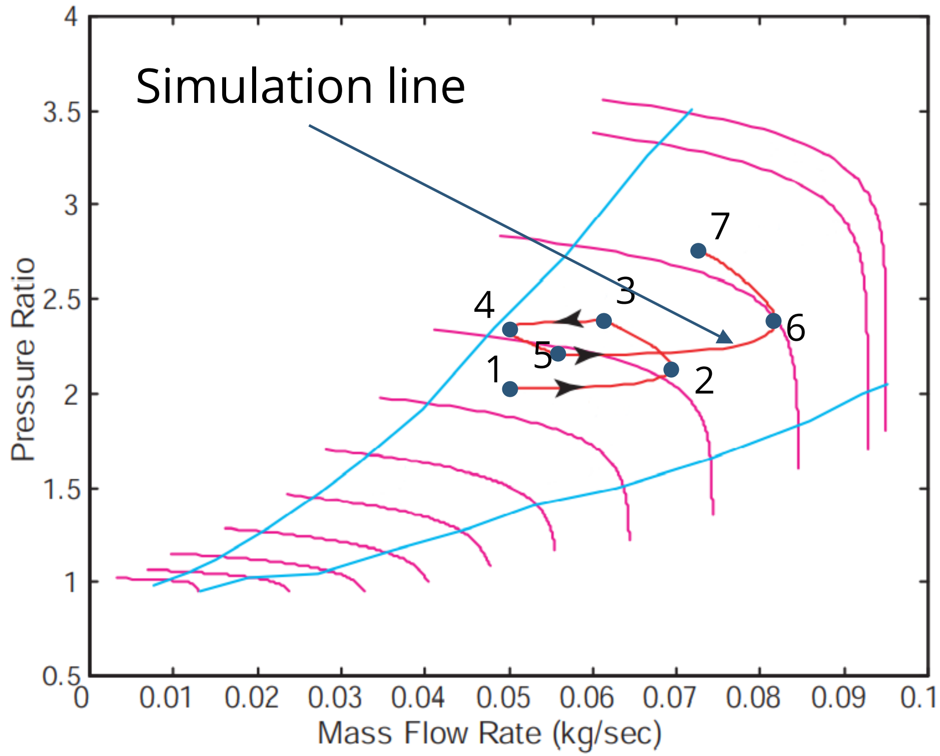


Let's consider in more detail the section 1-2-3 of the simulation line:
1-2: Stack Current - ↑, Stack Voltage - ↓, Mass Flow Rate - ↑, Total Pressure Ratio - const, Power (Stack/Compressor) - ↑;
2-3: Stack Current - const, Stack Voltage - ↑, Mass Flow Rate - ↓, Total Pressure Ratio - ↑, Power (Stack/Compressor) - const;

Based on the foregoing, since in section 2-3 the power of the fuel cell is constant and the power consumed by the compressor also remains constant. In this section, the equality of compressor powers at points 2 and 3 must be observed. And this will be one of the conditions for compressor design.

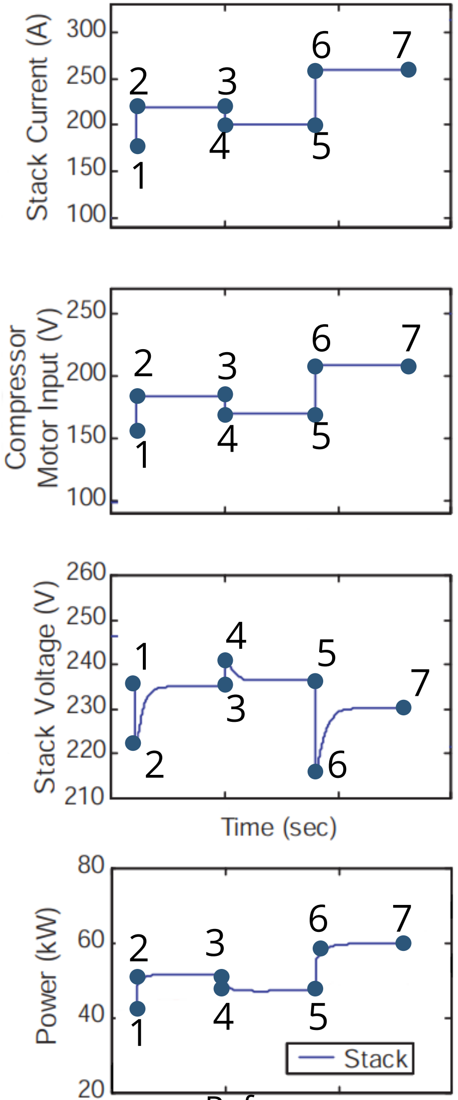


Current-voltage trajectories

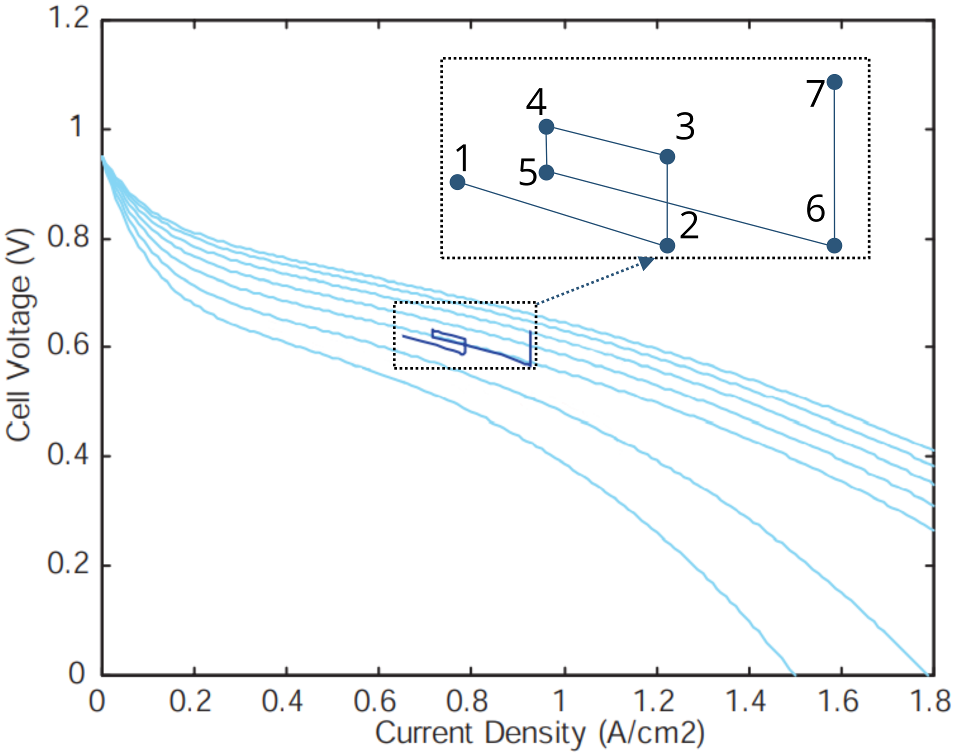


Compressor flow / Pressure trajectories

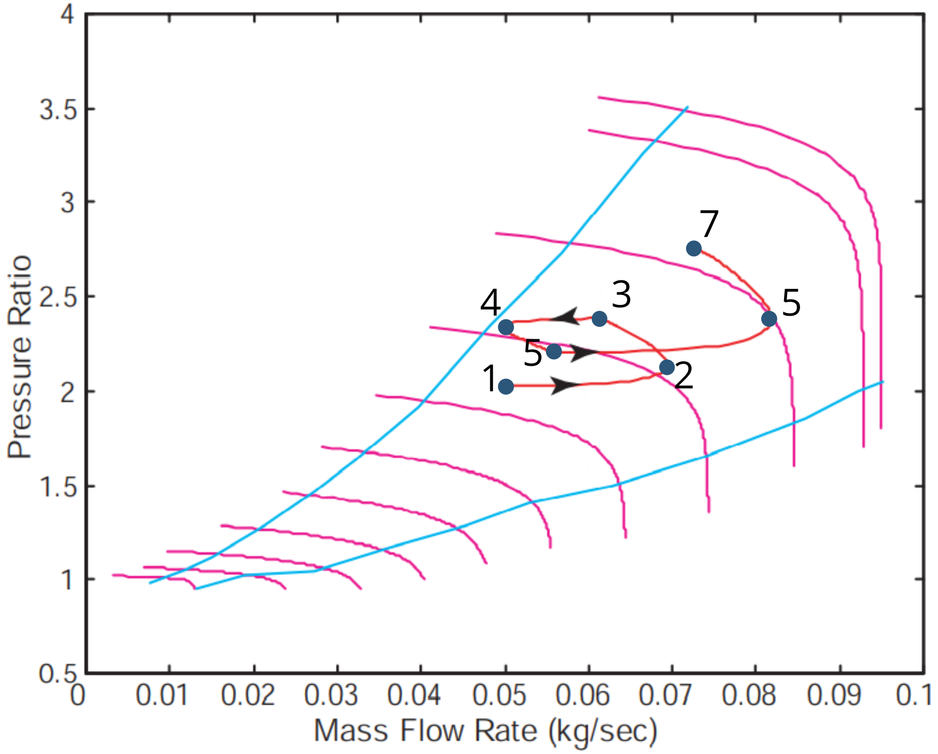
EQUAL POWER CONDITION



Reference [1]



Current-voltage trajectories



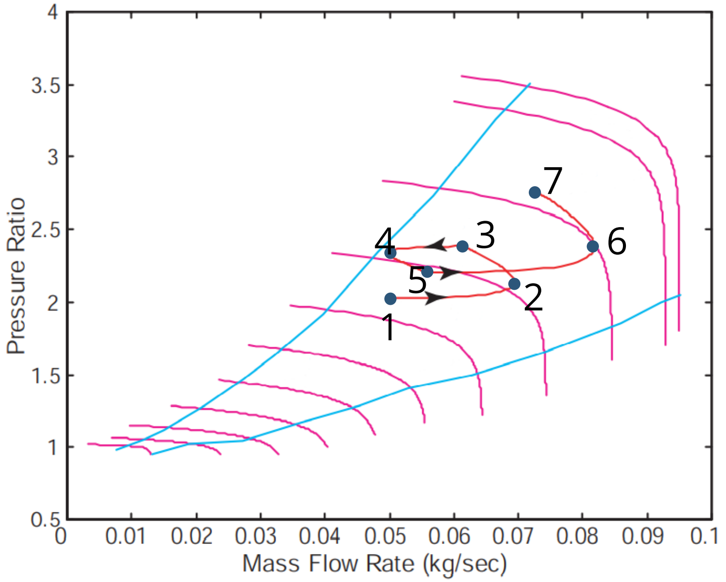
Compressor flow / Pressure trajectories

Equal power condition for compressor design:

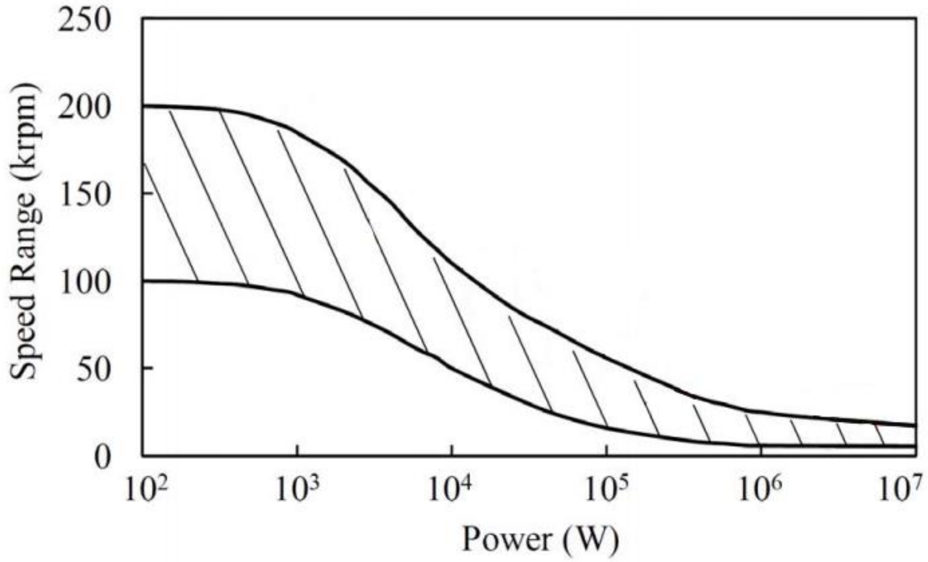
$$N_2 = N_3;\ N_4 = N_5;\ N_6 = N_7$$

COMPRESSOR DESIGN REQUIREMENT

- It is necessary to make an <u>initial design of the compressor to estimate the power consumption of the compressor and the required shaft rotation speed</u>. An initial design is also needed to <u>evaluate the compressor performance map</u> (how the simulation line is located in relation to the compressor speedlines).



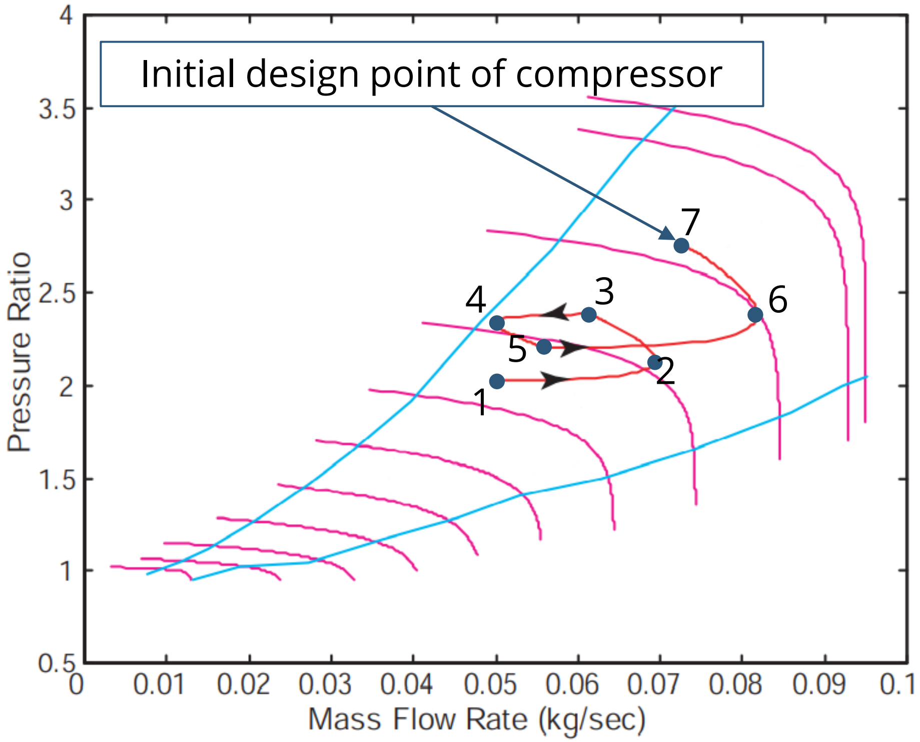
- Design requirements:
  - Use a ready-made electric motor that is available on the market
  - Use an electric motor without a multiplier (reduction gear)
  - Maintain small overall dimensions of the compressor (at the available shaft rotation speed)
  - Chosen compressor configuration is vaneless diffuser and volute outlet

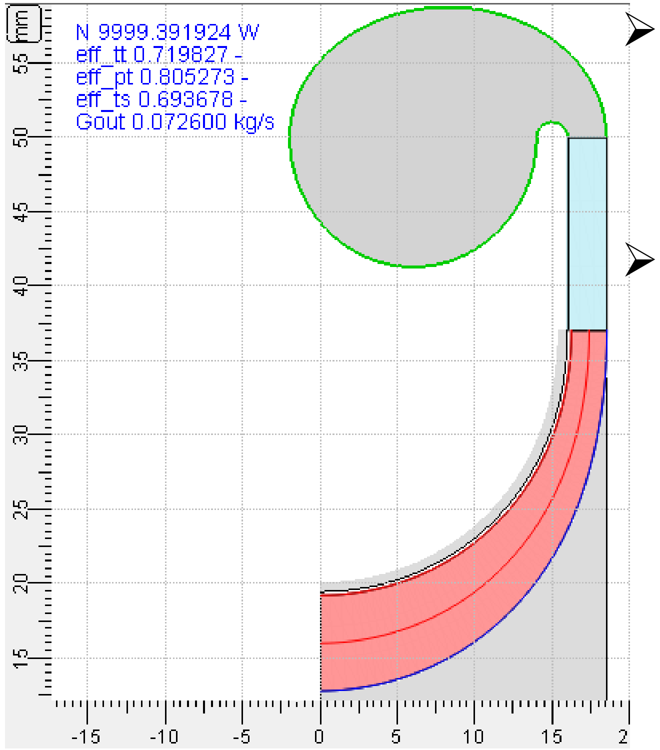


Initial Design of Compressor

INITIAL DESIGN OF COMPRESSOR

- A initial design of the compressor was carried out for estimation of the compressor power, determination of the rotational speeds and also the estimation of the compressor performance map and the simulation line.

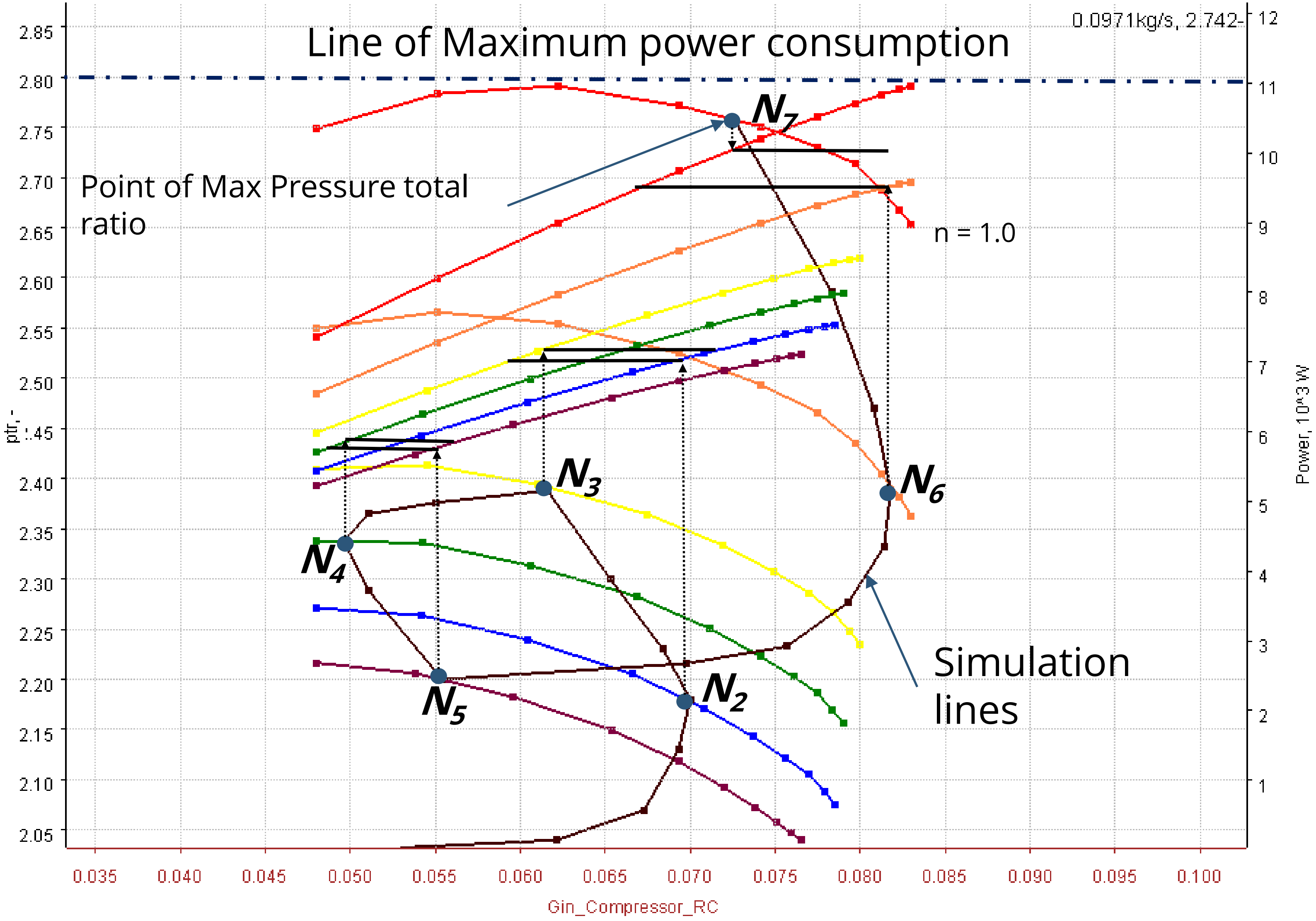



```
N 9999.391924 W
eff_tt 0.719827 -
eff_pt 0.805273 -
eff_ts 0.693678 -
Gout 0.072600 kg/s
```

- Compressor initial design is designed for max pressure total ratio.

- Parameters:
  - MFR = 0.0726 kg/s
  - Ptr = 2.758
  - n = 100 krpm
  - N = 10 kW
  - D2 = 74.1 mm
  - lc = 2.3 mm

PERFOMANCE MAP OF INITIAL COMPRESSOR

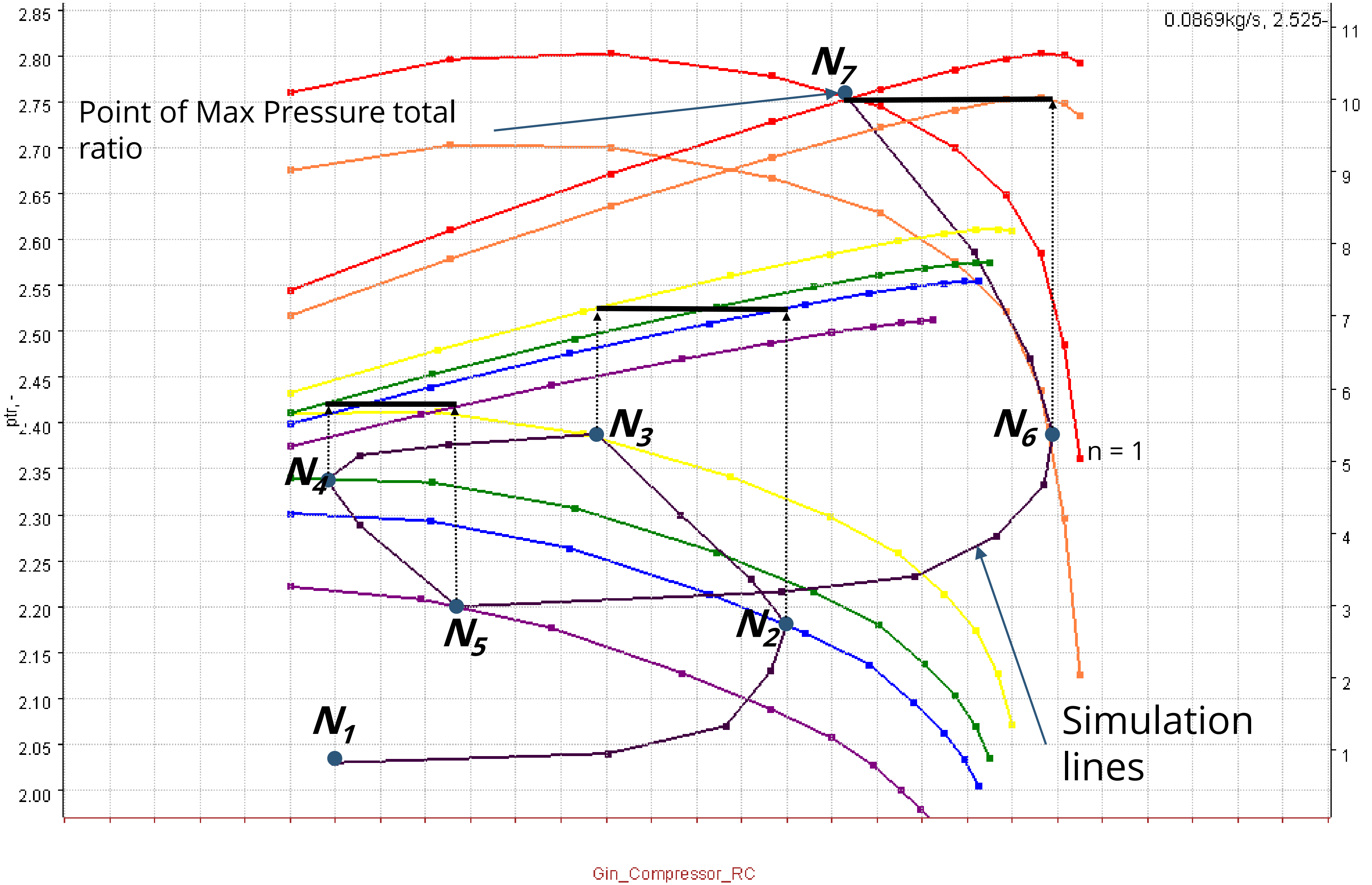


● Main points

— Lines of not-equal power

- Powers are not equal:
$N_2 \neq N_3$; $N_4 \neq N_5$; $N_6 \neq N_7$;
- The maximum power consumption of the compressor in the off-design mode is 11 kW;

ESTIMATED PERFOMANCE MAP OF DESIRED COMPRESSOR



● Main points

▬ Lines of equal power

- ➢ Powers are equal:

$N_2 = N_3; N_4 = N_5; N_6 = N_7;$

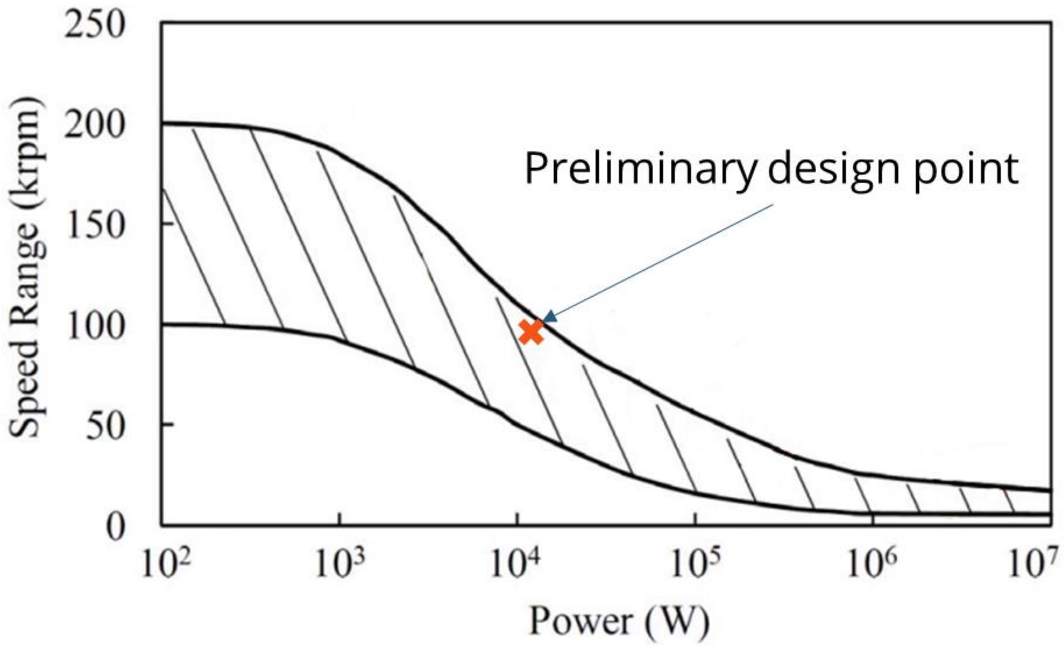
- ➢ This compressor performance map corresponds to the requirement of equal power and hence the final compressor design.

Electro Drive Motor Selection

CHOOSING AN ELECTRIC MOTOR

- Analysis of existing electric motors gives a graph of the dependence of the Shaft rotation speed on the Motor power.
- With an increase in the rotational speed, the power of the electric motor decreases. And this gives a narrow range of motor selection.
- The preliminary design of the centrifugal compressor gives an expected power of about 11kW and an electric motor speed of 100k rpm.

- When designing the initial compressor and evaluating the compressor's performance, the following conclusions can be drawn:
  - Compressor Power ≈ 11 kW
  - Shaft Speed ≈ 100RPM+



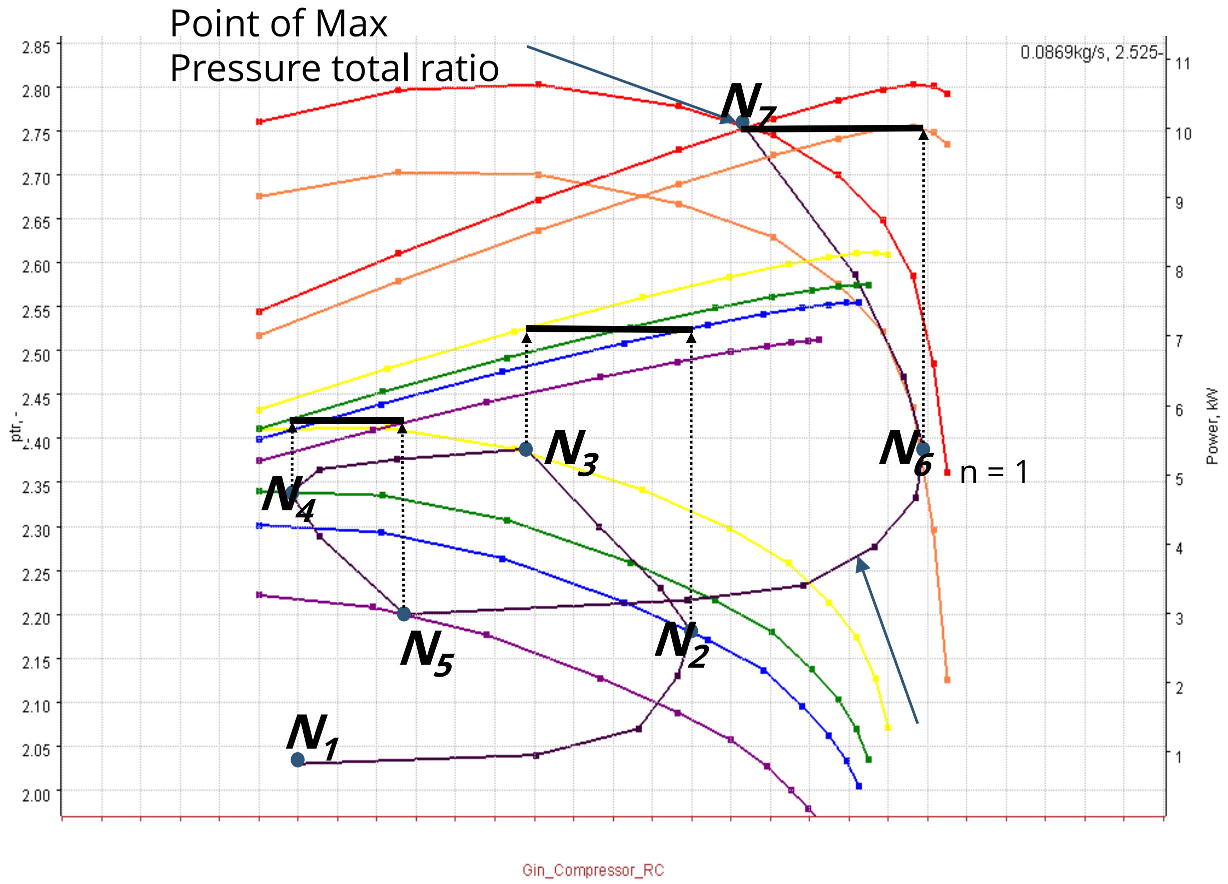
Relationship between high speed and power rate

HIGH SPEED ELECTRO DRIVE MOTOR

	Power (kW)	Max speed (krpm)	Developed by
1	1	280	Celeroton
2	1	200	EPFL
3	2.2	100	Zhejiang
4	2.5	250	Celeroton
5	3	120	ZJU
6	10	110	DBS
7	12.5	50	Vohoboo
8	15	88	ZJU
9	15.7	45	Parker
10	17	120	Equipmake
11	20	70	ZJU
12	30	75	DBS
13	30	96	Capstone
14	50	70	BLDC

STATEMENT OF THE PROBLEM FOR THE COMPRESSOR DESIGN

- Problem statement:
  - Design a compressor for the selected electric motor (shaft rotation speed)
  - Design a compressor that satisfies the conditions of equal power ($N_2 = N_3; N_4 = N_5; N_6 = N_7$)
  - Design a compressor that satisfies the conditions of constant total pressure ratio ($P_1 = P_2; P_3 = P_4; P_5 = P_6$)
  - Since designing a compressor for the given conditions can take a lot of time, it is necessary to use a system for <u>automatic design</u>



Point of Max
Pressure total ratio

- **How will this be achieved:**
  - To achieve these objectives, the compressor must be designed for maximum total pressure ratio (point 7)
  - Further, it is necessary to evaluate the power for each point
  - If these conditions are not met, the compressor must be redesigned for new boundary conditions.

BLOCK SCHEME FOR AUTOMATIC DESIGN OF COMPRESSOR

1. Compressor designed for maximum pressure total ratio

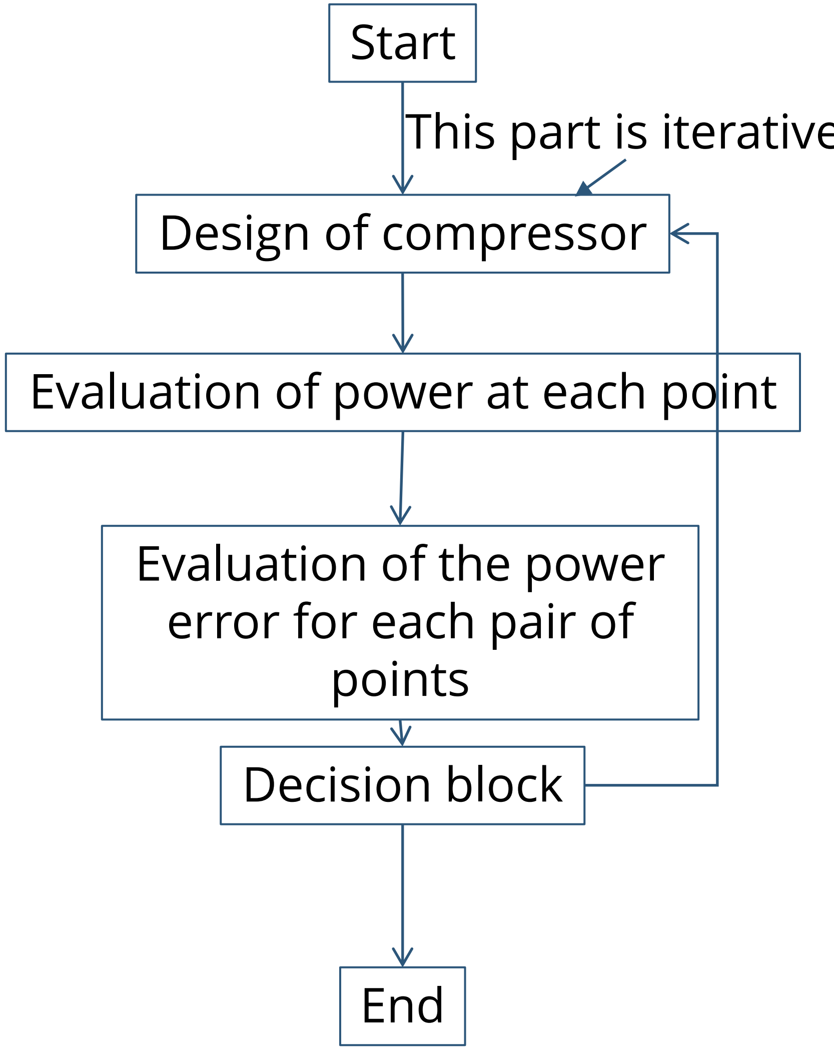
2. Evaluation of power at each operating point

3. Power error evaluation (sum error) for each pair of points (2-3, 4-5, 6-7)

4. If this error is greater than our threshold, then we return to the Design of Compressor block and change the boundary conditions for design (MFR, etc.)

5. We repeat cycle 1-4

6. If the obtained error is less than threshold, then the iterative workflow and design is completed.



Start

This part is iterative

Design of compressor

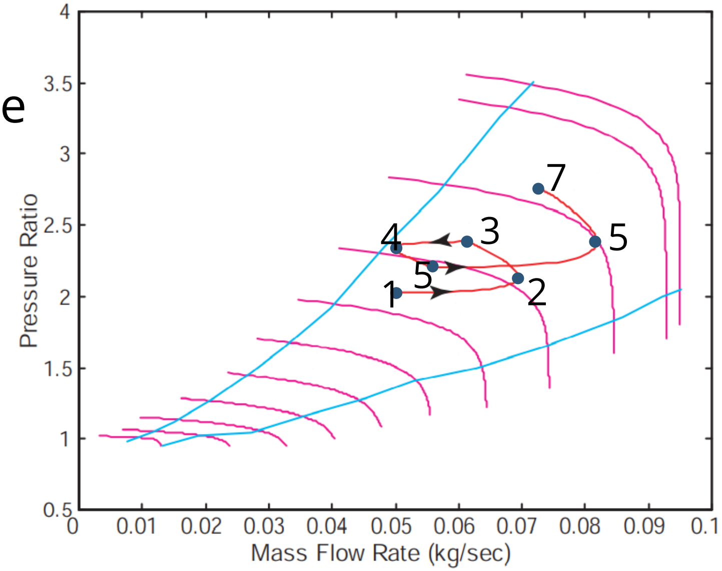
Evaluation of power at each point

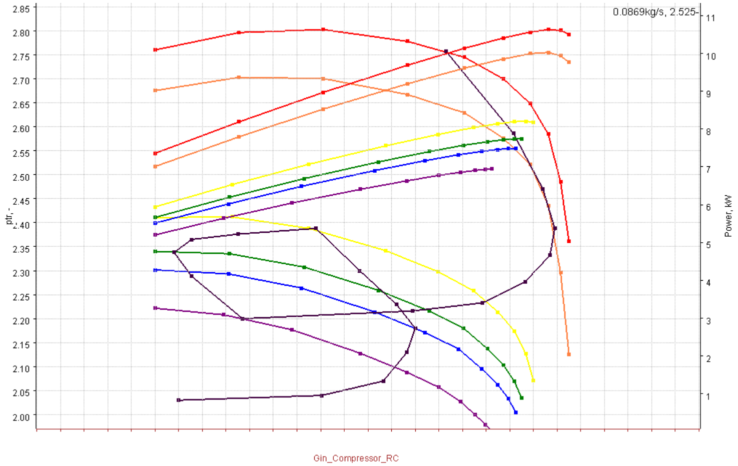
Evaluation of the power error for each pair of points

Decision block

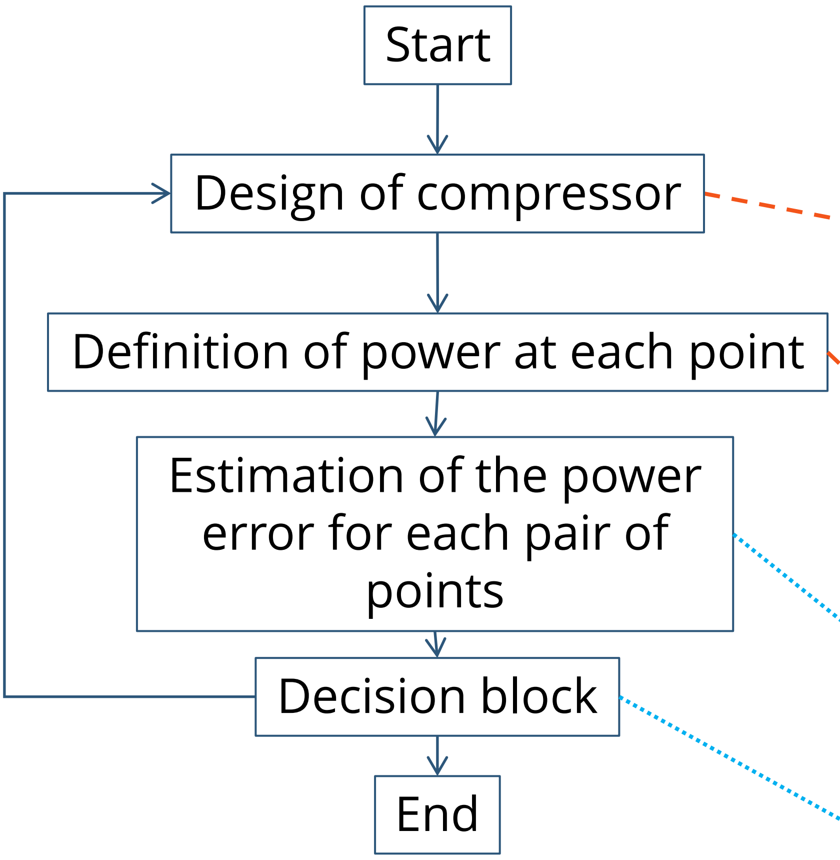
End

Simple block scheme





OVERALL VIEW OF ION SCHEME


Start

Design of compressor

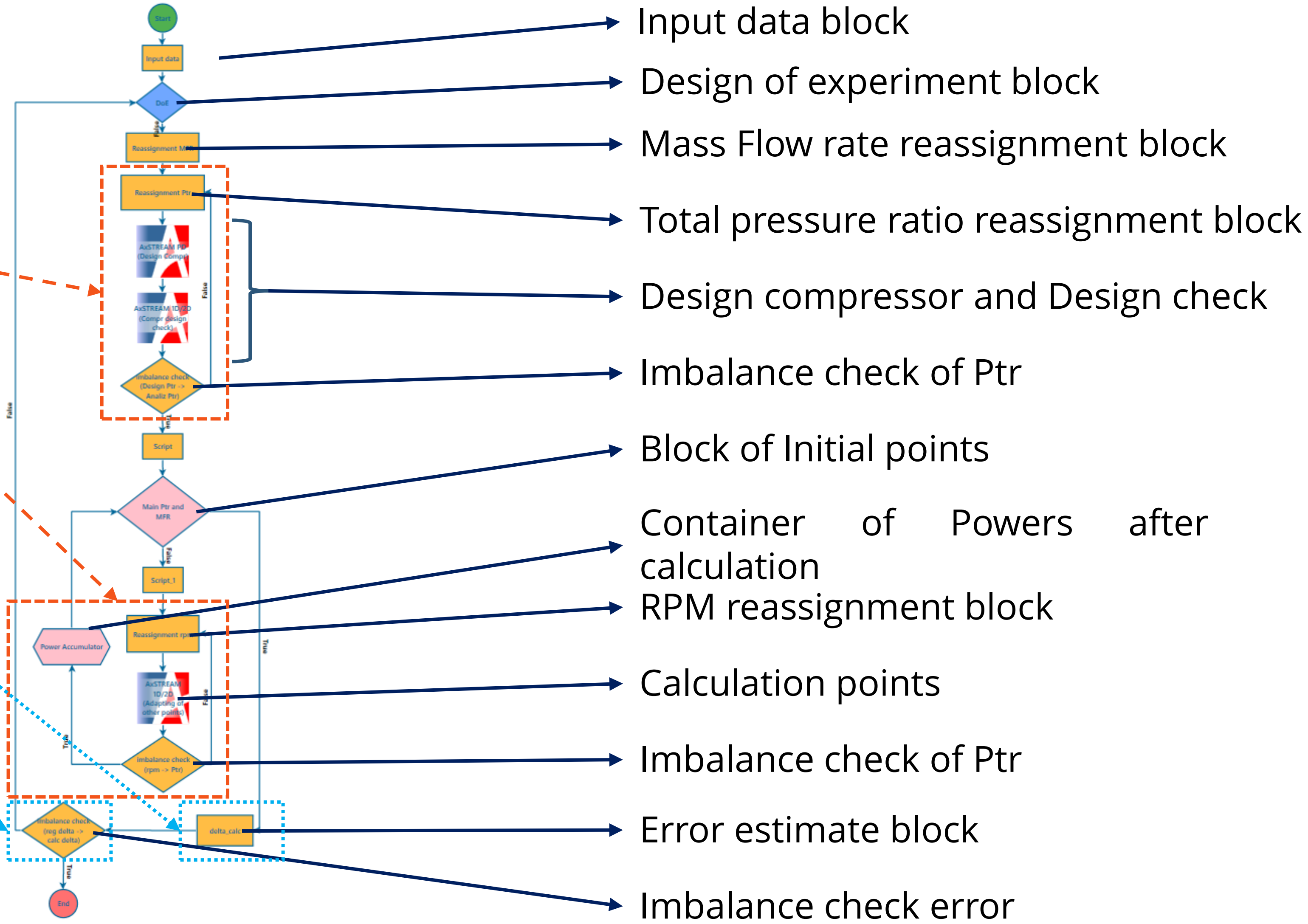
Definition of power at each point

Estimation of the power error for each pair of points

Decision block

End

Simple block scheme



Input data block

Design of experiment block

Mass Flow rate reassignment block

Total pressure ratio reassignment block

Design compressor and Design check

Imbalance check of Ptr

Block of Initial points

Container of Powers after calculation

RPM reassignment block

Calculation points

Imbalance check of Ptr

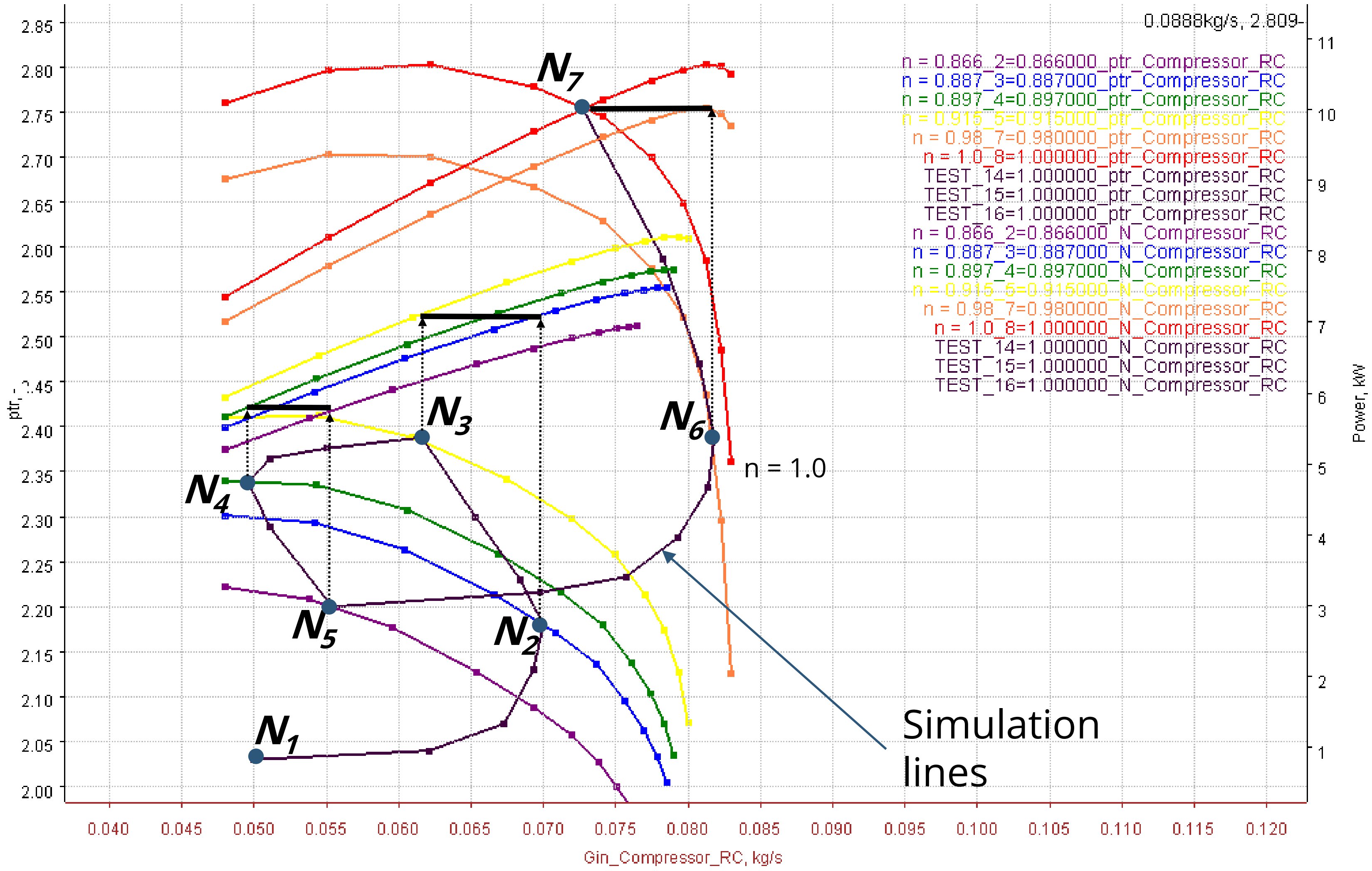
Error estimate block

Imbalance check error

Integration and automation scheme

Results

PERFORMANCE MAP AFTER AUTOMATIC DESIGN



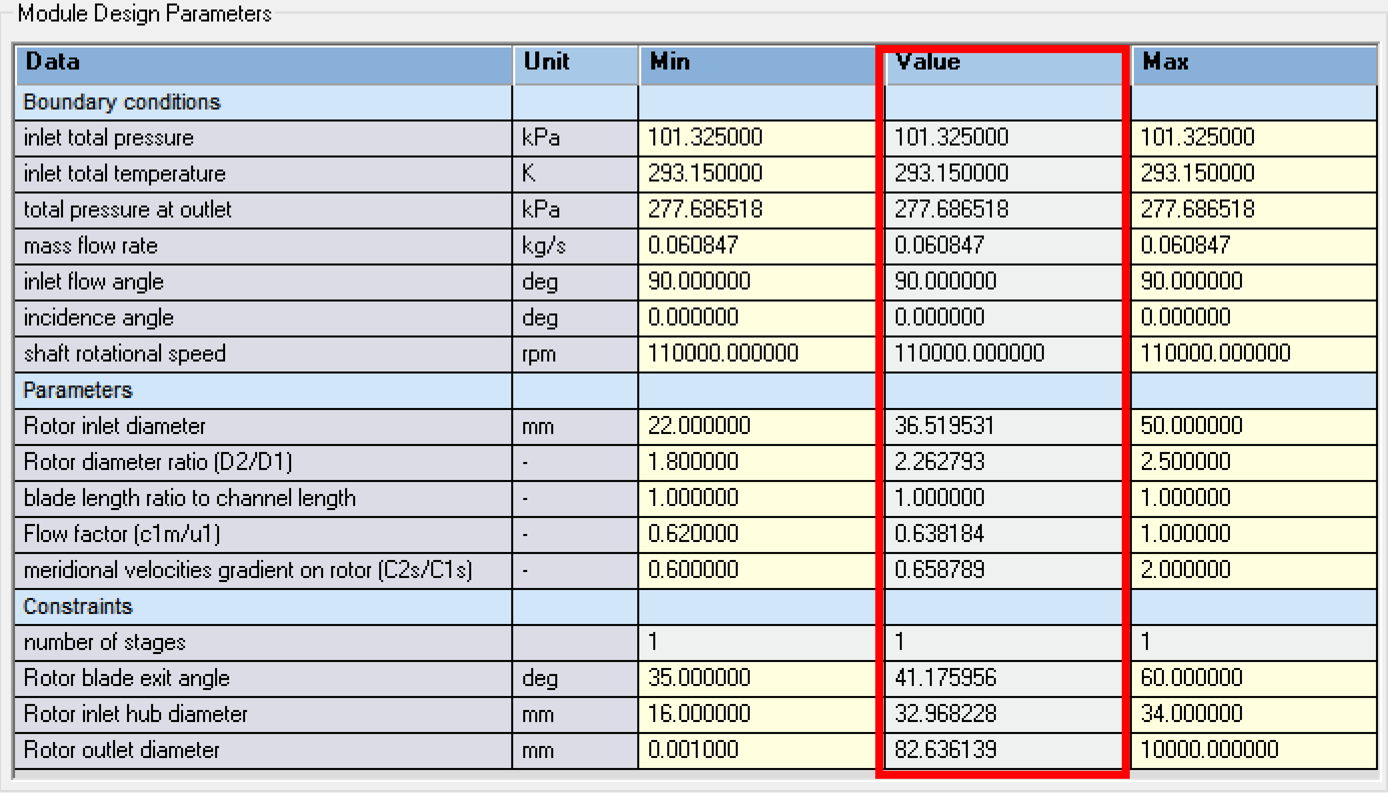
- ➢ Power are equal:

$N_2 = N_3; N_4 = N_5; N_6 = N_7;$

- ➢ This performance correspond to a compressor designed for 110 krpm.

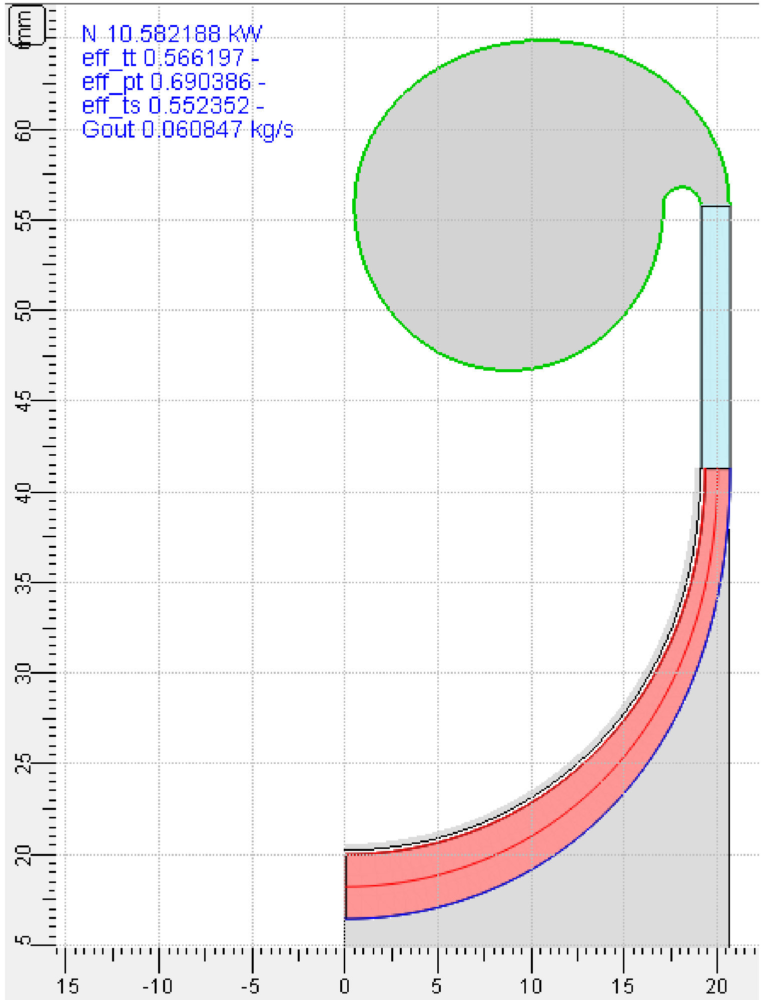
COMPRESSOR AFTER AUTOMATED DESIGN

- This compressor is designed for 110 krpm.
- The calculation error is 2.3%



Module Design Parameters

Data	Unit	Min	Value	Max
Boundary conditions				
inlet total pressure	kPa	101.325000	101.325000	101.325000
inlet total temperature	K	293.150000	293.150000	293.150000
total pressure at outlet	kPa	277.686518	277.686518	277.686518
mass flow rate	kg/s	0.060847	0.060847	0.060847
inlet flow angle	deg	90.000000	90.000000	90.000000
incidence angle	deg	0.000000	0.000000	0.000000
shaft rotational speed	rpm	110000.000000	110000.000000	110000.000000
Parameters				
Rotor inlet diameter	mm	22.000000	36.519531	50.000000
Rotor diameter ratio (D2/D1)	-	1.800000	2.262793	2.500000
blade length ratio to channel length	-	1.000000	1.000000	1.000000
Flow factor (c1m/u1)	-	0.620000	0.638184	1.000000
meridional velocities gradient on rotor (C2s/C1s)	-	0.600000	0.658789	2.000000
Constraints				
number of stages		1	1	1
Rotor blade exit angle	deg	35.000000	41.175956	60.000000
Rotor inlet hub diameter	mm	16.000000	32.968228	34.000000
Rotor outlet diameter	mm	0.001000	82.636139	10000.000000

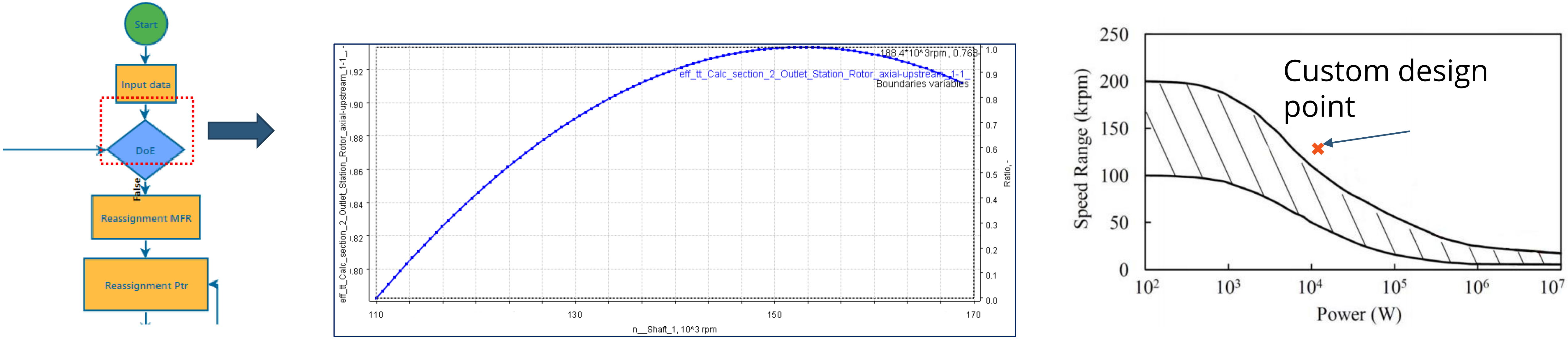


SUMMARY

- This compressor design is not optimal due to insufficient shaft rotation speeds.
- Low rotational speeds led to an increase in the outlet diameter of impeller (large channel length) which led to an increase in hydraulic losses.
- An increase in the outlet diameter led to a decrease in the height of the blade at the outlet and an increase in the relative clearance (relative clearance = 20%).
- Compressor efficiency is 56%.
- The obtained parameters of the compressor do not meet the optimal compressor design.

DETERMINATION OF THE OPTIMAL ROTATIONAL SPEEDS FOR THE COMPRESSOR

- The next step we will build design of experiment for determination optimal compressor.
- Let us construct the dependence of the efficiency on the shaft rotation speed and determine the point with the maximum efficiency. This step is performed automatically in the Design of experiment block.

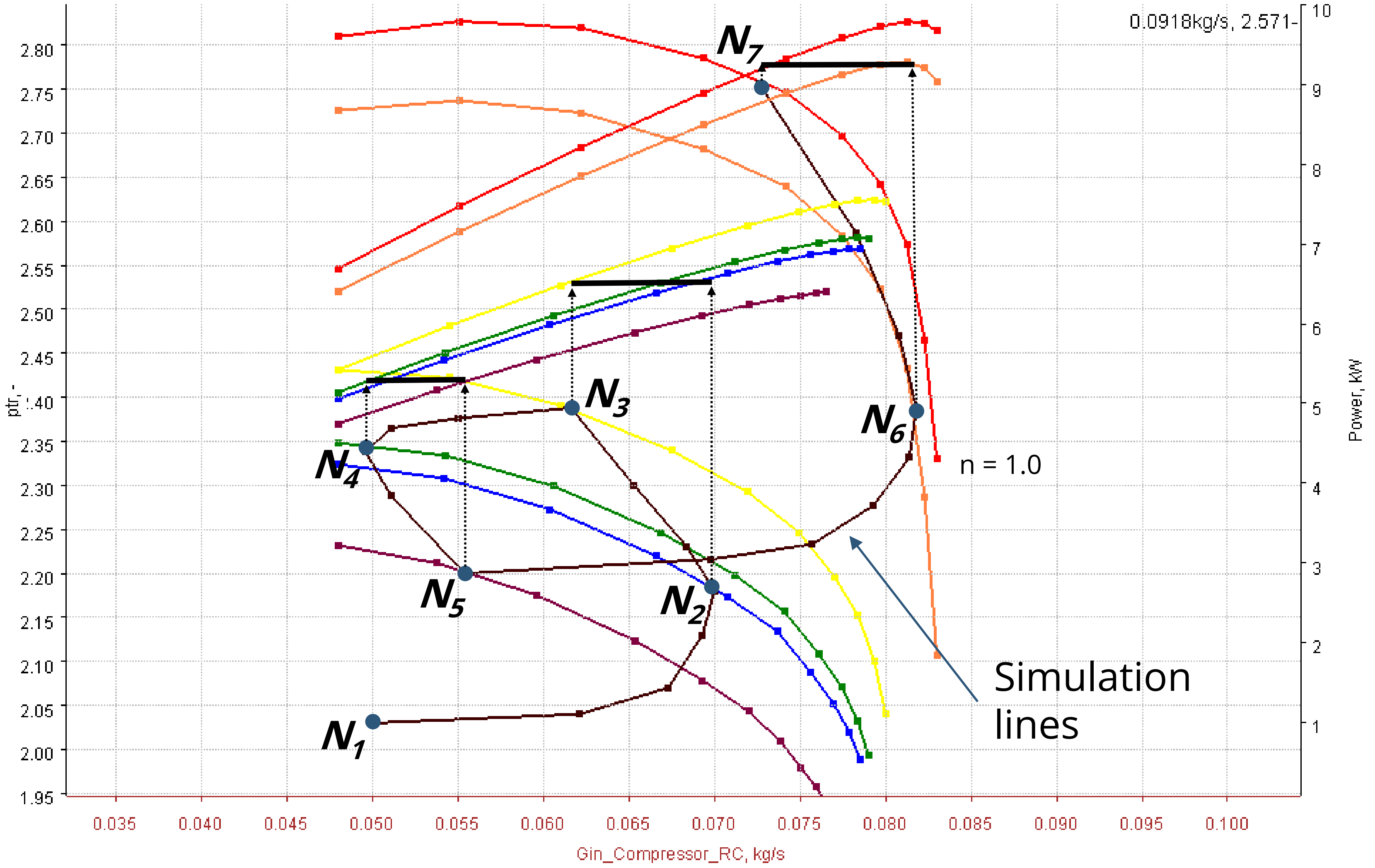


Simple block scheme (left), DoE dependency of efficiency on shaft rotation speed (center), dependence on motor power and rotation speed (right)

- For the point of maximum efficiency of the impeller, the shaft speed corresponds to 150 krpm.
- Assuming we have a **"*custom*" electric motor with 150 krpm and required power**. The performance of this electric motor is outside the range of existing electric motors but theoretically can be achieved.

Result of Redesign

REDESIGN OF PERFORMANCE MAP

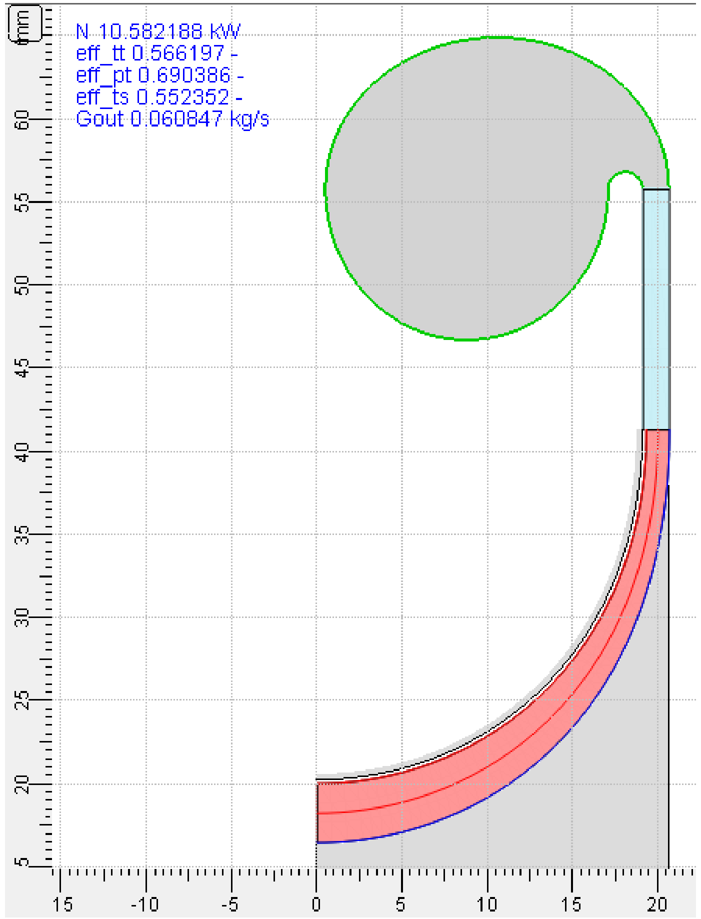


- Power are equal:

  $N_2 = N_3; N_4 = N_5; N_6 = N_7;$

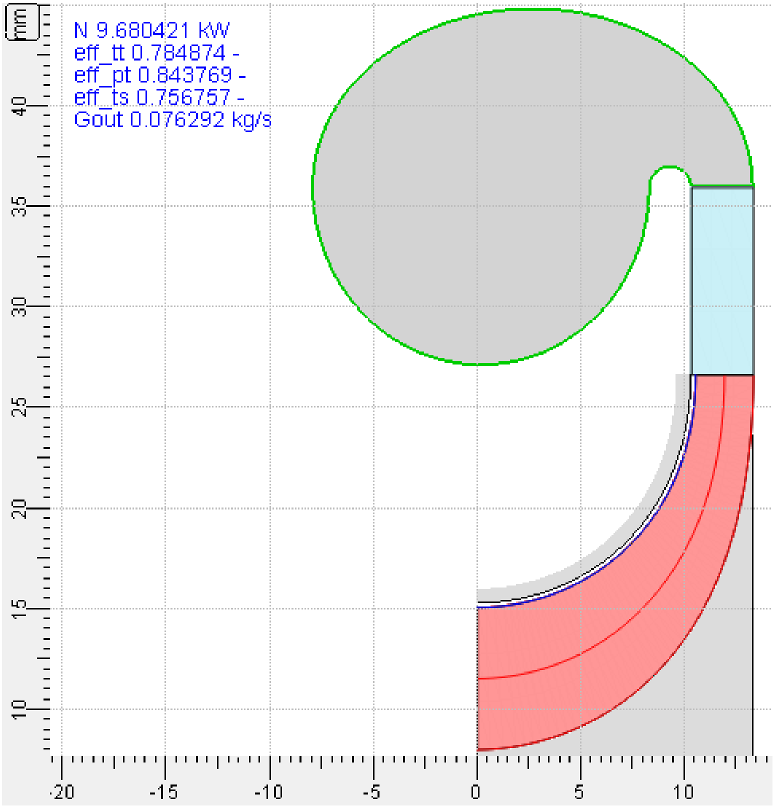
- This performance correspond to a compressor designed for 150 krpm.

COMPARISON OF COMPRESSOR DESIGNS



Compressor design for 110k rpm

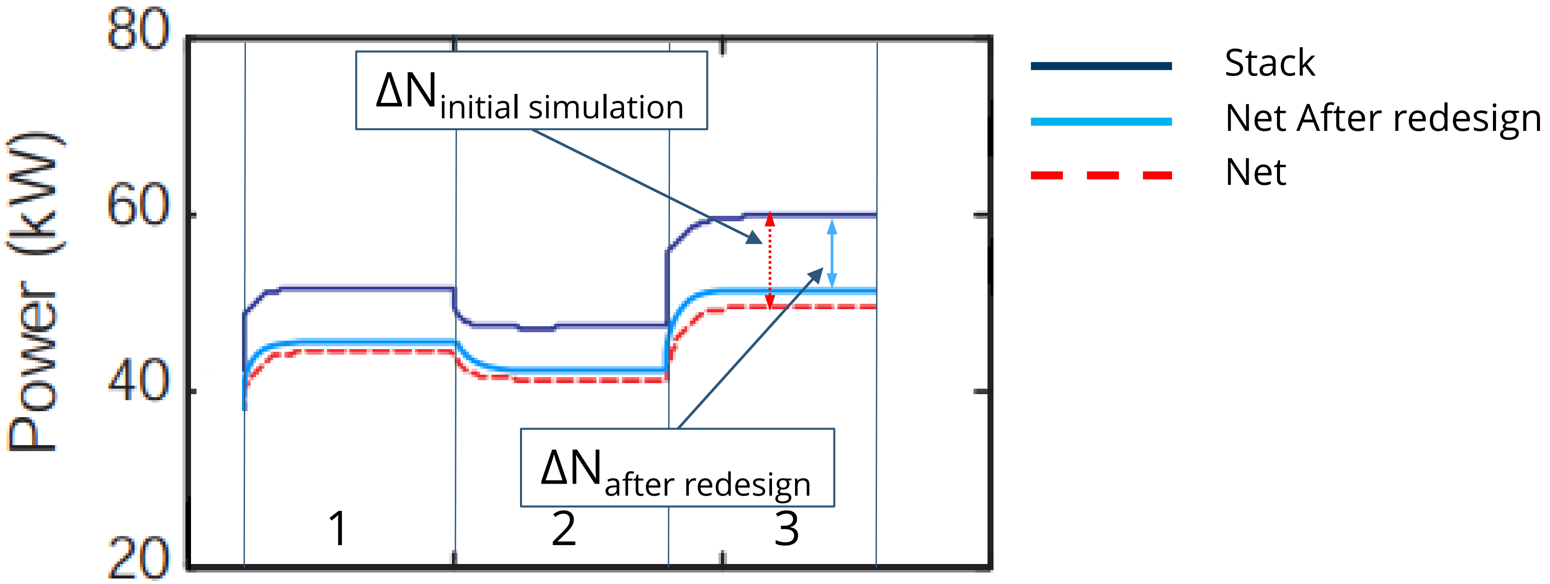
Design	Parameters	Redesign
110 000	Shaft speed, rpm	150 000
0.0608	Mass Flow Rate, kg/s	0.0763
10.58	Power, kW	9.68
56.61	Total efficiency, %	78.48
32.96	D1 hub, mm	16.0
82.63	D2, mm	53.28
3.55	Ic1, mm	7.07
1.34	Ic2, mm	2.78
20.65	Axial length, mm	13.32
129.71	Tip diam on Volute exit, mm	89.64



Compressor design for 150k rpm

CONCLUSIONS OF COMPRESSOR DESIGN

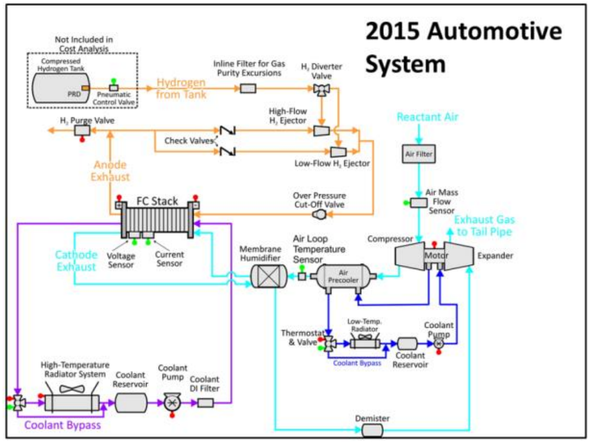
- Increased rotational speeds led to a decrease in the outlet diameter of the impeller (small channel length), respectively, a decrease in hydraulic losses. The height of the outlet blade has increased resulting in a decrease in the relative clearance (which is 7%). Compressor efficiency is equal to 78.4%. This compressor design is optimal and satisfies the design parameters.
- The resulting compressor powers are plotted in the graph below. The new compressor has a lower power consumption.
- Designed compressor which was shown is aerodynamically realizable and was formulated with consideration of physical scientific and engineering principles. Furthermore, the design conforms to the objective whole-map performance characteristics laid out by the system requirements, which is the fuel cell, at the very beginning.
- An algorithm for the automatic design of the compressor was developed, which meets the required parameters for design and provides conditions for building a performance map.



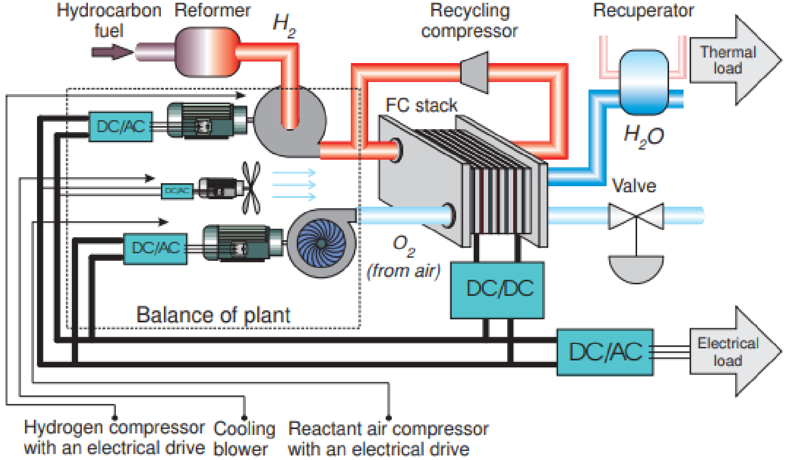
	1	2	3
Stack, kW	51.7	47.4	60
Net (after redesign), kW	45.6	42.2	50.7
Net, kW	44.3	41	49.5

SCHEMES OF COMPRESSOR IN FUEL CELL SYSTEM

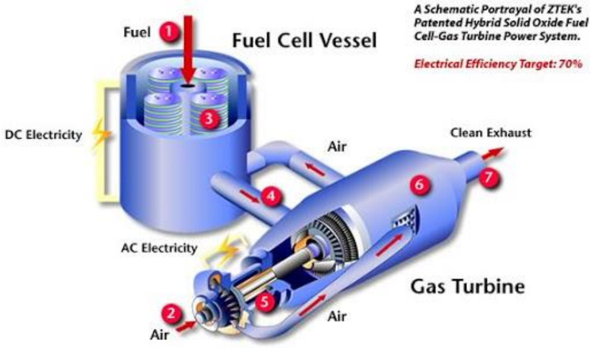
- Next, consider the fuel cell systems where the compressor is used. This is mainly the field of Automotive and Power system.
- The figures show schematic diagrams of using a compressor in a fuel cell system.

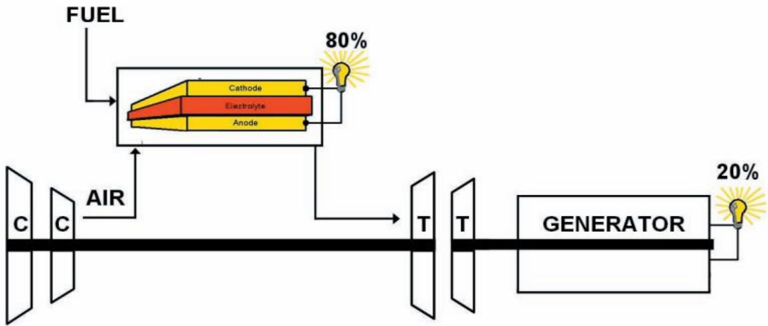


Flow schematic for automotive fuel cell system



Simplified diagram of a fuel cell system for residential applications





Basic design concept of a hybrid gas turbine fuel cell system

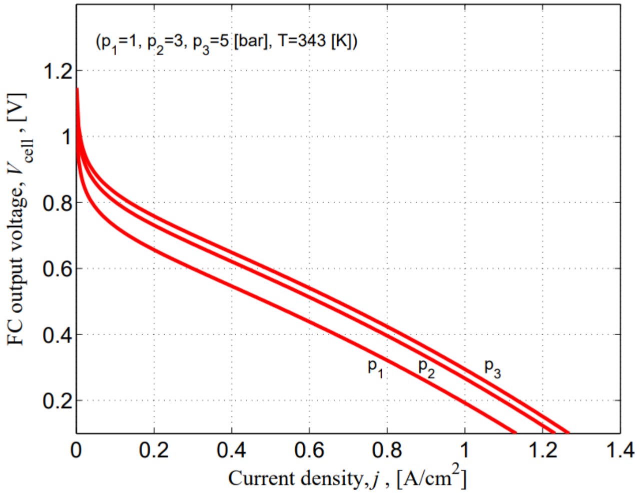
USING CENTRIFUGAL COMPRESSOR IN FUEL CELL SYSTEM

- The most used compressors in a fuel cell are axial compressor and centrifugal compressor.
- It is **preferable to use a centrifugal compressor** due to its characteristics / properties. The appropriate characteristics of the centrifugal compressor, like simple and compact mechanical design, wide operating range, high reliability, high efficiency, no lubrication requirements, relatively high pressure capabilities and continuous mass flow make them very suitable.

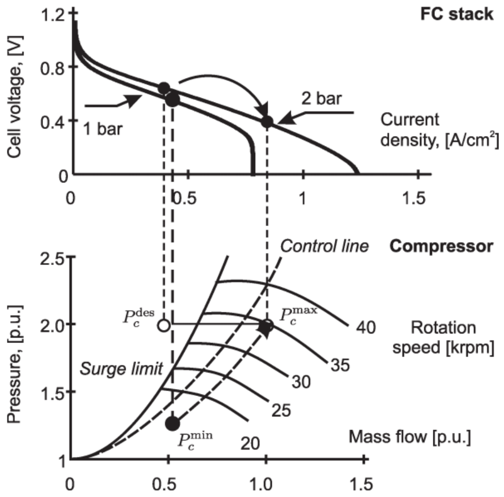
Two stage centrifugal compressor for fuel cell system

COMPRESSOR FEATURES IN FUEL CELL SYSTEM

- An air compressor is employed in a fuel cell system to deliver the reactant oxygen to the fuel cell stack. The FC systems exist in two variants: pressurized and ambient pressure. Pressurization of a FC stack normally results in higher efficiency, improved response characteristics and higher power density of a FC system. However, pressurization uses part of the FC output power and, in some cases, may lead to a reduction in the system net efficiency. Hence, the compressor used to increase the pressure has a direct effect on the FC system performance.



Performance of fuel cell



Fuel cell and compressor operation point

- FC stack with a particular cell area and number of cells can deliver higher power at higher pressure and mass flow. On the other hand, an increased mass flow and pressure would result in extra power consumption by the compression system which supplies air into the stack.

SUMMARY

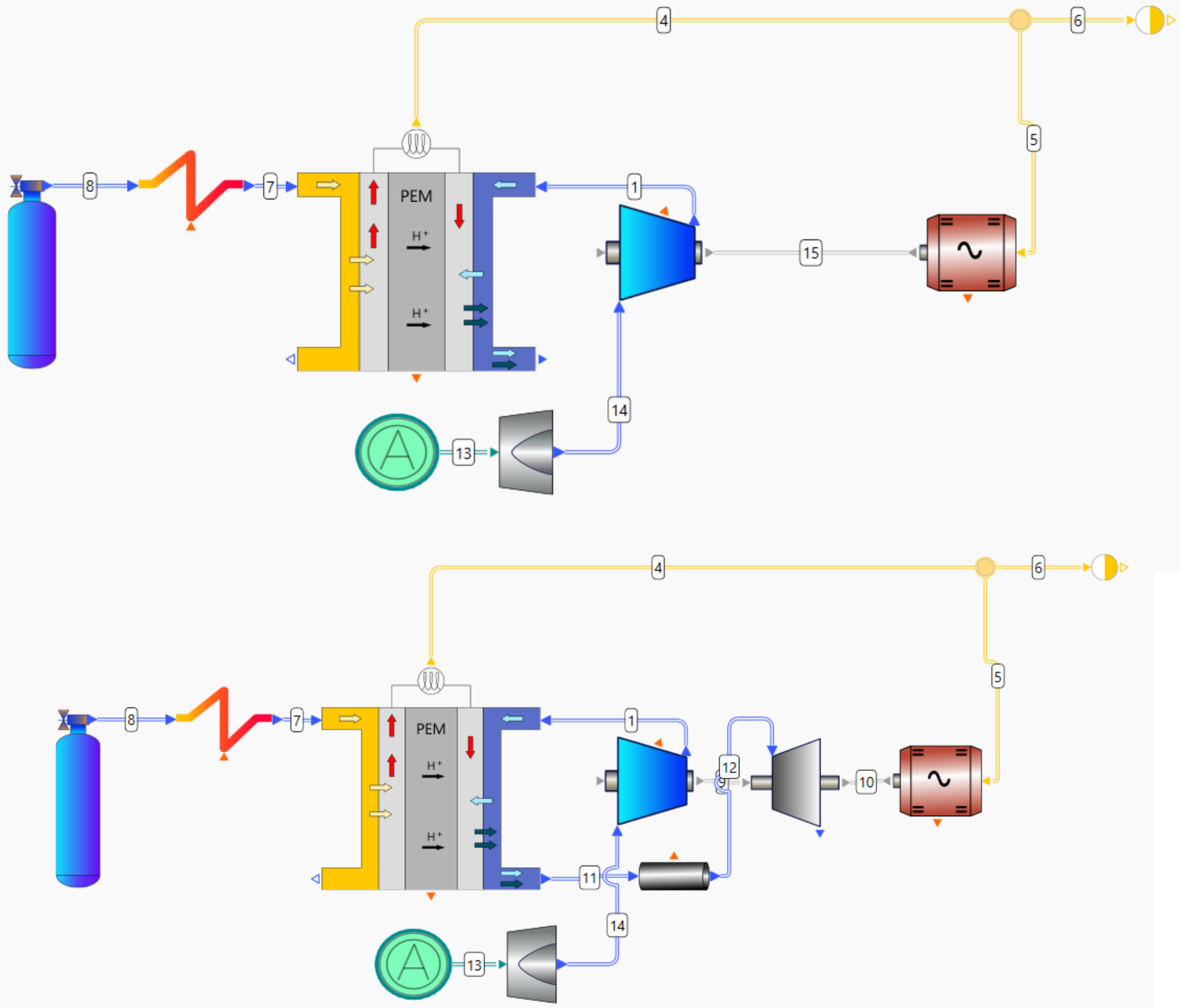
- For a turbocharger (gas turbine/turbocompressor), the compressor is driven by a turbine (expander). For a compressor in a fuel cell system, the compressor is driven by an electric drive that is supplied from the fuel cell. And the power consumption of the compressor must be taken into account. So that the power consumption of the compressor does not exceed the power output of the entire fuel cell system.

- The compressor is the most inertial object in the fuel cell system. And it is necessary to take into account the supply of air to the fuel cell in order to avoid burnout. Since the electrochemical reaction of fuel oxidation occurs instantly.

- Also, the compressor must be compact mechanical design and have a wide range of operation.

A BASIC EXAMINATION OF RECOVERY

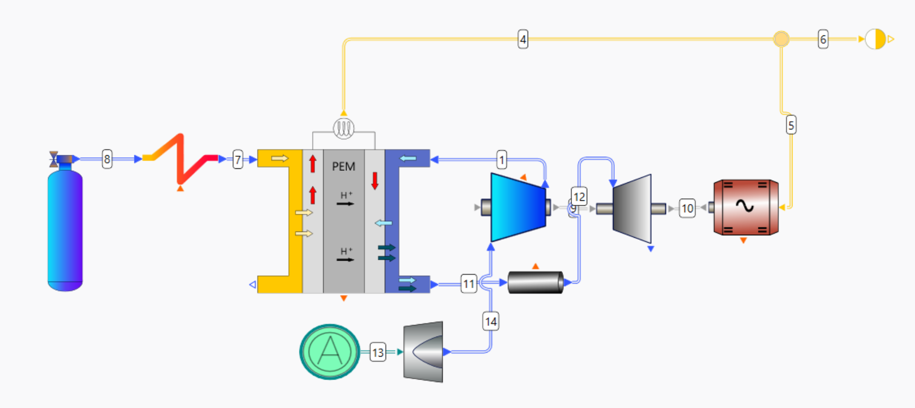
- Similar systems displayed to the left
- Top system exhausts FC stack to ambient (system w/o expander)
- Bottom system sends FC stack exhaust to turboexpander
  - Results in lower electrical power requirement to drive the compressor
  - Effects will be more noticeable with higher stack partial pressure

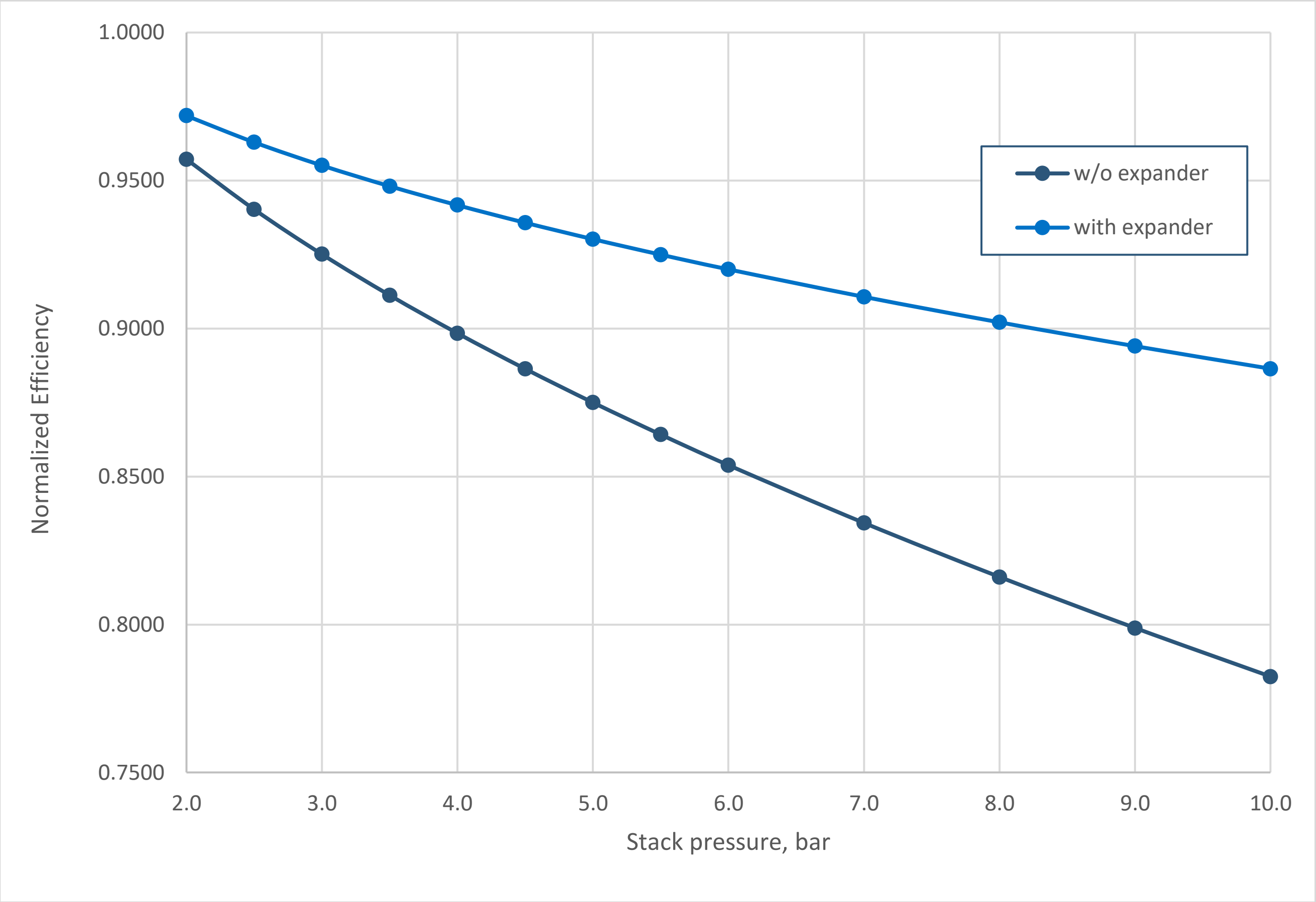


EFFECT OF RECOVERING EXHAUST PRESSURE

Your actual mileage may vary:

- Depending on parameters of system components
- Typically, peak efficiency at particular pressure
- Other equipment
  - Aftercoolers
  - Recuperators

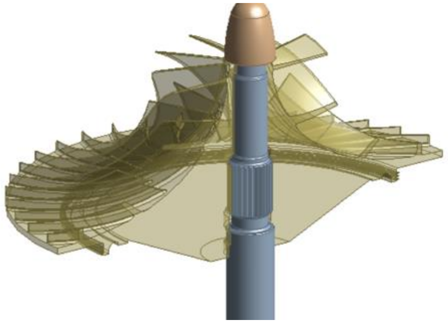




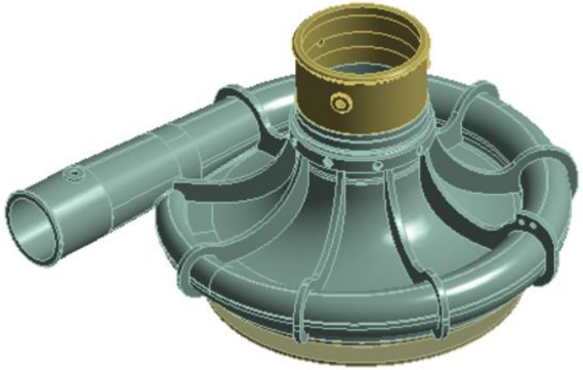
2.2.3 System Design

PROJECT 1

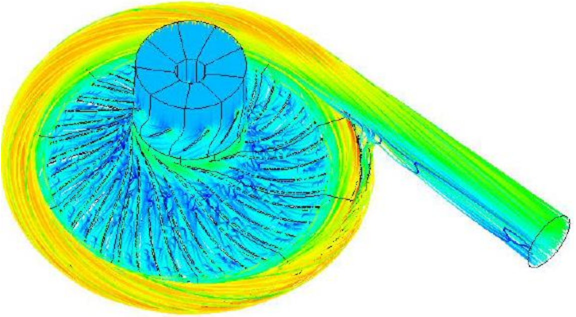
- Application: Hydrogen fuel cell applied in aerospace product
- Scope: System engineering and full development of oxidizer air compressor and integration into overall system

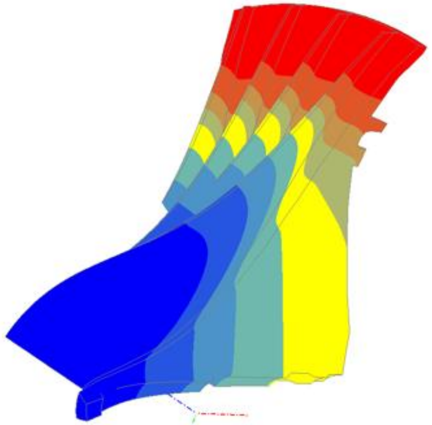


1. System-level definition of technology integration
   - Produced multiple system models of candidate architectures
   - System-level mechanical layout of complete H_2 powertrain system
2. Compressor design
   - Challenging system level constraints on compressor, while optimizing for low mass and volume constraints
   - Conceptual design of compressor to evaluate various configuration of single stage, multiple stages, and stage orientation
   - Off-design performance prediction in early stage of concept design
   - Selection of optimum turbomachinery configuration from produced designs for further detailed design



PROJECT 1



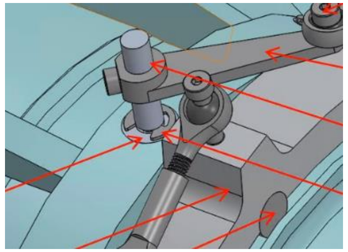


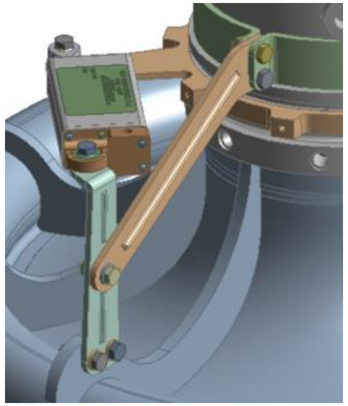
2. Compressor design (continued)

- Detailed design involved full scope aerodynamic and mechanical analysis as part of detailed design validation
  - Full flow path CFD aerodynamic analysis at variable operating conditions and variable inlet guide vane geometries
  - Structural static and dynamic FEA analysis to verify design integrity

3. Additional tasks

- Detailed design of all auxiliaries, including operational instrumentation and control actuation hardware
- Design included focus on product reliability and safety, involving several iterations to mitigate risk of mechanical failure
- Certification considerations taken into account

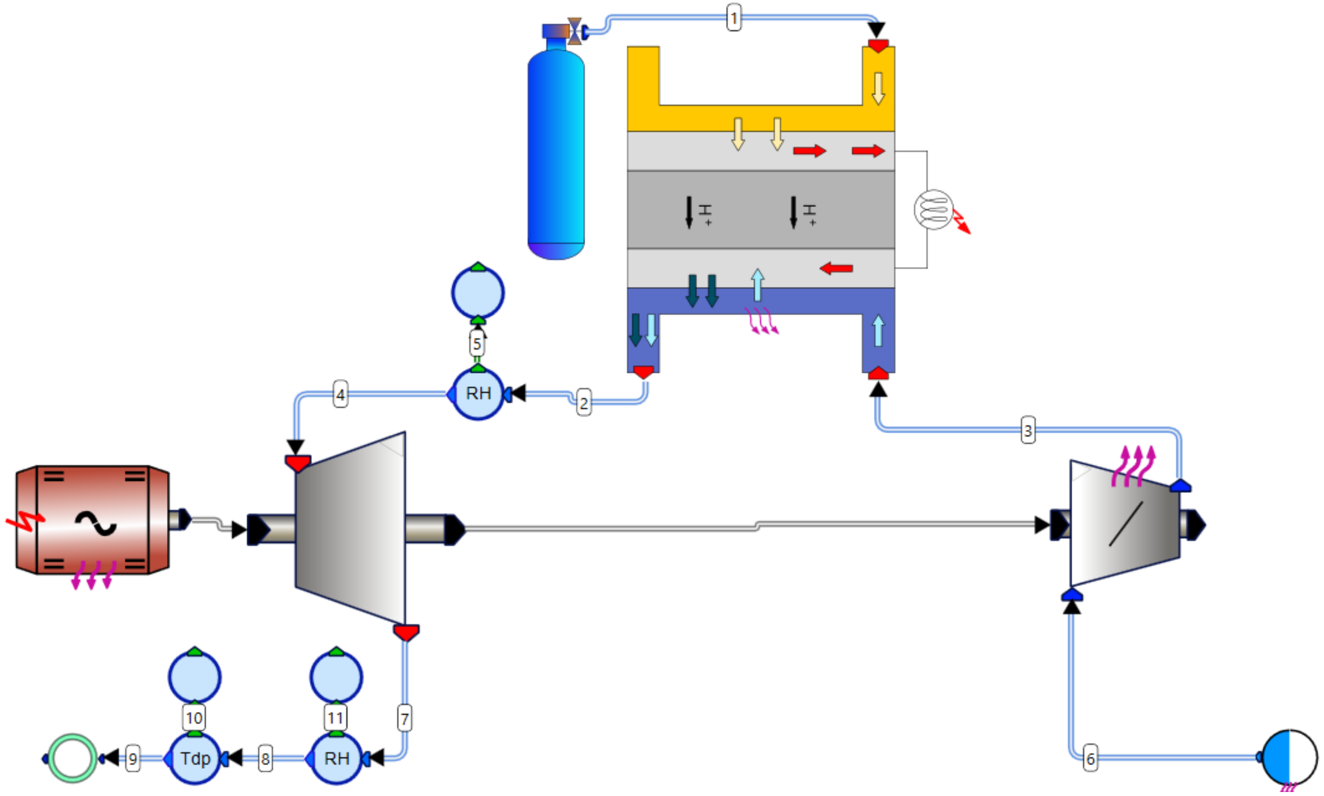




PROJECT 2

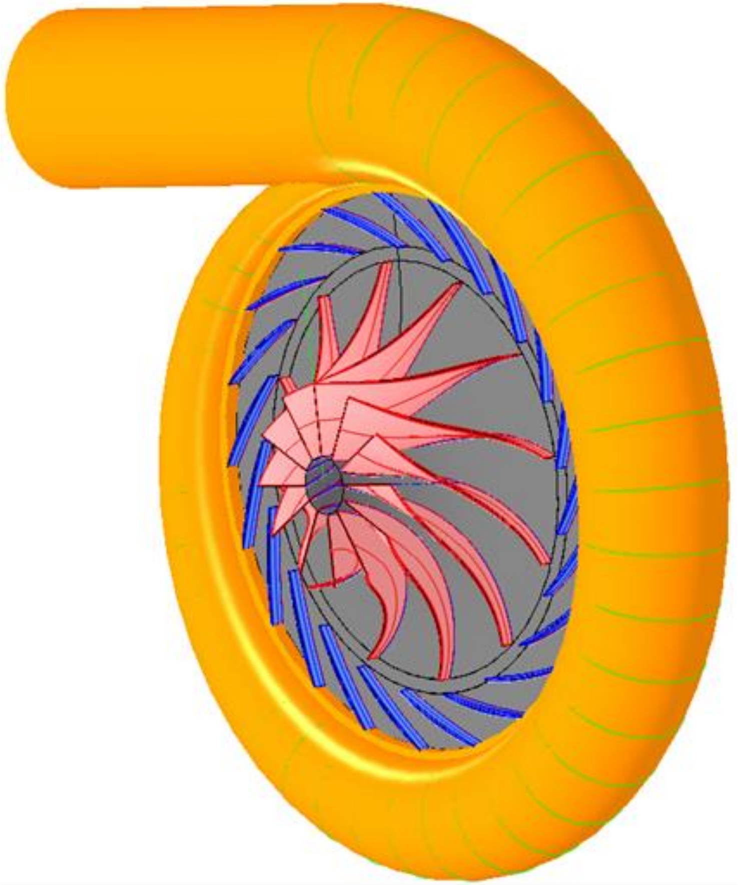
- Application: Pressurization and Cooling of Fuel Cell Stacks for primary propulsion systems
- Scope: Turbo-compressors Development for Hydrogen Fuel Cell Aviation Propulsion

1. System development:
    - Fuel cell-powered propulsion system modeling to calculate turbine and motor power at different ambient and flight conditions
        - Climb, hover & cruise flight phases
    - Full operability assessment (incl. severe weather conditions) across mission profile based on actual turbomachine performance
    - Integrated electric motor for sustained power capability
    - System layout for high compactness and low weight
    - Integration of solutions for high durability and reliability



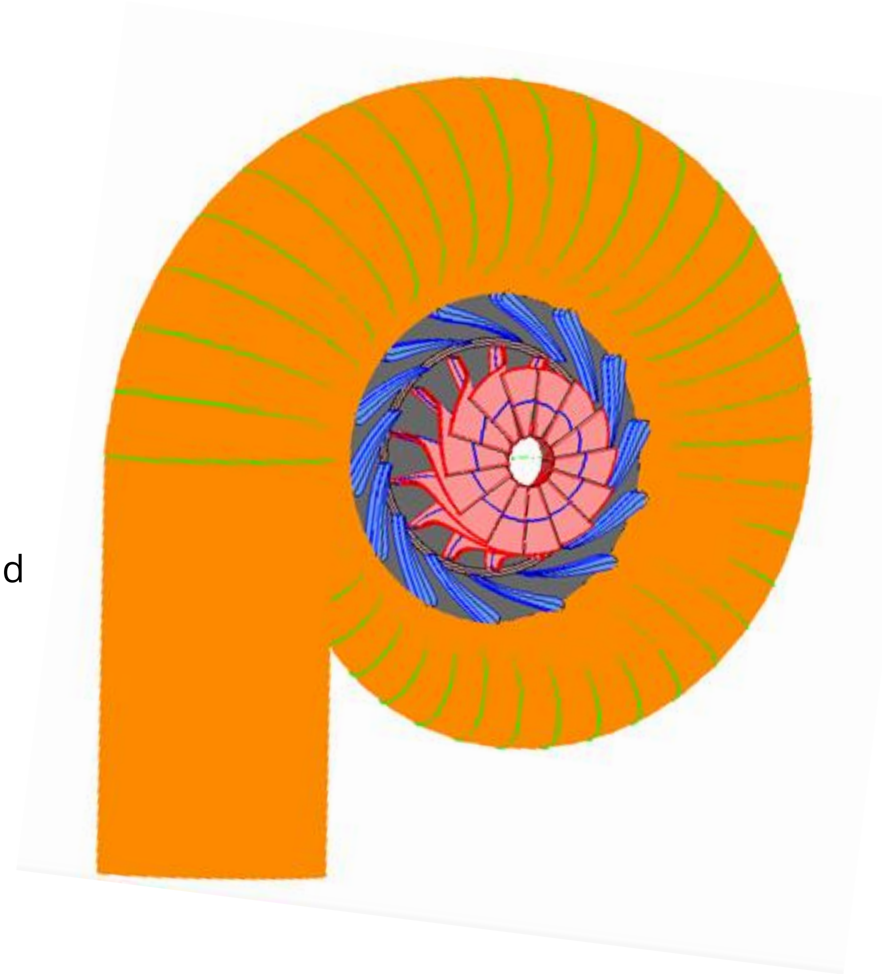
Fuel cell-based propulsion system modelling for aviation application

PROJECT 2



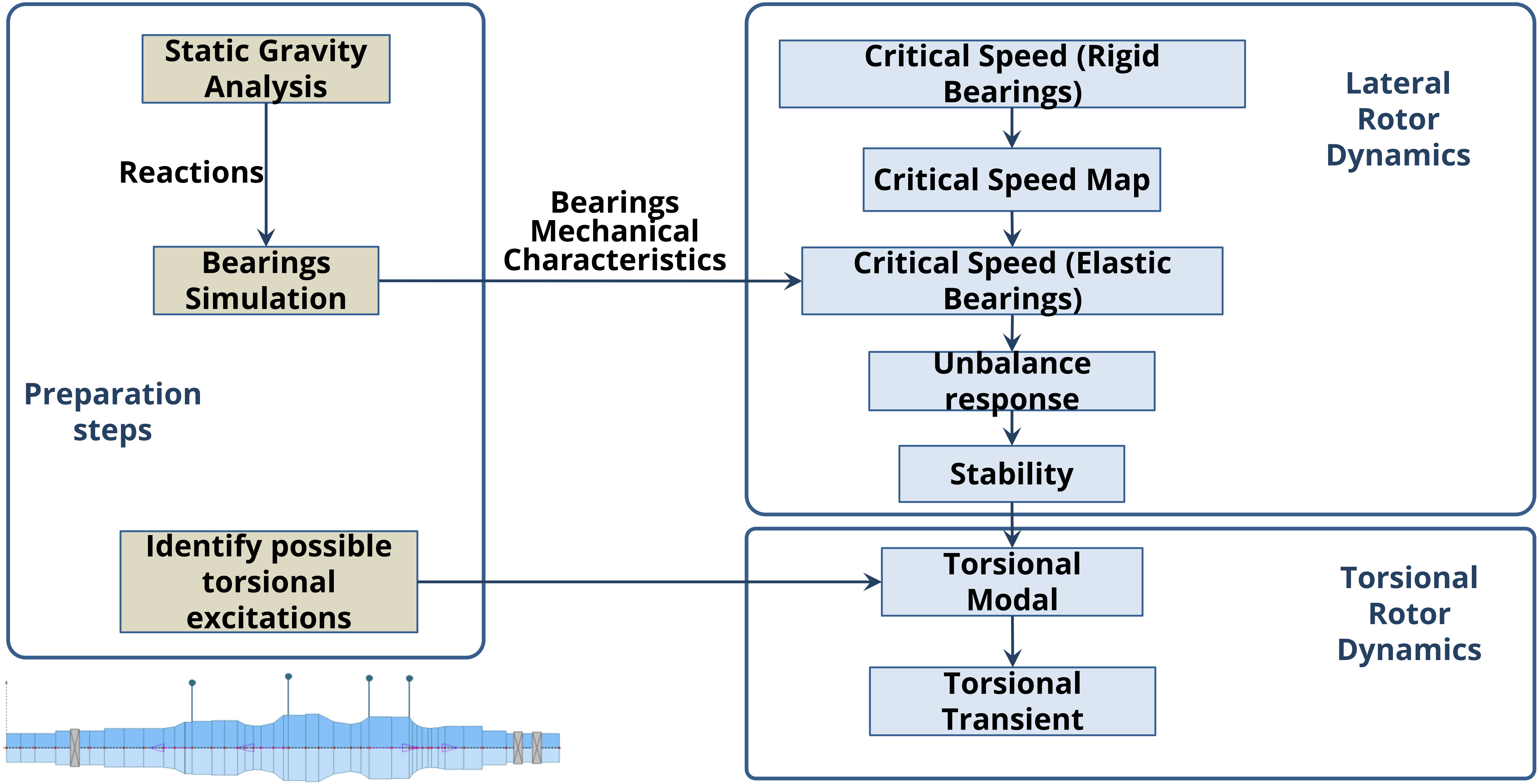
3D geometry of designed compact high-speed single-stage centrifugal compressor

2. Turbomachinery development:
  - Complete aerodynamic design and performance
    - Determination of performance based on actual operating conditions experienced during flight
  - Very high efficiency with demanding operating envelope
  - Overall design for rapid operational transients



High efficiency single-stage radial turbine with variable nozzles for wide operability and reliability

ROTOR DYNAMICS ANALYSIS PROCEDURE



Static Gravity Analysis

Reactions

Bearings Simulation

Preparation steps

Identify possible torsional excitations

Bearings Mechanical Characteristics

Critical Speed (Rigid Bearings)

Critical Speed Map

Critical Speed (Elastic Bearings)

Unbalance response

Stability

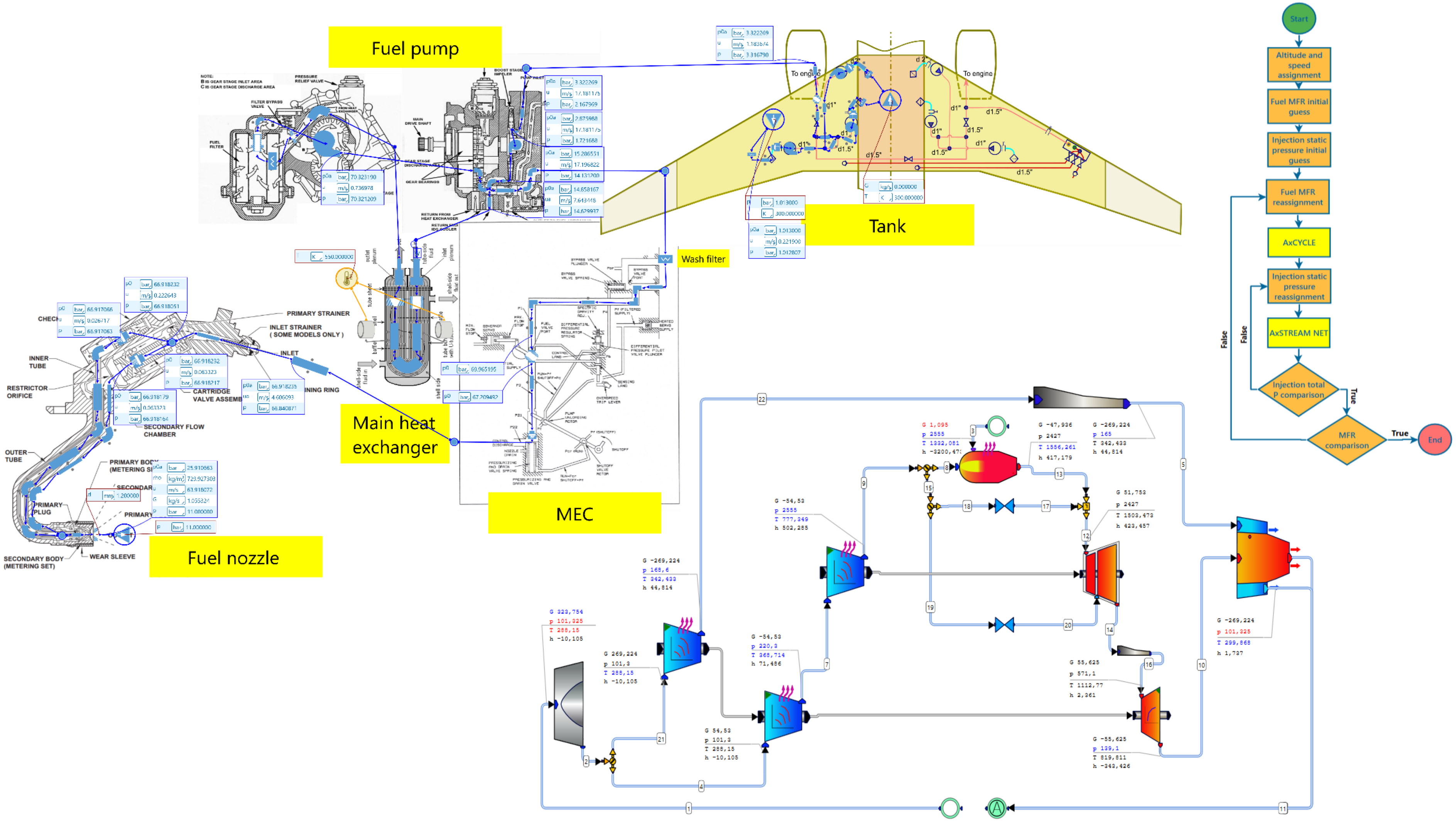
Lateral Rotor Dynamics

Torsional Modal

Torsional Transient

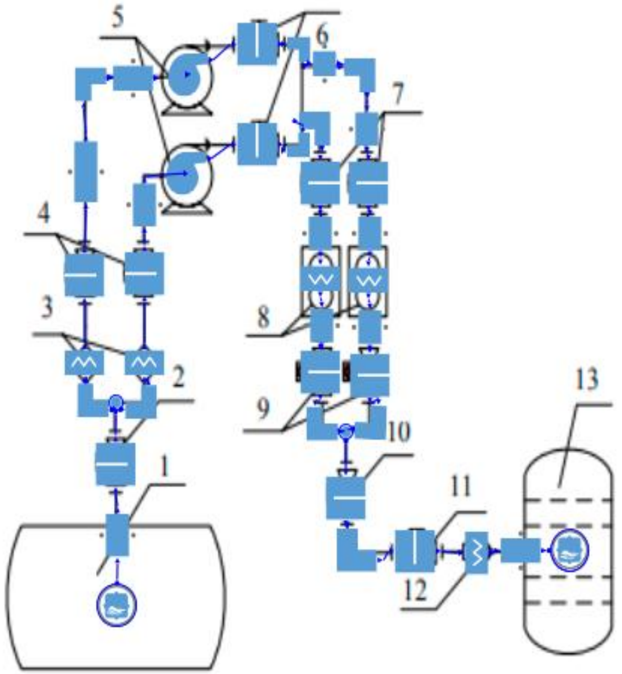
Torsional Rotor Dynamics

AIRPLANE FUEL SUPPLY SYSTEM AND PROPULSION



GROUND SYSTEM EQUIPMENT – MODELLING OF LIQUID ROCKET ENGINE PROPELLANT FEED SYSTEM

- Goal: Modelling of cryogenic fluid pipelines for liquid rocket engines filling.
- Fluid, surface, and thermal libraries contain general elements that can be used to model systems like of GSE for tank filling including but not limited to pump (with possibility of optional map setting), pipeline, fittings (elbow, curves, etc.), valves, etc.
  - Account for gravity in pipelines as well as flow level in tanks
  - Preliminary estimation of system loss of performance due to leakages and blockage
  - Evaluation of equipment’s subsystems:
    - Pumps lubrication, pump upgrade, electromotor cooling, etc.;
  - Evaluation of system pressure distribution for future stress analysis of fittings
  - Evaluation of heat transfer coefficients and temperatures in the system including sizing of heat exchangers
- Designers can perform steady and transient analysis calculations to estimate the fluid flow parameters in the entire system such as pressure levels, temperatures, flow velocities, estimate filling time, etc.
  - Transient analysis of chill down of suction pipelines and fittings before main oxidizer supply to the rocket stages:



1-Propellant Storage 2-Discharge Valve 3-Filter 4-Valve front of Pump 5-Filling Pump 6-Valve back of Pump 7-Valve front of Fluid Sensor 8-Fluid Sensor 9-Relief Valve 10 Outlet Valve 11 Inflow Valve 12-Compensator 13-Propellant Tank

Schematic of possible ground propellant filling system

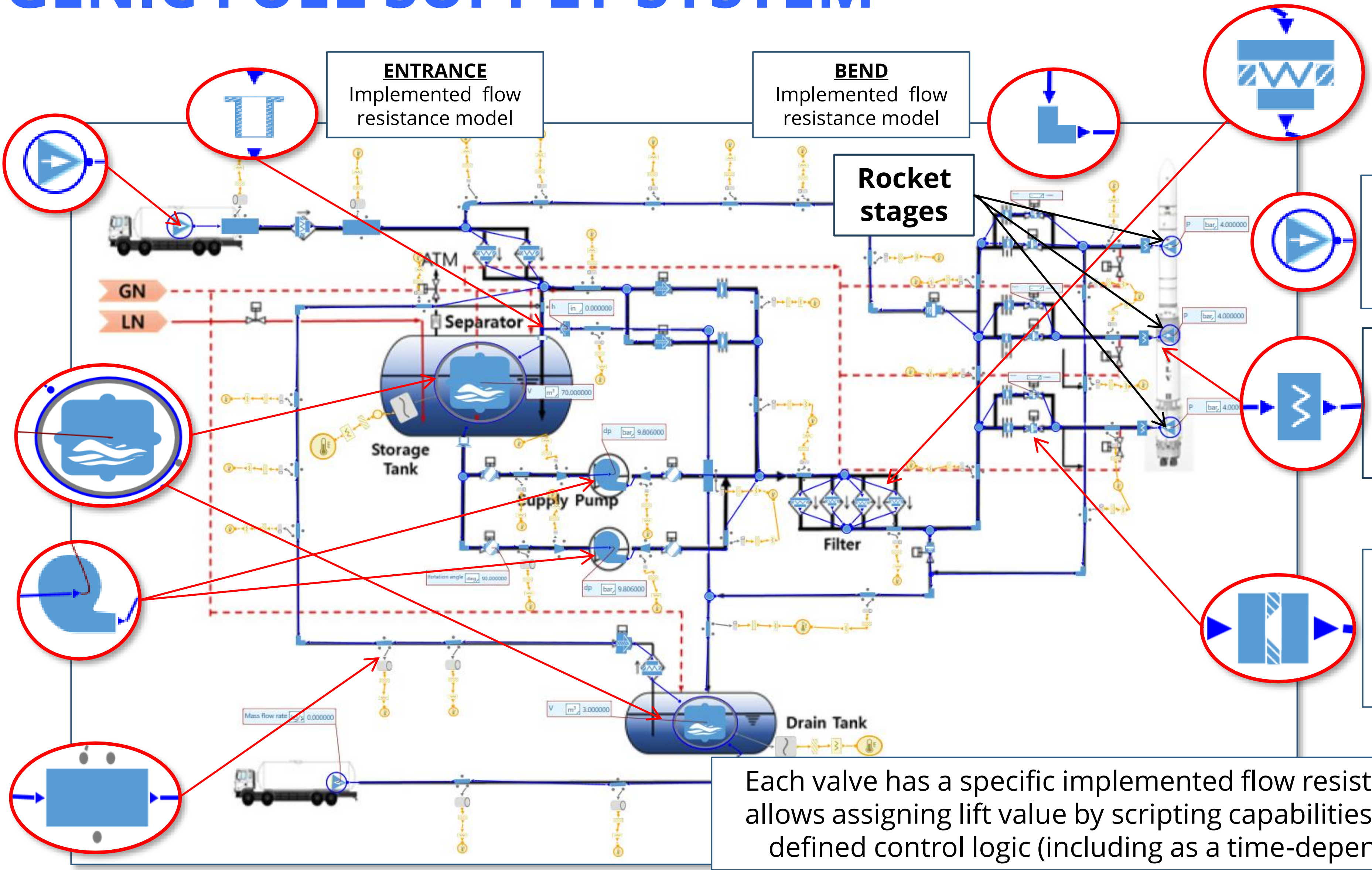
CRYOGENIC FUEL SUPPLY SYSTEM

INLET
Allows setting up inlet boundary conditions such as total pressure and temperature. The boundary conditions can be modified using script and table capabilities while performing transient analysis of the system and taking into account its changing in time.

CHAMBER
Allows modeling storage and drain tank with volume, heat sources

PUMP
Allows setting up pump pressure difference and efficiency including using performance map

PIPE
Implemented flow resistance model based on pipe geometry, roughness and flow conditions.



ENTRANCE
Implemented flow resistance model

BEND
Implemented flow resistance model

Rocket stages

FILTER
Allows assigning user-defined script using C# or Python for resistance description of filters

OUTLET
Allows setting up outlet boundary conditions - static pressure in rocket stage vessels

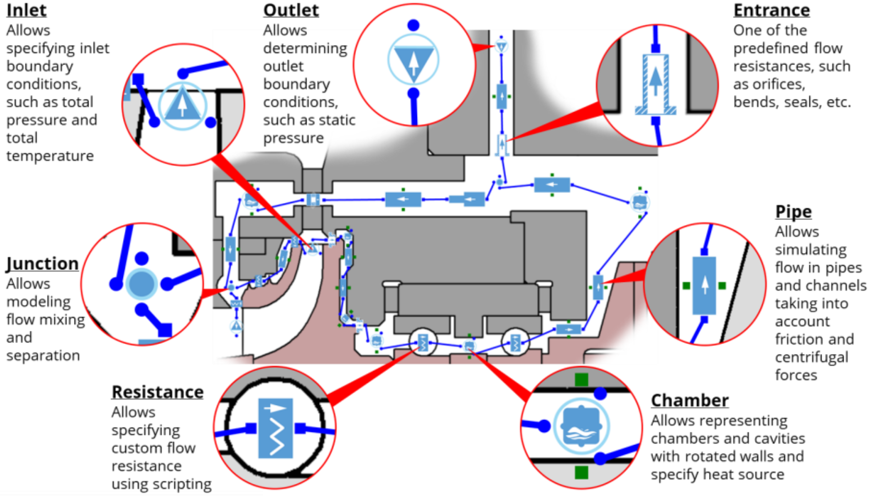
COMPENSATOR
Allows assigning user-defined script using C# or Python for resistance description of different compensators' types

ORIFICE IN STRAIGHT CONDUIT
Implemented flow resistance model for throttle orifice modeling

Each valve has a specific implemented flow resistance model which allows assigning lift value by scripting capabilities according to user-defined control logic (including as a time-dependent parameter)

TURBOPUMP SECONDARY FLOW MODELLING

- ➢ <u>Goal:</u> Creation of digital sibling of turbopump secondary flow in order to determine leakages, seals, flow swirl, pressure losses, heat transfer, axial loads, etc. in turbopump along with calculation of buffer fluid minimum pressure to ensure safe operation



Inlet
Allows specifying inlet boundary conditions, such as total pressure and total temperature

Outlet
Allows determining outlet boundary conditions, such as static pressure

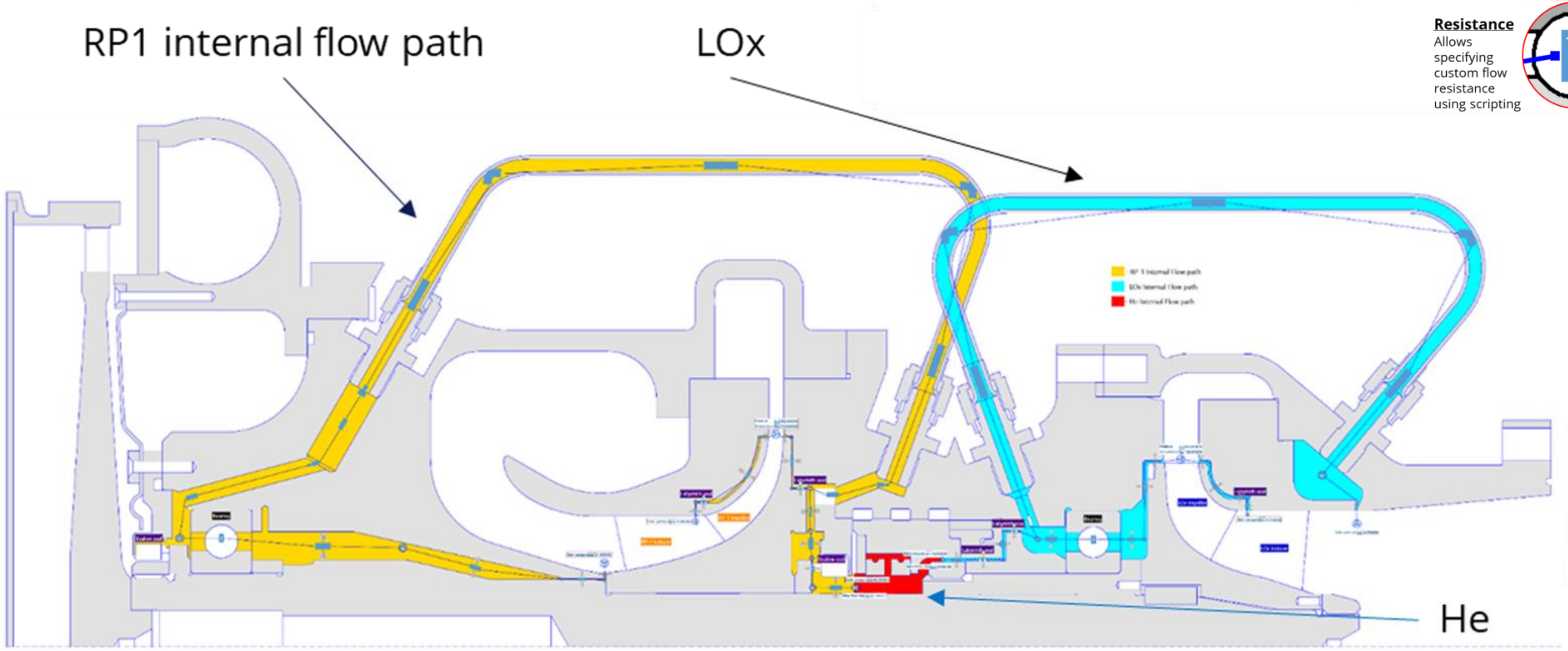
Entrance
One of the predefined flow resistances, such as orifices, bends, seals, etc.

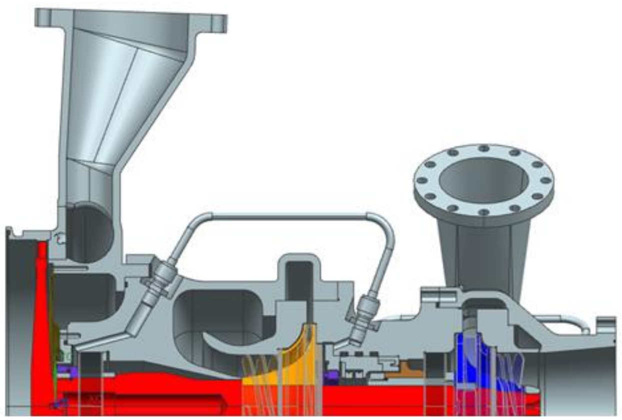
Junction
Allows modeling flow mixing and separation

Pipe
Allows simulating flow in pipes and channels taking into account friction and centrifugal forces

Resistance
Allows specifying custom flow resistance using scripting

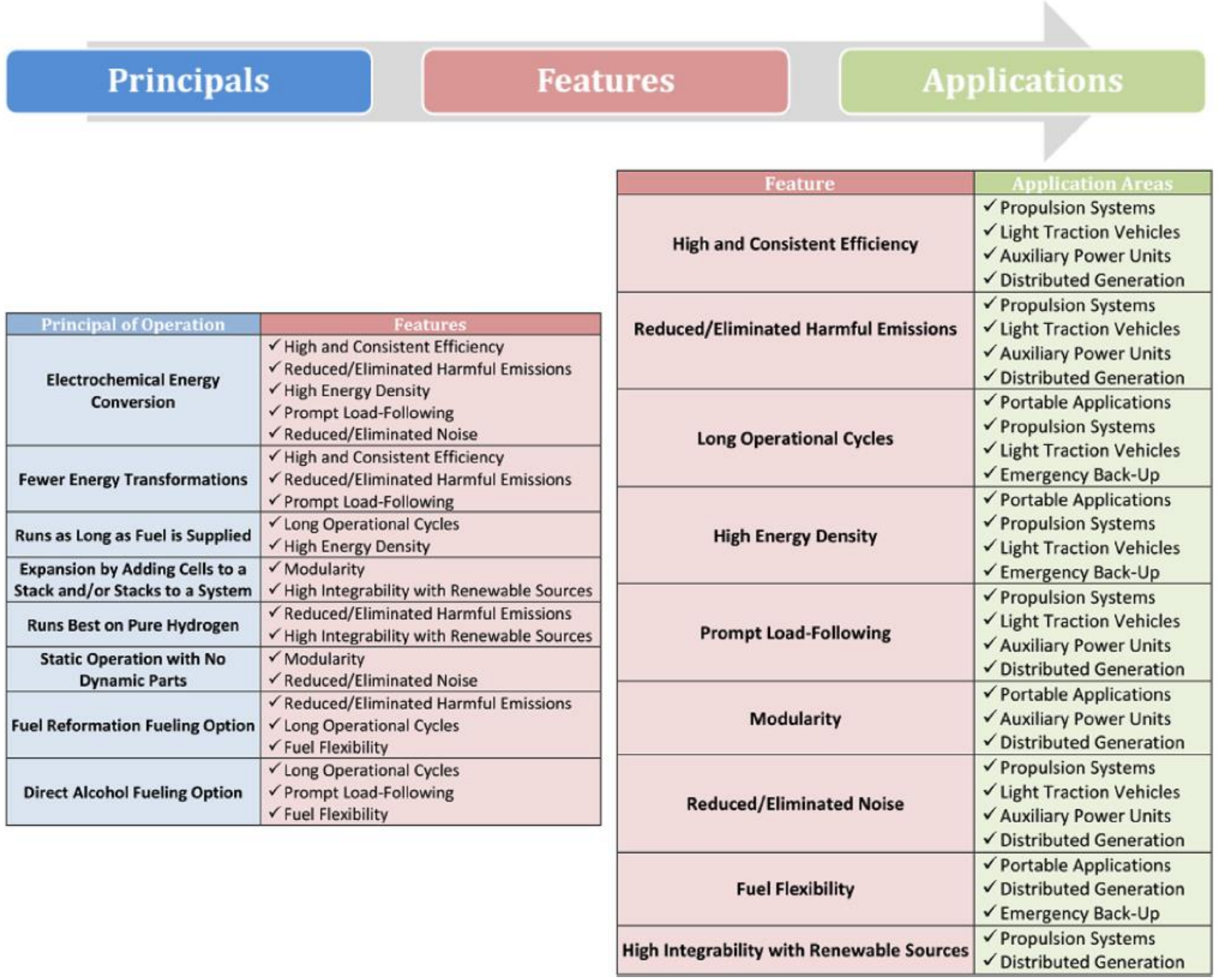
Chamber
Allows representing chambers and cavities with rotated walls and specify heat source





3. Applications & Examples

PRINCIPAL OF OPERATION, FEATURES AND APPLICATIONS OF FUEL CELLS



Principal of Operation	Features
Electrochemical Energy Conversion	✓ High and Consistent Efficiency ✓ Reduced/Eliminated Harmful Emissions ✓ High Energy Density ✓ Prompt Load-Following ✓ Reduced/Eliminated Noise
Fewer Energy Transformations	✓ High and Consistent Efficiency ✓ Reduced/Eliminated Harmful Emissions ✓ Prompt Load-Following
Runs as Long as Fuel is Supplied	✓ Long Operational Cycles ✓ High Energy Density
Expansion by Adding Cells to a Stack and/or Stacks to a System	✓ Modularity ✓ High Integrability with Renewable Sources
Runs Best on Pure Hydrogen	✓ Reduced/Eliminated Harmful Emissions ✓ High Integrability with Renewable Sources
Static Operation with No Dynamic Parts	✓ Modularity ✓ Reduced/Eliminated Noise
Fuel Reformation Fueling Option	✓ Reduced/Eliminated Harmful Emissions ✓ Long Operational Cycles ✓ Fuel Flexibility
Direct Alcohol Fueling Option	✓ Long Operational Cycles ✓ Prompt Load-Following ✓ Fuel Flexibility

Feature	Application Areas
High and Consistent Efficiency	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Reduced/Eliminated Harmful Emissions	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Long Operational Cycles	✓ Portable Applications ✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Emergency Back-Up
High Energy Density	✓ Portable Applications ✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Emergency Back-Up
Prompt Load-Following	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Modularity	✓ Portable Applications ✓ Auxiliary Power Units ✓ Distributed Generation
Reduced/Eliminated Noise	✓ Propulsion Systems ✓ Light Traction Vehicles ✓ Auxiliary Power Units ✓ Distributed Generation
Fuel Flexibility	✓ Portable Applications ✓ Distributed Generation ✓ Emergency Back-Up
High Integrability with Renewable Sources	✓ Propulsion Systems ✓ Distributed Generation

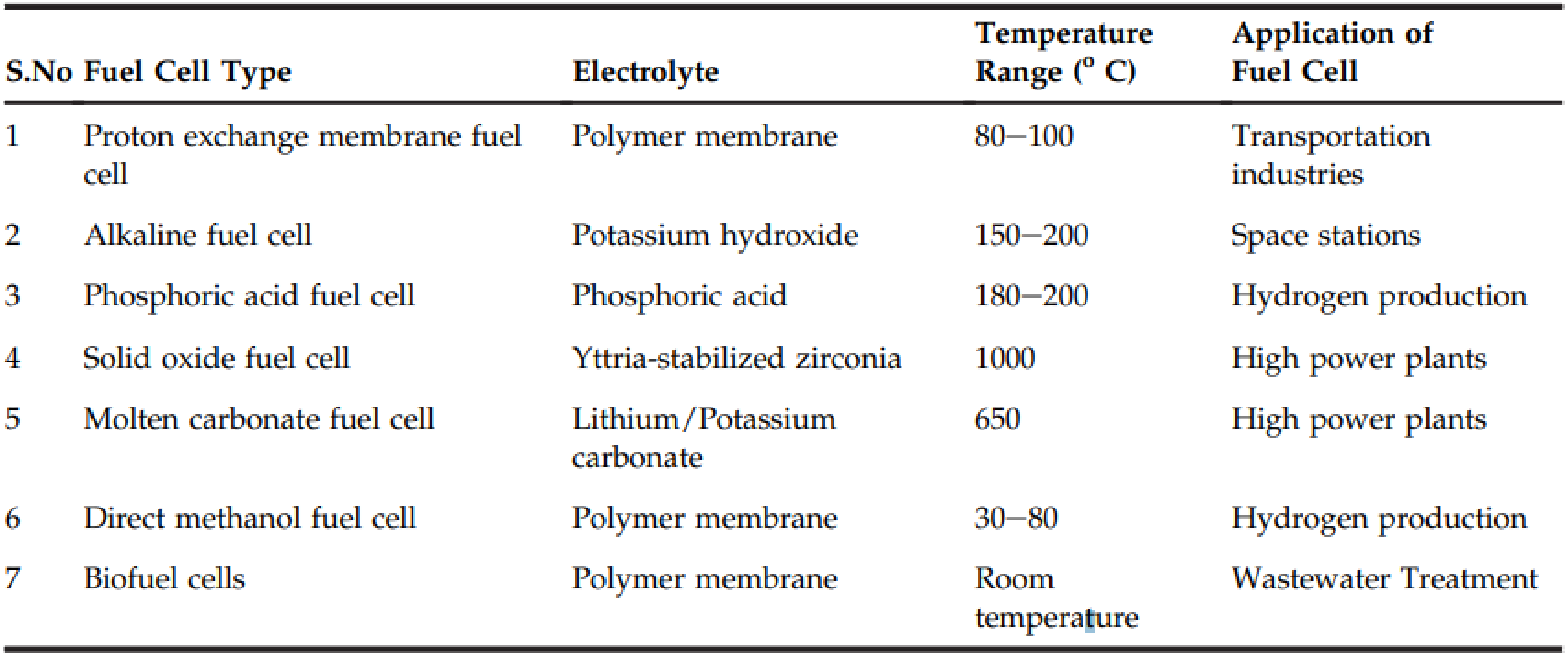
Outline of the relations between a fuel cell’s principals of operation, advantages and features, and main areas of applications
O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

FUEL CELL APPLICATIONS

Fuel Cell

- Automotive
  - Automobile
  - Bus
  - Forklift
  - Motorcycle
  - Bicycle
- Airplane
  - Propeller-driven airplane
  - UAV (drone)
- Marine
  - Boats
  - Submarine
- Power system
  - Power plant
  - Emergency power system
  - Uninterrupted power supply
  - Small heating appliances

TYPICAL APPLICATION PER FUEL CELL TYPE



S.No	Fuel Cell Type	Electrolyte	Temperature Range (^{o} C)	Application of Fuel Cell
1	Proton exchange membrane fuel cell	Polymer membrane	80–100	Transportation industries
2	Alkaline fuel cell	Potassium hydroxide	150–200	Space stations
3	Phosphoric acid fuel cell	Phosphoric acid	180–200	Hydrogen production
4	Solid oxide fuel cell	Yttria-stabilized zirconia	1000	High power plants
5	Molten carbonate fuel cell	Lithium/Potassium carbonate	650	High power plants
6	Direct methanol fuel cell	Polymer membrane	30–80	Hydrogen production
7	Biofuel cells	Polymer membrane	Room temperature	Wastewater Treatment

3.1 Stationary Power Generation

STATIONARY POWER GENERATION USES

- Fuel cells can play an integral part in the residential, commercial, and industrial stationary power generation sectors.
  - Stationary fuel cells market accounts for about 70% of the annual fuel cell shipments on a MW-level

- Utilized for both grid-independent (AKA stand-alone) and grid-assisted power supply.

- Stationary fuel cell applications include:

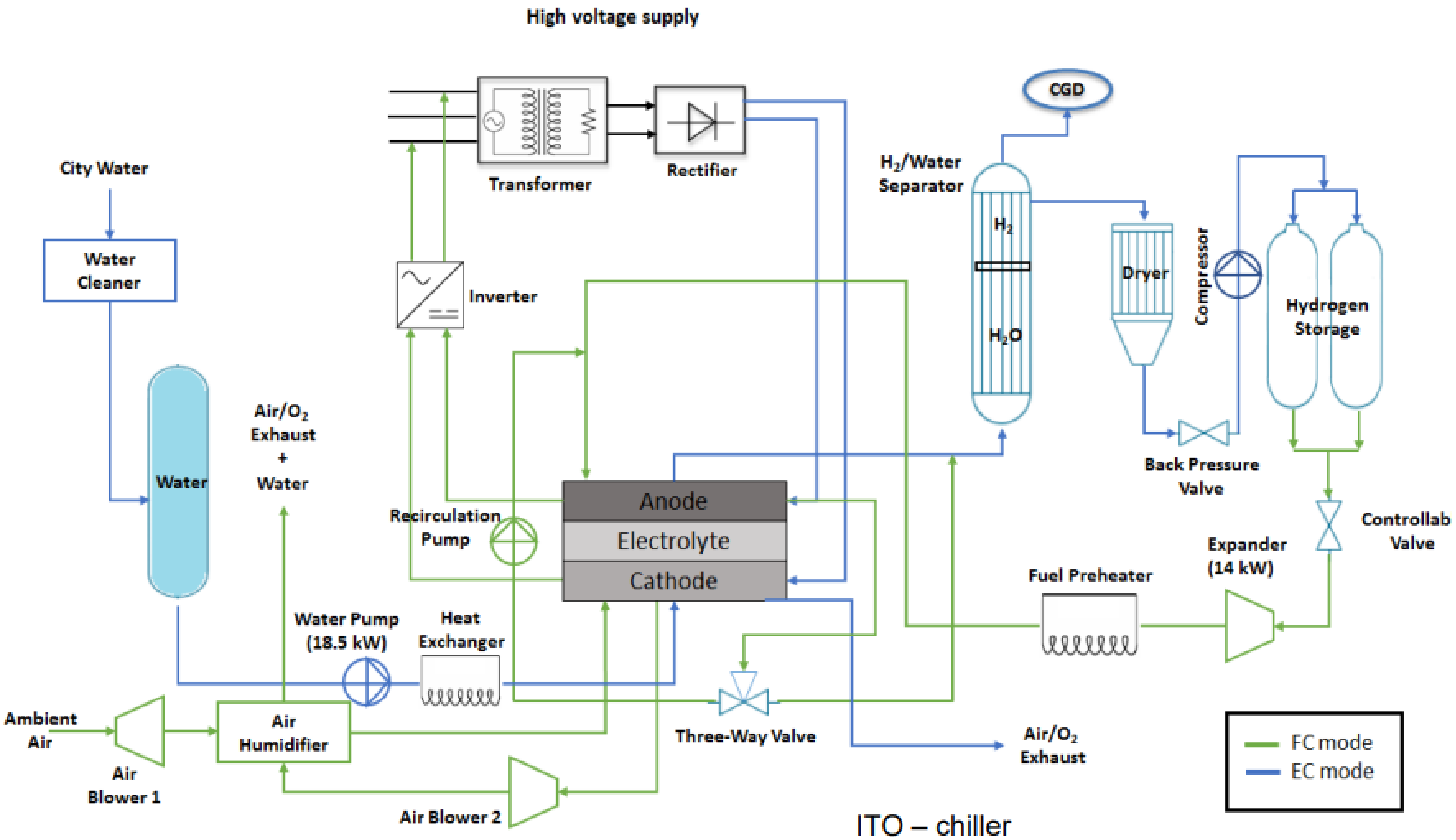
- Emergency back-up power supply (EPS) | AKA Uninterrupted power supply (UPS)
  - FCs becoming attractive (especially in the telecommunications market) vs. batteries due to:
    - High energy and power densities, high modularity, longer operation times (2–10 times longer vs. current lead-acid batteries), compact size, and ability to operate under harsh ambient conditions
    - **PEMFCs** and **DMFCs** dominantly-chosen fuel cell types
    - Other fuel cell EPS markets include hospitals, data centers, banks, and government agencies where continuous power supply (~2-8 kW) is critical when grid power is unavailable

STATIONARY POWER GENERATION USES

- Remote-area power supply (RAPS)
    - In grid-isolated locations, (islands, deserts, forests, remote technical installations, holiday retreats, and remote research facilities) providing power could be problematic.
        - Usually, more economical to deploy RAPS solutions vs. extend electric grid power lines.
    - Most common RAPS solution is diesel engines (high carbon footprints and noisy operation)
        - Delivering of natural gas or hydrocarbon fuels through pipelines or other means makes this alternative less appealing for rural and remote locations.
        - Hybrid and integrated energy systems that couple a renewable energy source (such as hydro, biomass, solar, wind, etc.), depending on available natural resources, with a storage mechanism (lead-acid batteries, lithium-ion batteries, hydrogen systems, etc.) provide a more sustainable and autonomous solution for RAPS.

- Distributed power/CHP generation
    - FC may allow shift from large centralized power generation to decentralized distributed generation.
    - Few kW-Few MW for residential CHP FC system to provide electric power, space heating, and domestic water heating requirements.
        - Cooling could also be added to power generation and heating (known as combined cooling, heating, and power (CCHP) systems) if an absorption chiller, thermally- driven heat pump, or an appropriate technique is integrated with the system to utilize the waste heat of the fuel cell stack in a dual-mode heating/cooling cycle

FUEL CELL – EXAMPLE OF SYSTEM 250 KW

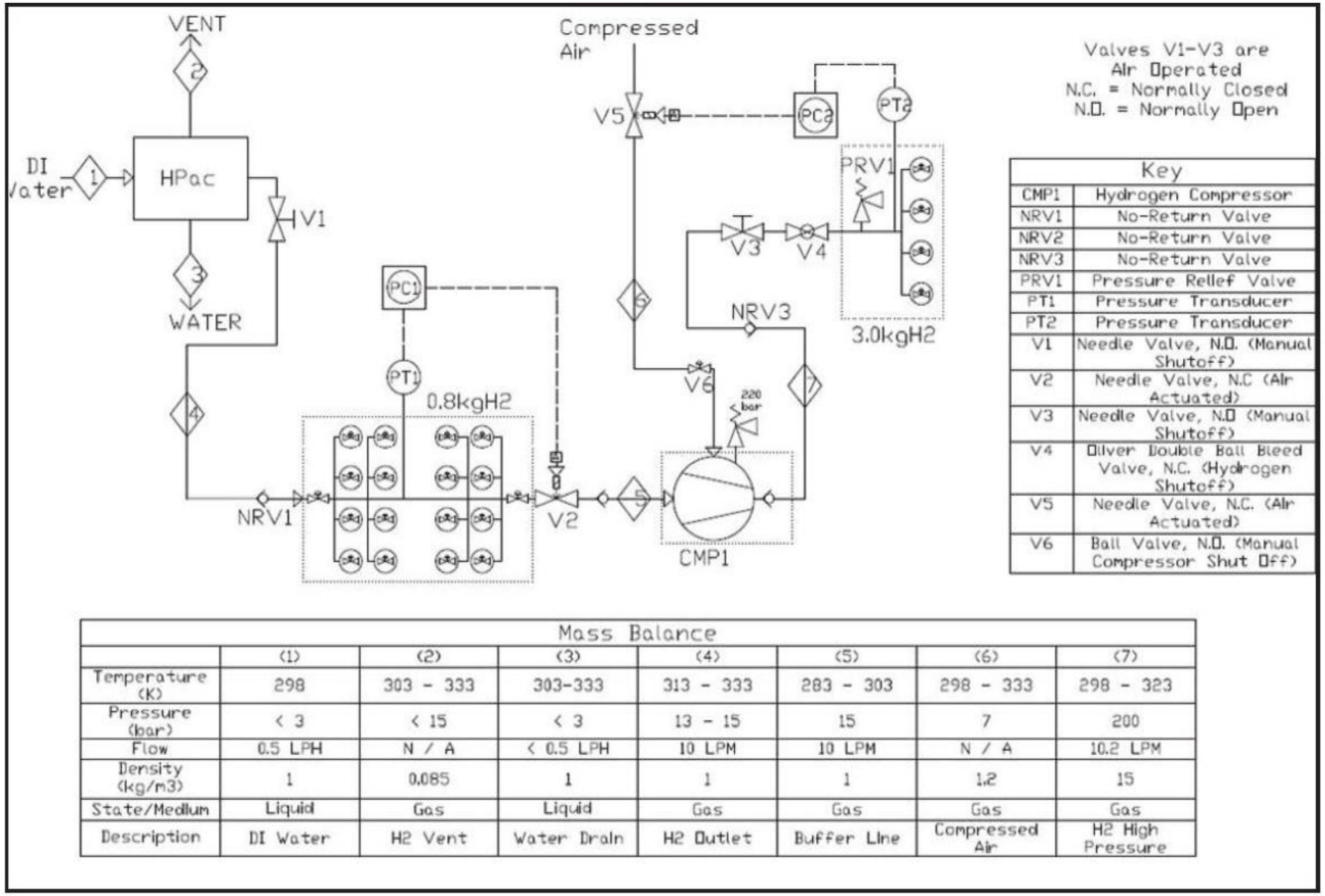


ITO – chiller

O2/ water separator – H2O circulation loop

Reversible Fuel Cell Cost Analysis (energy.gov)

ON-SITE HYDROGEN PRODUCTION FOR HYDROGEN FUEL CELL VEHICLE REFUELING STATION



Valves V1-V3 are Air Operated
N.C. = Normally Closed
N.O. = Normally Open

Key	
CMP1	Hydrogen Compressor
NRV1	No-Return Valve
NRV2	No-Return Valve
NRV3	No-Return Valve
PRV1	Pressure Relief Valve
PT1	Pressure Transducer
PT2	Pressure Transducer
V1	Needle Valve, N.O. (Manual Shutoff)
V2	Needle Valve, N.C (Air Actuated)
V3	Needle Valve, N.O (Manual Shutoff)
V4	Oliver Double Ball Bleed Valve, N.C. (Hydrogen Shutoff)
V5	Needle Valve, N.C. (Air Actuated)
V6	Ball Valve, N.O. (Manual Compressor Shut Off)

Mass Balance

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Temperature (K)	298	303 - 333	303-333	313 - 333	283 - 303	298 - 333	298 - 323
Pressure (bar)	< 3	< 15	< 3	13 - 15	15	7	200
Flow	0.5 LPH	N / A	< 0.5 LPH	10 LPM	10 LPM	N / A	10.2 LPM
Density (kg/m3)	1	0.085	1	1	1	1.2	15
State/Medium	Liquid	Gas	Liquid	Gas	Gas	Gas	Gas
Description	DI Water	H2 Vent	Water Drain	H2 Outlet	Buffer Line	Compressed Air	H2 High Pressure

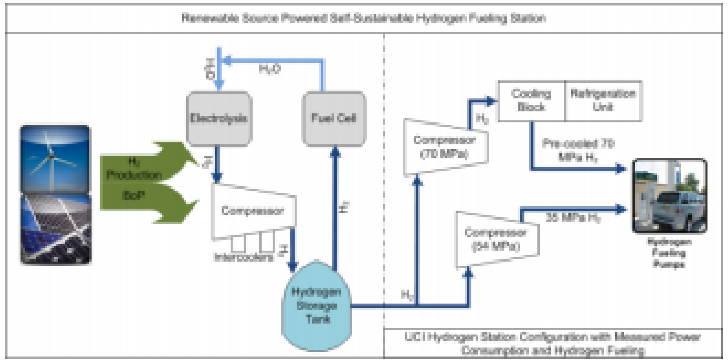
- **System Components:**
  - *Photovoltaic Cells*
  - *DI Water Supply*
  - *Electrolyser – HPac10*
  - *Buffer Storage*
  - *Hydrogen Compressor*
  - *High Pressure Storage*

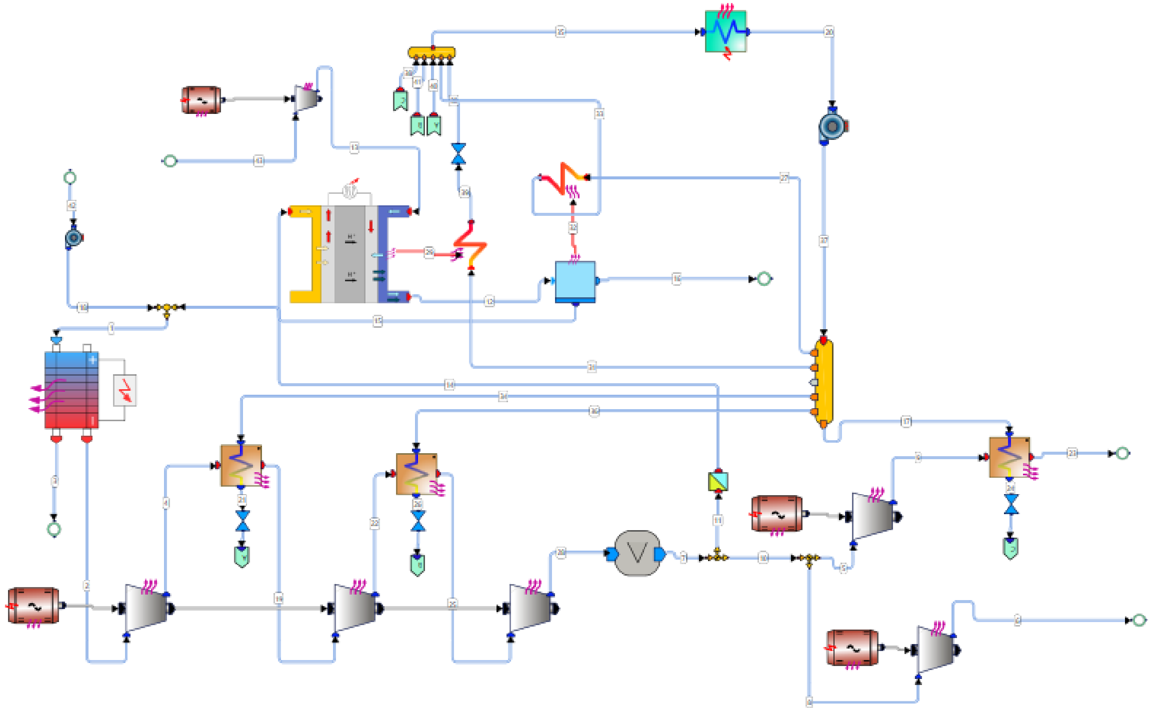
HPac10 Electrolyser

Design for On-Site Hydrogen Production for Hydrogen Fuel Cell Vehicle Refueling Station at University of Birmingham, U.K. - ScienceDirect

SIMULATION OF FUEL CELL-BASED SYSTEMS

- <u>Goal:</u> Simulation of self-sustained hydrogen fueling station concept using renewable resources:
  - Electrolyzer
  - Fuel cell (PEM)*
  - Wind turbines for electrolyzer power
  - Hydrogen compressor & storage tank
  - Refrigeration unit

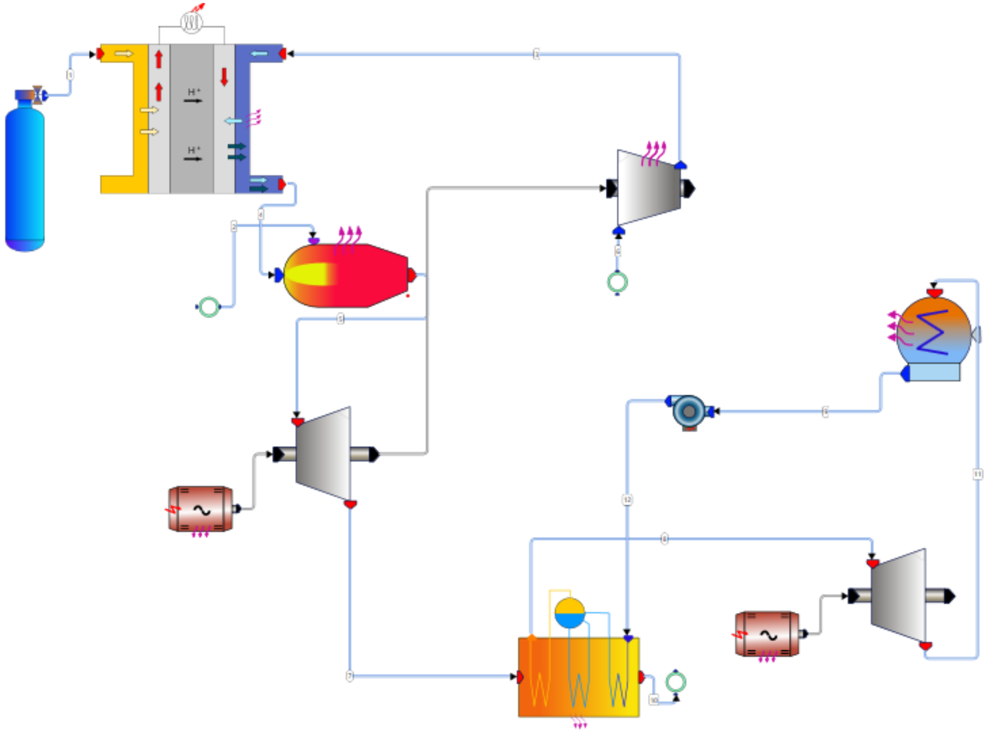




Example of public hydrogen fueling station configuration of UC Irvine is utilized in the model, with 35 MPa and 70 MPa fueling and a refrigeration unit.

TRIPLE COMBINED CYCLE POWER GENERATION SYSTEM

- Example of a high-performance (70% LHV) 3-tiered combined cycle for power generation (FCCC – Fuel Cell Combined Cycle)
  - Solid oxide fuel cells (SOFC)
  - Gas turbine combined cycle (GTCC using natural gas)

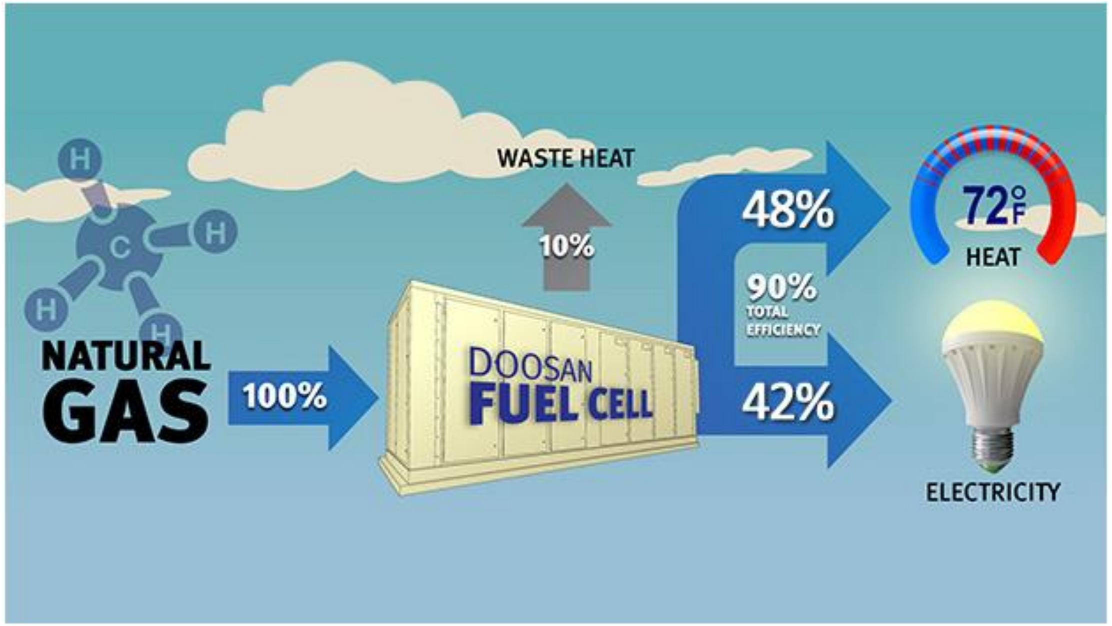


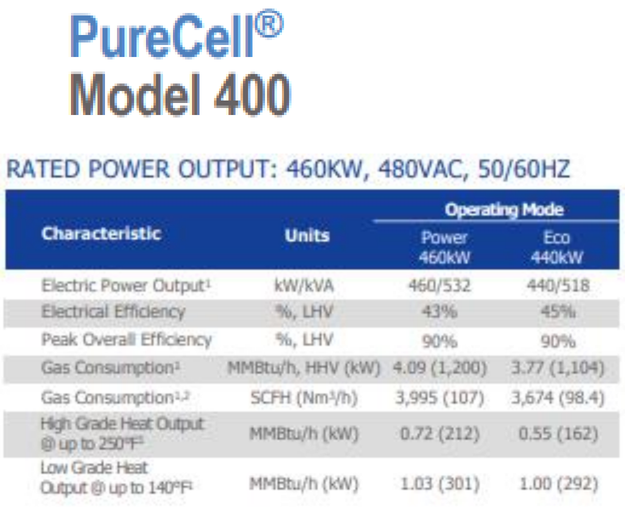
https://www.greencarcongress.com/2012/06/mhi-20120601.html

HANWHA ENERGY. HYDROGEN-FUEL-CELL POWER PLANT

50 MW of hydrogen fuel cells - https://www.hanwha.com/en/news_and_media/press_release/hanwha-energy-celebrates-its-completion-of-the-worlds-first-and-largest-byproduct-hydrogen-fuel-cell-power-plant.html

ENERGY PRODUCTION USING FUEL CELLS





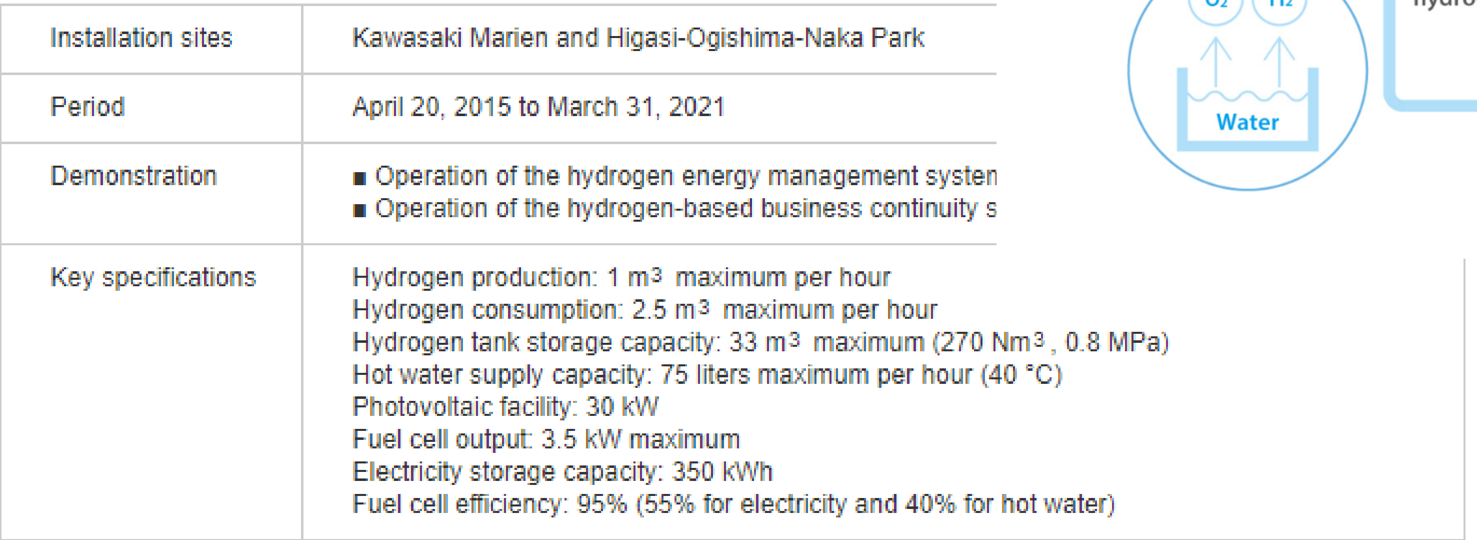
PureCell®
Model 400

RATED POWER OUTPUT: 460KW, 480VAC, 50/60HZ

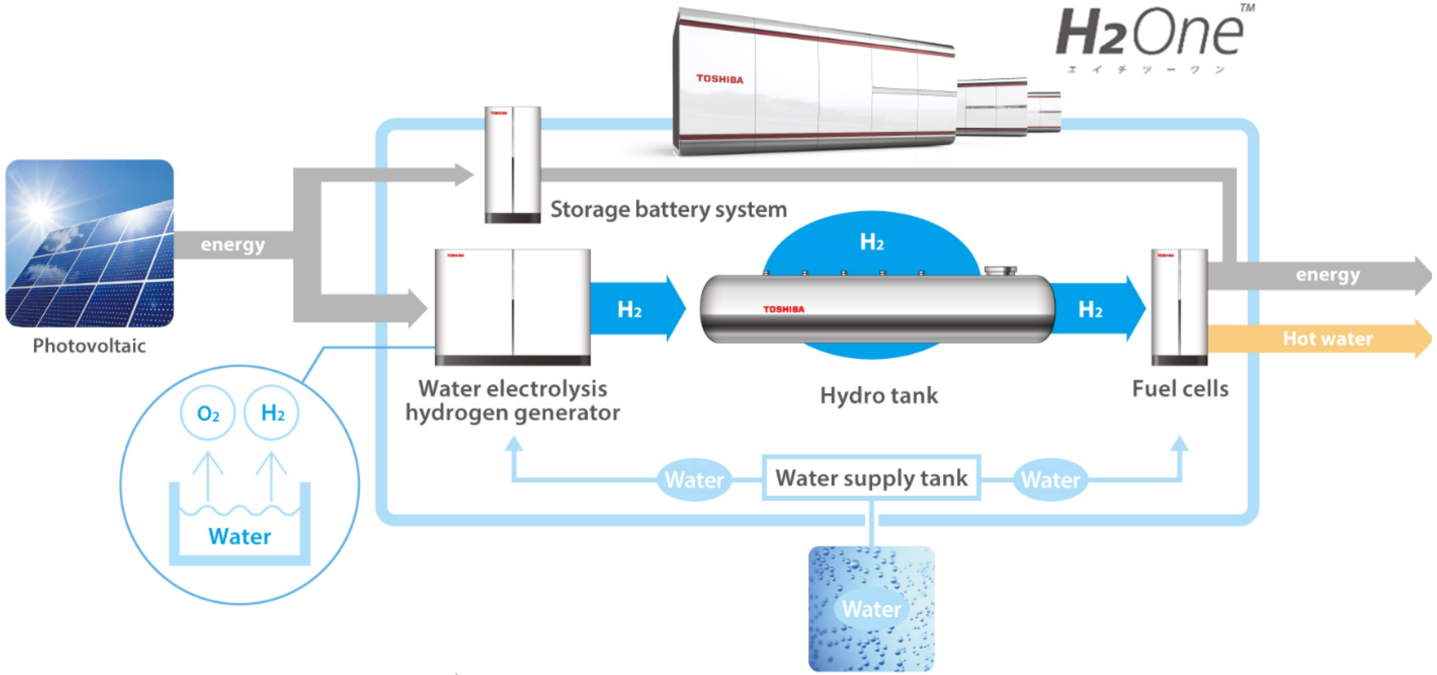
Characteristic	Units	Operating Mode	
		Power 460kW	Eco 440kW
Electric Power Output[1]	kW/kVA	460/532	440/518
Electrical Efficiency	%, LHV	43%	45%
Peak Overall Efficiency	%, LHV	90%	90%
Gas Consumption[1]	MMBtu/h, HHV (kW)	4.09 (1,200)	3.77 (1,104)
Gas Consumption[1,2]	SCFH (Nm^3/h)	3,995 (107)	3,674 (98.4)
High Grade Heat Output @ up to 250°F[3]	MMBtu/h (kW)	0.72 (212)	0.55 (162)
Low Grade Heat Output @ up to 140°F[3]	MMBtu/h (kW)	1.03 (301)	1.00 (292)

http://www.doosanfuelcellamerica.com/en/fuel-cell-solutions/combined-cooling-heat-and-power/

ENERGY PRODUCTION USING FUEL CELLS

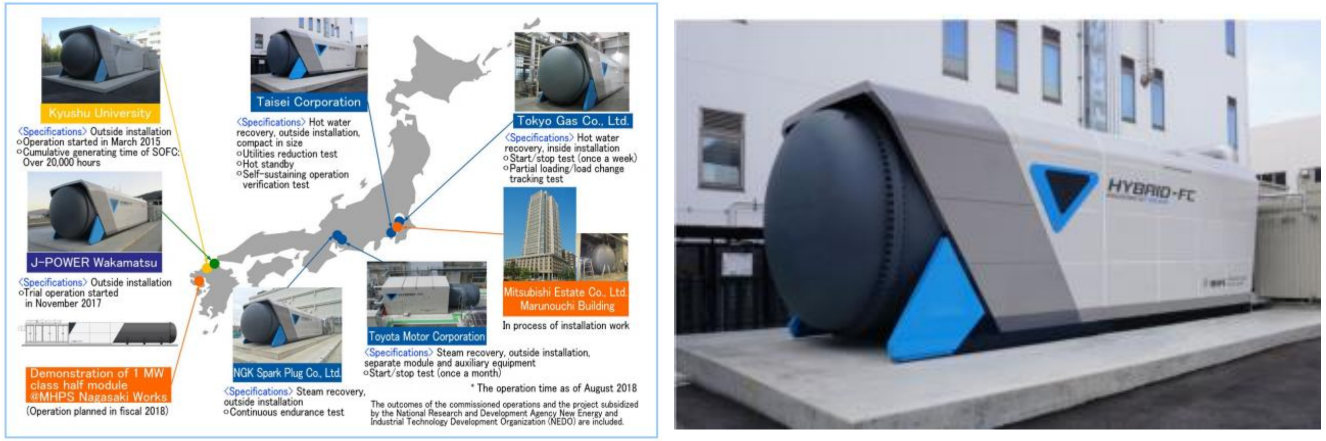


Installation sites	Kawasaki Marien and Higasi-Ogishima-Naka Park
Period	April 20, 2015 to March 31, 2021
Demonstration	■ Operation of the hydrogen energy management systen ■ Operation of the hydrogen-based business continuity s
Key specifications	Hydrogen production: 1 m^3 maximum per hour Hydrogen consumption: 2.5 m^3 maximum per hour Hydrogen tank storage capacity: 33 m^3 maximum (270 Nm^3, 0.8 MPa) Hot water supply capacity: 75 liters maximum per hour (40 °C) Photovoltaic facility: 30 kW Fuel cell output: 3.5 kW maximum Electricity storage capacity: 350 kWh Fuel cell efficiency: 95% (55% for electricity and 40% for hot water)

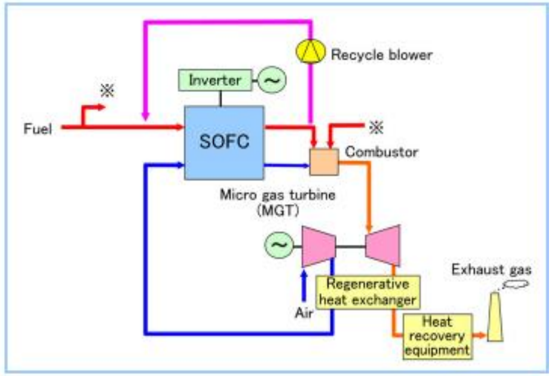


https://www.toshiba-energy.com/en/hydrogen/product/fuel-cell.htm

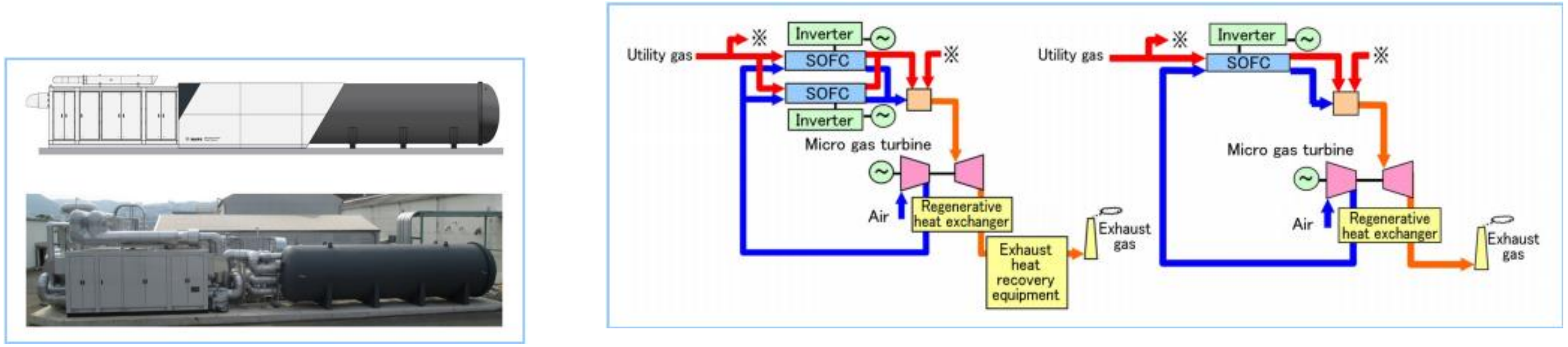
HYBRID SYSTEM OF SOLID OXIDE FUEL CELLS (SOFC) AND MICRO GAS TURBINES (MGT)



Operation and planning status for the fuel cell SOFC



Hybrid system 250 kW class



Hybrid system 1 MW class

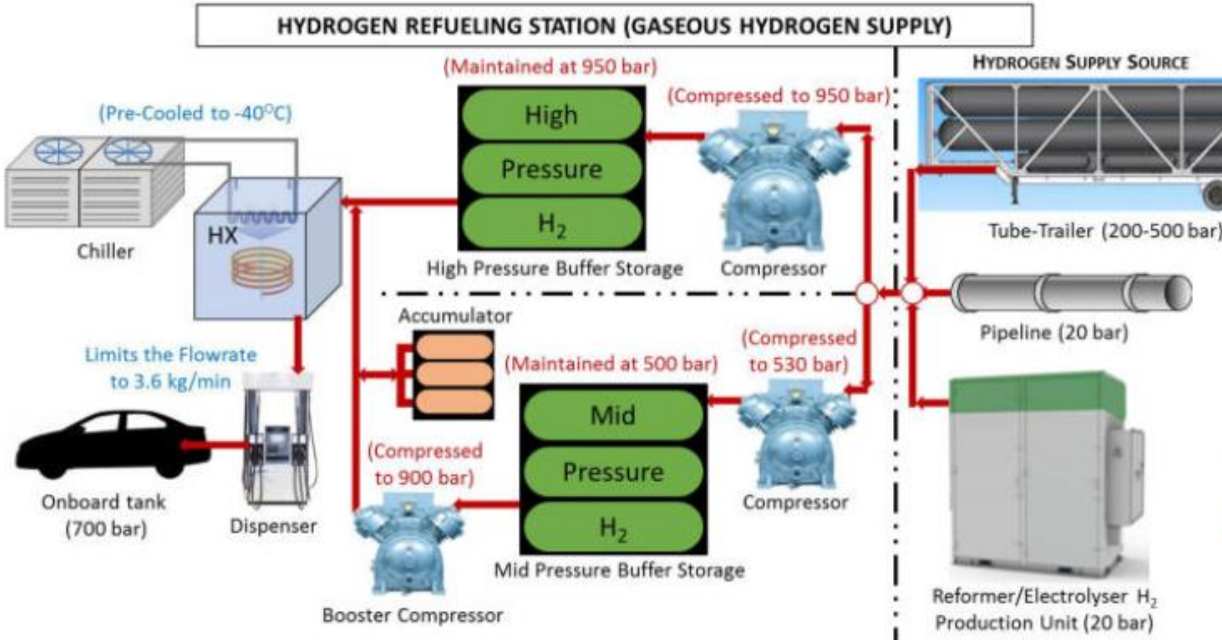
Efforts toward Introduction of SOFC-MGT Hybrid System to the Market KAZUO TOMIDA, KIMI KODO, DAIGO KOBAYASHI, YOSHIKI KATO, SHIGENORI SUEMORI, YASUTAKA URASHITA.- Mitsubishi Heavy Industries Technical Review Vol. 55 No. 4 (December 2018)

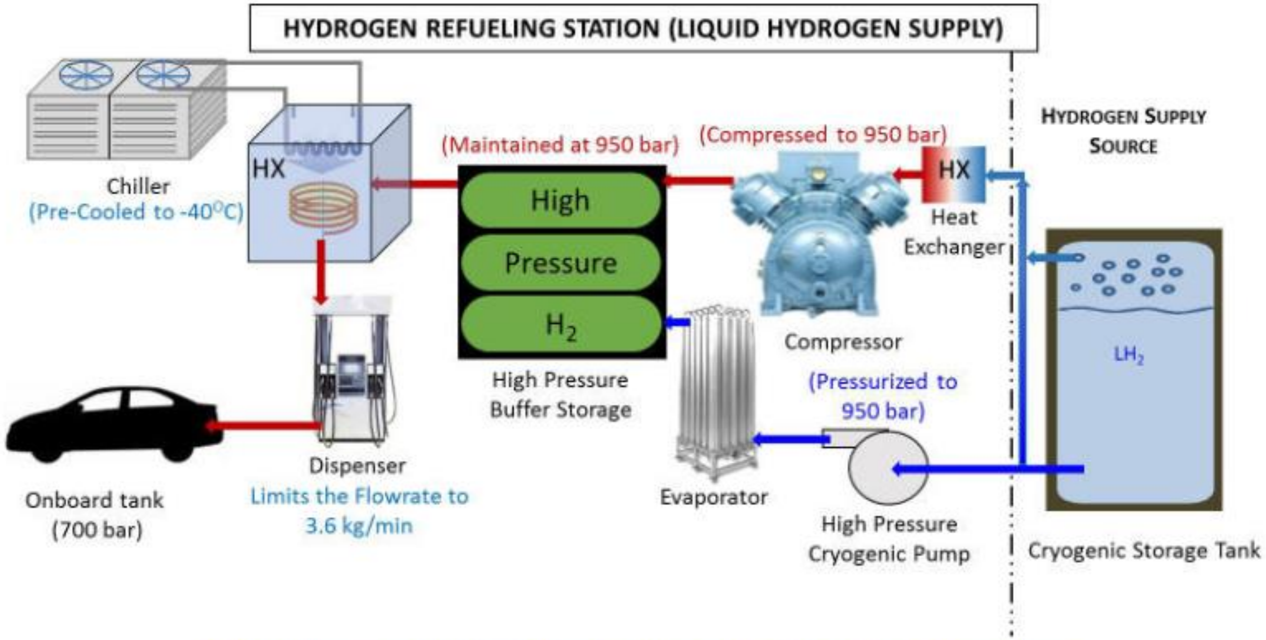
HYBRID SYSTEM OF SOLID OXIDE FUEL CELLS (SOFC) AND MICRO GAS TURBINES (MGT)

Concept of Siemens-Westinghouse.

Fuel Cells Fundamentals and Applications.- L. Carrette, K. A. Friedrich U. Stimming.-FUEL CELLS 2001, 1, No. 1.-pp39 - https://www.comsos.eu/com18/com18-cont/uploads/2018/07/POLITO-comsos-brochure-giugno2018-5digitale.pdf

GASEOUS HYDROGEN REFUELLING STATIONS





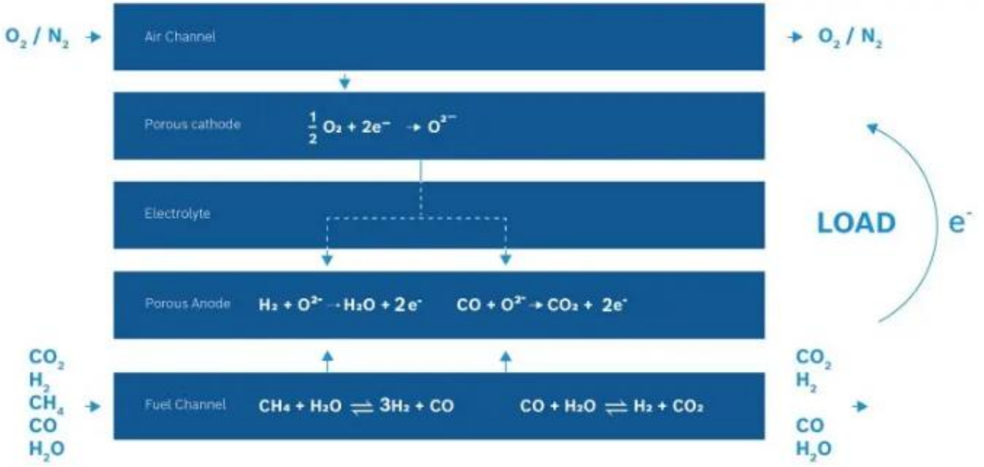
Schematic representation of liquid hydrogen refueling station configurations

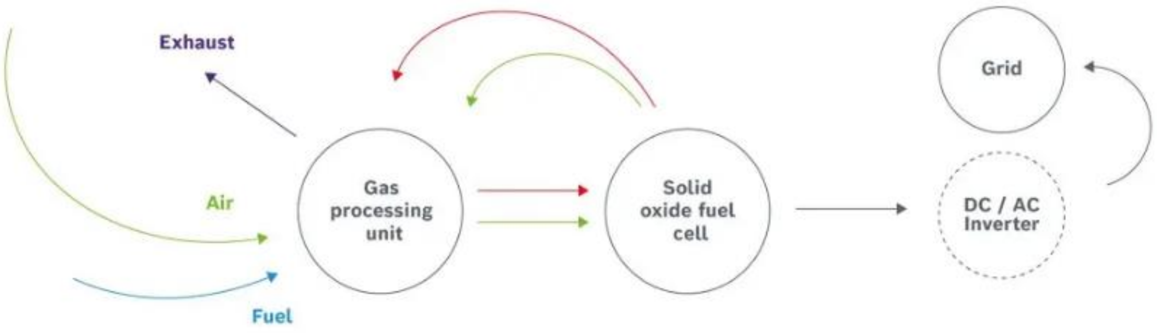
Schematic representation of gaseous hydrogen refueling station configurations (anl.gov)

ENERGY-EFFICIENT INTO THE FUTURE – STATIONARY FUEL CELL SYSTEM BY BOSCH

High-temperature fuel cell systems

BOSCH





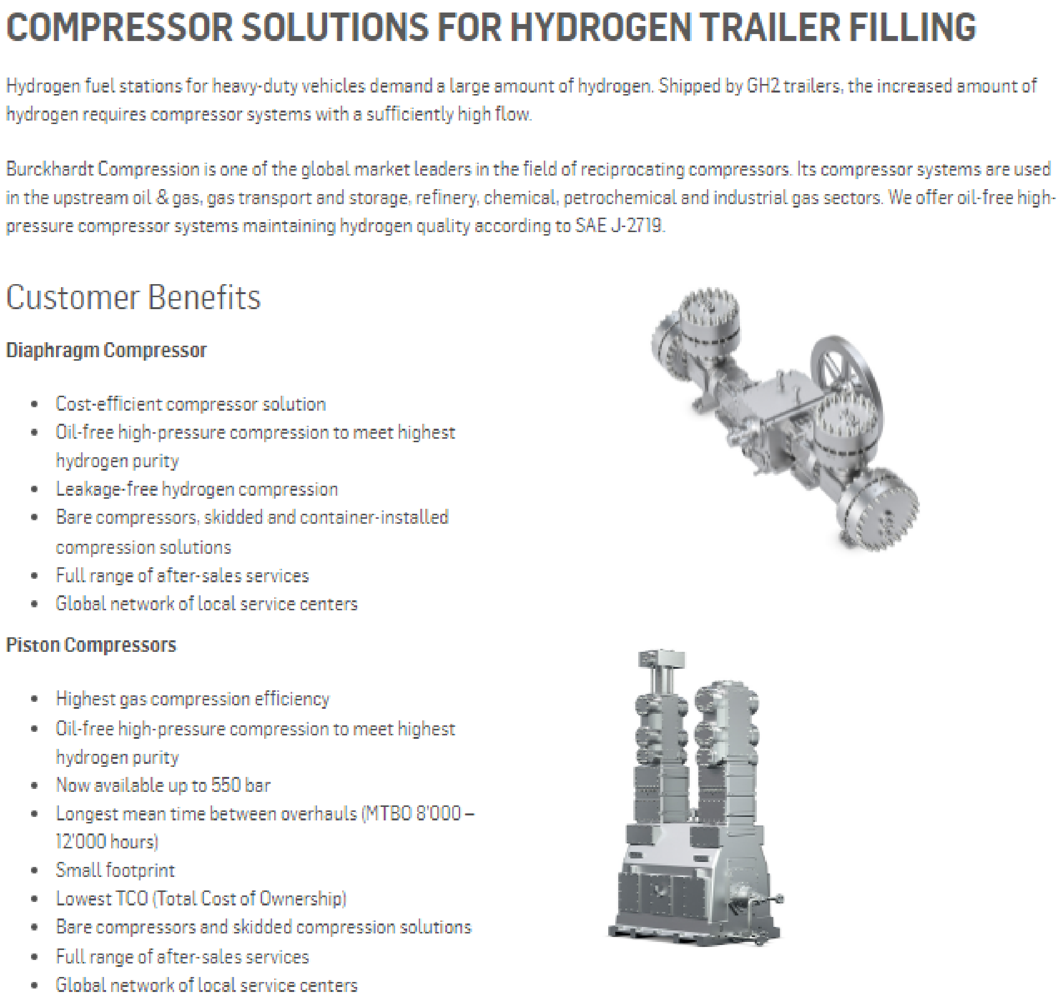
Unique features of the SOFC system

Transformation towards H_2

Local, decentralized & demand-driven

Use of existing gas infrastructure

THE FUTURE OF HYDROGEN AND REQUIRED COMPRESSOR SOLUTIONS, BURCKHARDT COMPRESSION



COMPRESSOR SOLUTIONS FOR HYDROGEN TRAILER FILLING

Hydrogen fuel stations for heavy-duty vehicles demand a large amount of hydrogen. Shipped by GH2 trailers, the increased amount of hydrogen requires compressor systems with a sufficiently high flow.

Burckhardt Compression is one of the global market leaders in the field of reciprocating compressors. Its compressor systems are used in the upstream oil & gas, gas transport and storage, refinery, chemical, petrochemical and industrial gas sectors. We offer oil-free high-pressure compressor systems maintaining hydrogen quality according to SAE J-2719.

Customer Benefits

Diaphragm Compressor

- Cost-efficient compressor solution
- Oil-free high-pressure compression to meet highest hydrogen purity
- Leakage-free hydrogen compression
- Bare compressors, skidded and container-installed compression solutions
- Full range of after-sales services
- Global network of local service centers

Piston Compressors

- Highest gas compression efficiency
- Oil-free high-pressure compression to meet highest hydrogen purity
- Now available up to 550 bar
- Longest mean time between overhauls (MTBO 8'000 – 12'000 hours)
- Small footprint
- Lowest TCO (Total Cost of Ownership)
- Bare compressors and skidded compression solutions
- Full range of after-sales services
- Global network of local service centers

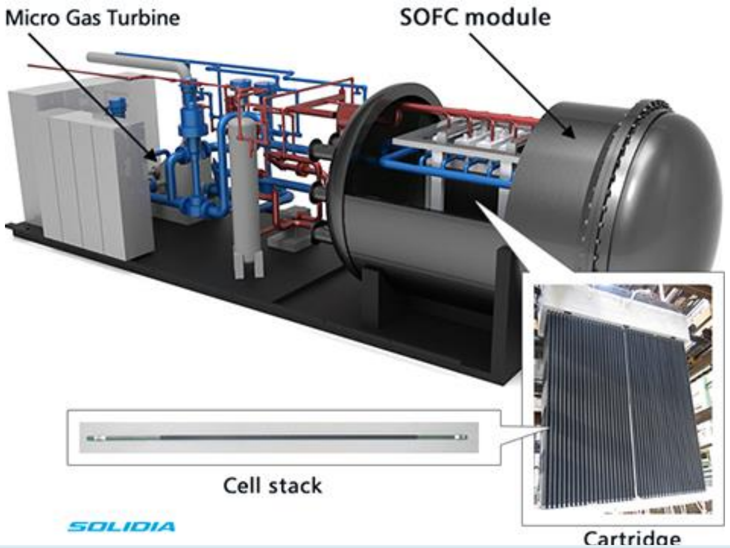
Choose an application below to get more detailed information

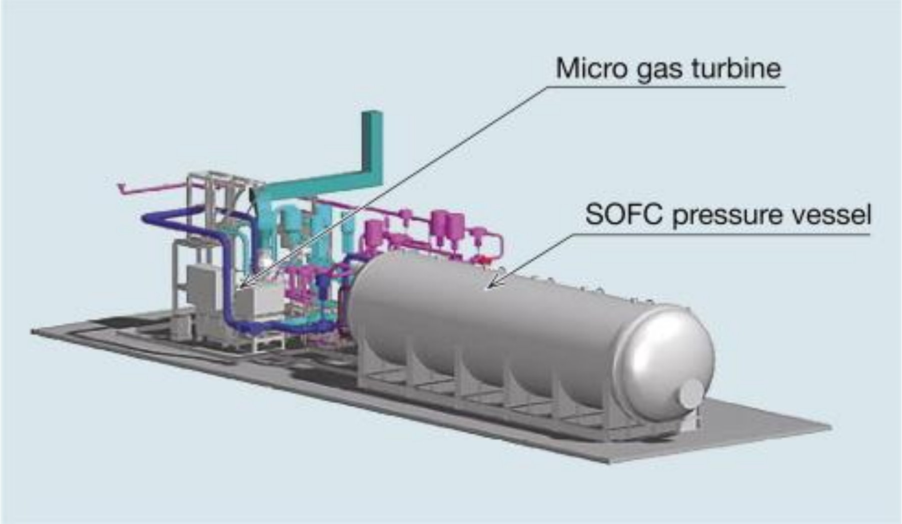
H_2 Fuel Stations

H_2 Trailer Filling

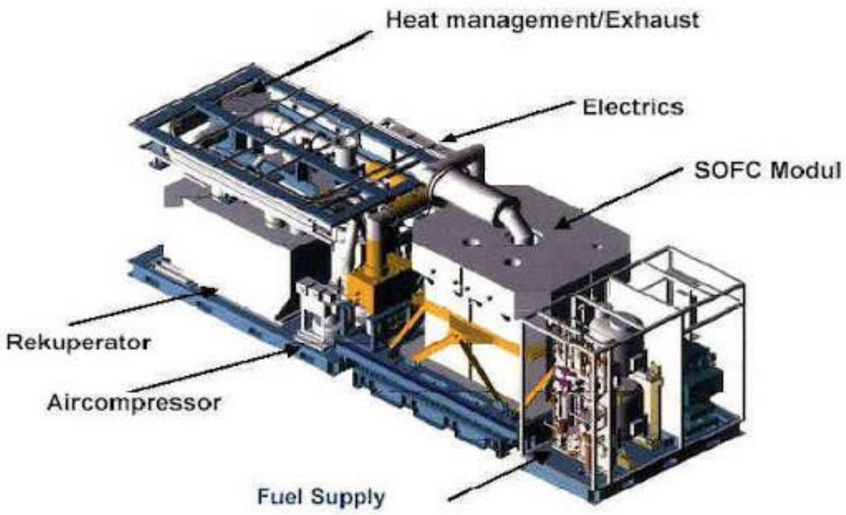
Power-to-Gas

STATIONARY FUEL CELL POWER APPLICATIONS

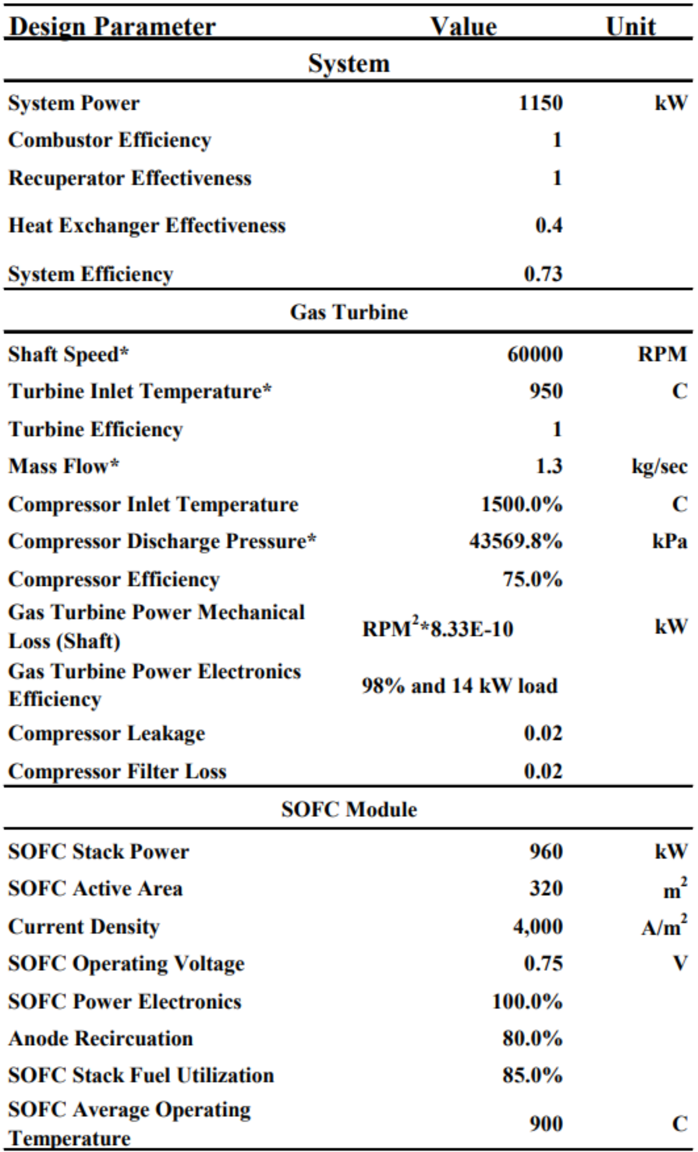




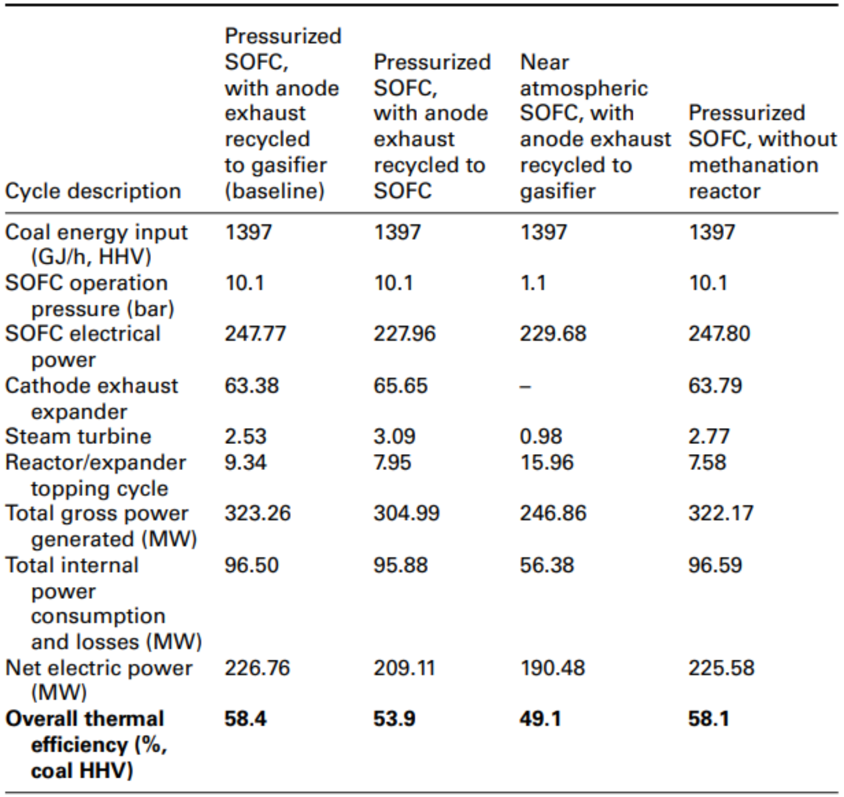
STATIONARY FUEL CELL POWER APPLICATIONS



DESIGN PARAMETERS OF GT SYSTEM

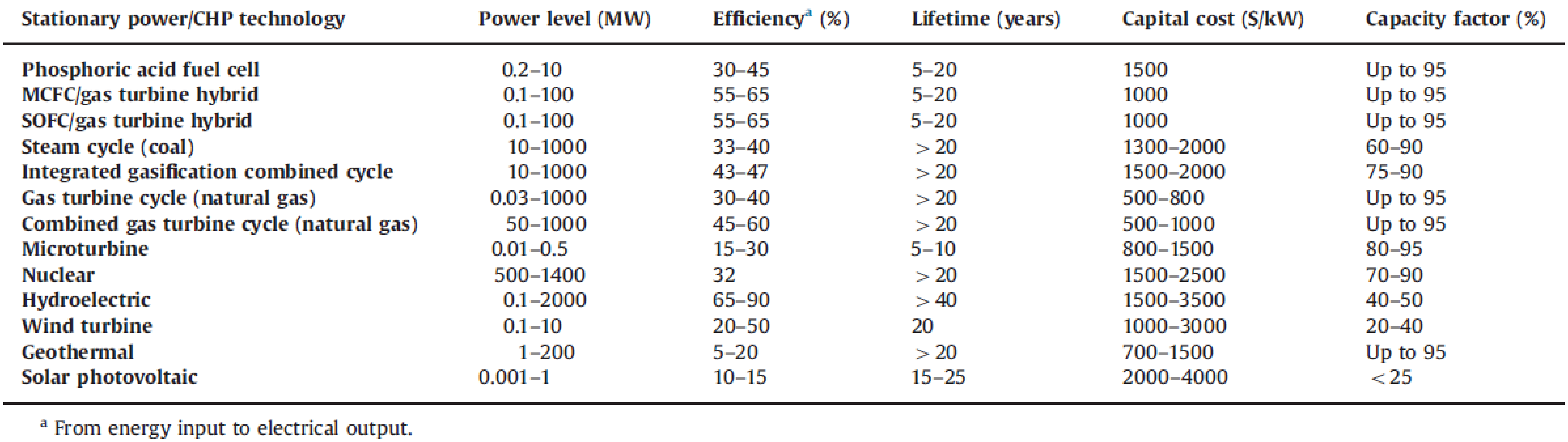


Design Parameter	Value	Unit
System		
System Power	1150	kW
Combustor Efficiency	1	
Recuperator Effectiveness	1	
Heat Exchanger Effectiveness	0.4	
System Efficiency	0.73	
Gas Turbine		
Shaft Speed*	60000	RPM
Turbine Inlet Temperature*	950	C
Turbine Efficiency	1	
Mass Flow*	1.3	kg/sec
Compressor Inlet Temperature	1500.0%	C
Compressor Discharge Pressure*	43569.8%	kPa
Compressor Efficiency	75.0%	
Gas Turbine Power Mechanical Loss (Shaft)	RPM^2*8.33E-10	kW
Gas Turbine Power Electronics Efficiency	98% and 14 kW load	
Compressor Leakage	0.02	
Compressor Filter Loss	0.02	
SOFC Module		
SOFC Stack Power	960	kW
SOFC Active Area	320	m^2
Current Density	4,000	A/m^2
SOFC Operating Voltage	0.75	V
SOFC Power Electronics	100.0%	
Anode Recircuation	80.0%	
SOFC Stack Fuel Utilization	85.0%	
SOFC Average Operating Temperature	900	C



Cycle description	Pressurized SOFC, with anode exhaust recycled to gasifier (baseline)	Pressurized SOFC, with anode exhaust recycled to SOFC	Near atmospheric SOFC, with anode exhaust recycled to gasifier	Pressurized SOFC, without methanation reactor
Coal energy input (GJ/h, HHV)	1397	1397	1397	1397
SOFC operation pressure (bar)	10.1	10.1	1.1	10.1
SOFC electrical power	247.77	227.96	229.68	247.80
Cathode exhaust expander	63.38	65.65	–	63.79
Steam turbine	2.53	3.09	0.98	2.77
Reactor/expander topping cycle	9.34	7.95	15.96	7.58
Total gross power generated (MW)	323.26	304.99	246.86	322.17
Total internal power consumption and losses (MW)	96.50	95.88	56.38	96.59
Net electric power (MW)	226.76	209.11	190.48	225.58
Overall thermal efficiency (%, coal HHV)	**58.4**	**53.9**	**49.1**	**58.1**

FC TECHNO-ECONOMIC COMPETITION (STATIONARY POWER)



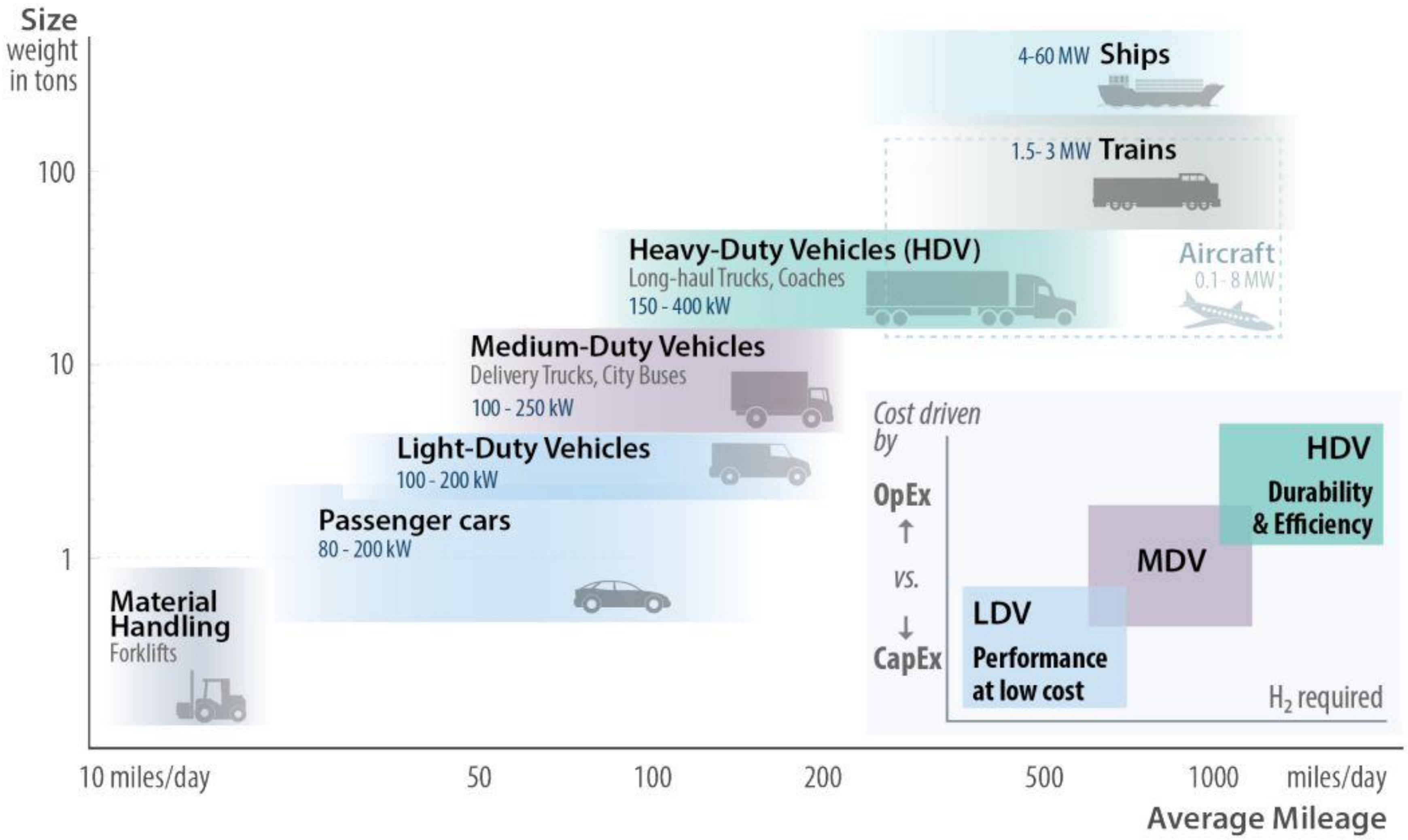
Stationary power/CHP technology	Power level (MW)	Efficiency[a] (%)	Lifetime (years)	Capital cost ($/kW)	Capacity factor (%)
Phosphoric acid fuel cell	0.2–10	30–45	5–20	1500	Up to 95
MCFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
SOFC/gas turbine hybrid	0.1–100	55–65	5–20	1000	Up to 95
Steam cycle (coal)	10–1000	33–40	> 20	1300–2000	60–90
Integrated gasification combined cycle	10–1000	43–47	> 20	1500–2000	75–90
Gas turbine cycle (natural gas)	0.03–1000	30–40	> 20	500–800	Up to 95
Combined gas turbine cycle (natural gas)	50–1000	45–60	> 20	500–1000	Up to 95
Microturbine	0.01–0.5	15–30	5–10	800–1500	80–95
Nuclear	500–1400	32	> 20	1500–2500	70–90
Hydroelectric	0.1–2000	65–90	> 40	1500–3500	40–50
Wind turbine	0.1–10	20–50	20	1000–3000	20–40
Geothermal	1–200	5–20	> 20	700–1500	Up to 95
Solar photovoltaic	0.001–1	10–15	15–25	2000–4000	< 25

[a] From energy input to electrical output.

Technoeconomic comparison between fuel cells and their competitors in the stationary power/CHP sector
O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

3.2 Automotive and Transportation

PROPULSION POWER TRAIN DUTIES



TRANSPORTATION INDUSTRY APPLICATIONS

- Transportation responsible for 17% of global green house gas emissions every year
  - Goal: invest in technologies that offering both significant reductions in harmful emissions and better energy conversion efficiencies.
- FC have demonstrated high efficiencies (53-59%) | ~2x conventional heat engines
  - **Mainly PEM**

- **Transportation markets for FC:**
  - Auxiliary power units (APUs)
  - Light traction vehicles (LTVs)
  - Light-duty fuel cell electric vehicles (L-FCEVs)
  - Heavy-duty fuel cell electric vehicles (H-FCEVs)
  - Aerial propulsion (see next section)
  - Marine propulsion.
- Most of the efforts in the transportation area are focused on APUs and L-FCEVs,

AUXILIARY POWER UNITS (APUS)

- On-board auxiliary power unit (APU) used for generation of non-propulsive power in any vehicle
  - APU load ranges from <1 kW up to 500 kW on large commercial airplanes
- Separation of main propulsion system from APU helps optimize overall vehicle energy consumption
  - APU provides power for air conditioning, refrigerating, entertainment, heating, lighting, communication, etc.
  - Used in car, boat, ship, locomotive, airplane, truck, bus, submarine, spaceship, military vehicle, etc.
  - Most promising APU markets for FCs (due to high on-board electrical energy demand): leisure yachts, planes, cars, heavy-duty trucks, utility and service vehicles, law enforcement vehicles and refrigeration vehicles

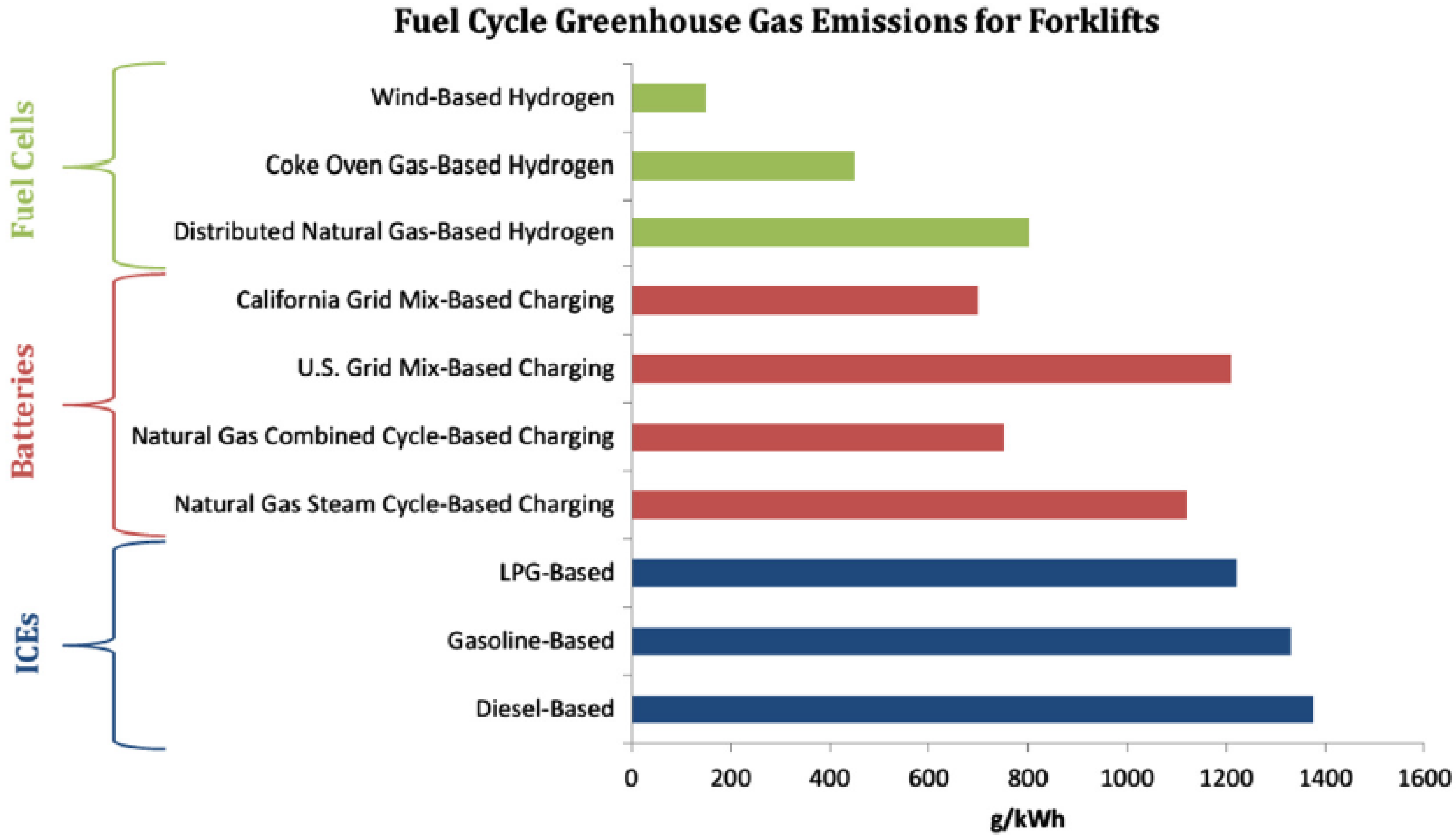
- Use of FC APUs in heavy-duty trucks in the US could decrease:
  - 10 emissions by up to 65% | NOx emissions by up to 95% | CO_2 emissions by more than 60%
- Heavy-duty truck idling ~20–40% of overall engine running time (~6h/day) at ~3% energy efficiency would be better off using an APU
  - Trucks on idle mode consume ~1 gal/h of diesel fuel
- PEMFCs, DMFCs, and SOFCs being developed for APU applications with pure hydrogen, natural gas, LPG, gasoline, methanol, and diesel as potential fuels
  - More energy-intensive vehicles (i.e., commercial airplanes and cargo ships), require APUs with high energy ratings, for which high-temperature fuel cells (SOFCs and MCFCs) are better suited

LIGHT TRACTION VEHICLES (LTV)

- LTVs in transportation: scooters, personal wheel-chairs, electric-assisted bicycles, airport tugs, motorbikes, golf carts
  - Scooters ~4-6 kW (travel distances up to 200 km)
  - Electric-assisted bicycles <1 kW of power (travel distance <1 km)
- LTVs in material handling vehicles and equipment: forklifts, tow trucks, pallet trucks, etc.
  - FC forklifts ~5–20 kW PEMFCs (some running on DMFCs) coupled with ultracapacitors

- Forklifts historically great demonstrators of FCs.
  - ~2.5 million forklifts in-operation in North America.
  - Most use rechargeable lead-acid batteries (usually with regenerative braking energy recovery) or combustion engines
  - FCs present considerable advantages for forklifts over batteries
    - Refueling ~2–5 min << recharging batteries (15–30 min) -> increases operational efficiency)
    - Longer operation cycles (battery cycles <8h)
    - Less sensitive to the ambient temperature (especially in refrigerated warehouses)
    - Do not self-degrade with charge and discharge cycles
    - Require much less space for refueling stations in contrast to battery charging and changing space,
    - Significantly less harmful emissions compared to combustion-based engines
    - Can operate indoor or outdoor (many combustion-based forklifts that cannot run indoors)
    - High efficiencies, excellent load-following dynamics, low maintenance

FUEL CYCLE GHG EMISSIONS FOR FORKLIFTS



Department of Energy hydrogen and fuel cells program plan: an integrated strategic plan for the research, development, and demonstration of hydrogen and fuel cell technologies. US Department of Energy; 2011.

LIGHT-DUTY FUEL CELL ELECTRIC VEHICLES (L-FCEV)

- L-FCEVs utilize a FC for propulsion
  - Most efforts focused on PEMFC
  - Can be coupled with a Li-ion battery for regenerative braking energy recovery
- Advantages compared to current internal combustion engine-based vehicles:
  - Quieter operation | More efficient energy use | Significantly less GHG emissions | More vehicle design and packaging flexibility.
- Advantages compared to light-duty battery electric vehicles(L-BEVs):
  - Longer range | Shorter refueling time (less than 2min) | Better tolerance of cold weather | Lighter weight
- Main challenges to commercialization:
  - Lifecycle cost and stack durability limitations | Total system weight and size | Air compression systems | Start-up in very cold weather and under frozen conditions | Heat dissipation | Catalyst tolerance to voltage cycling | Stack endurance of frequent start-stop cycles | Bipolar plates weight | On-board hydrogen storage | Membrane humidification | Hydrogen safety standards.

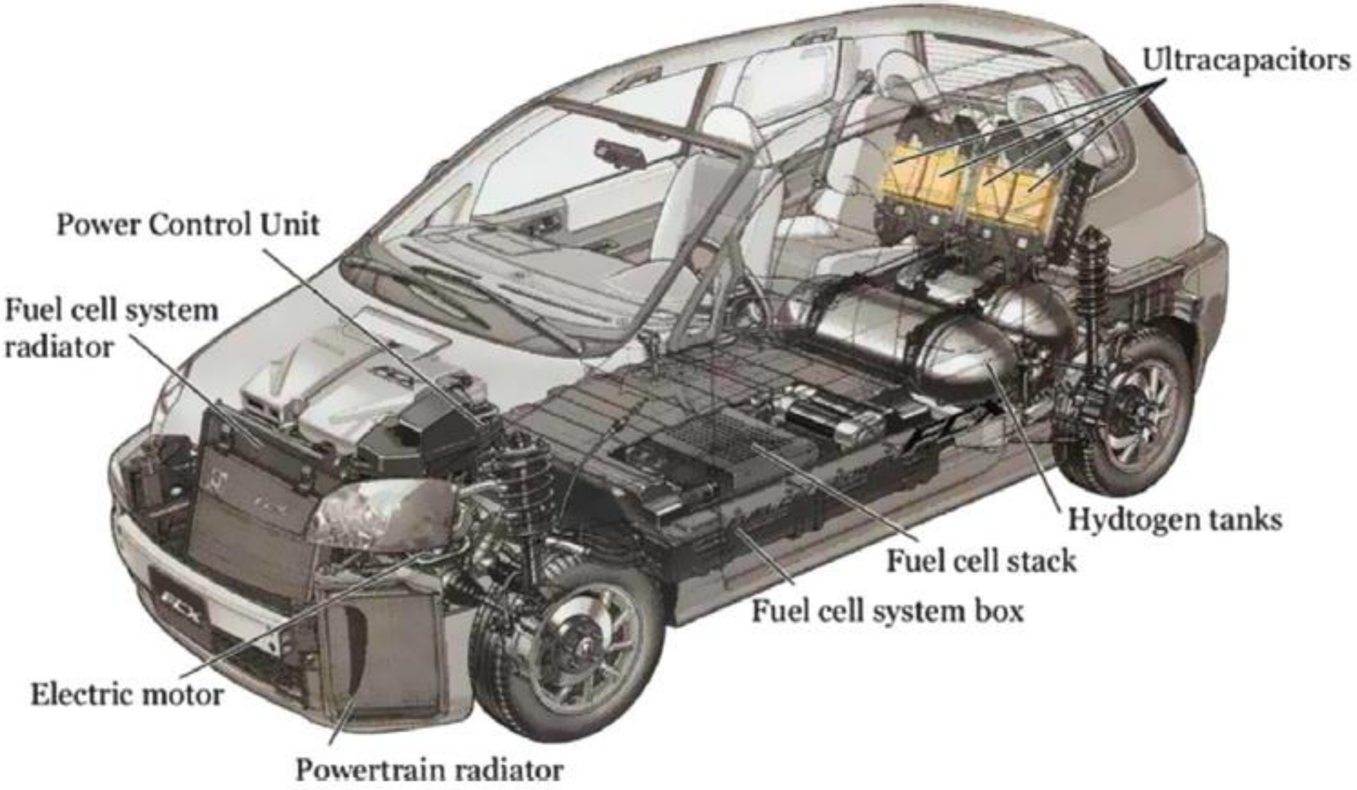
- L-FCEV hydrogen generated off-board and distributed in dedicated fueling stations.
- On-board hydrogen storage is one of the biggest challenges and most active research areas for FCEVs commercialization.
- More constraining on-board hydrogen storage vs. for stationary applications
  - Low cost | High efficiency | Low parasitic load (e. g. for compression, cooling, or discharging)
  - Gravimetric energy density (leading issue with metal-hydrides) | Volumetric energy density (leading issue with compressed gas) | Collision safety requirements | Fitting into vehicle’s space and shape | System complexity

HEAVY-DUTY FUEL CELL ELECTRIC VEHICLES (H-FCEV)

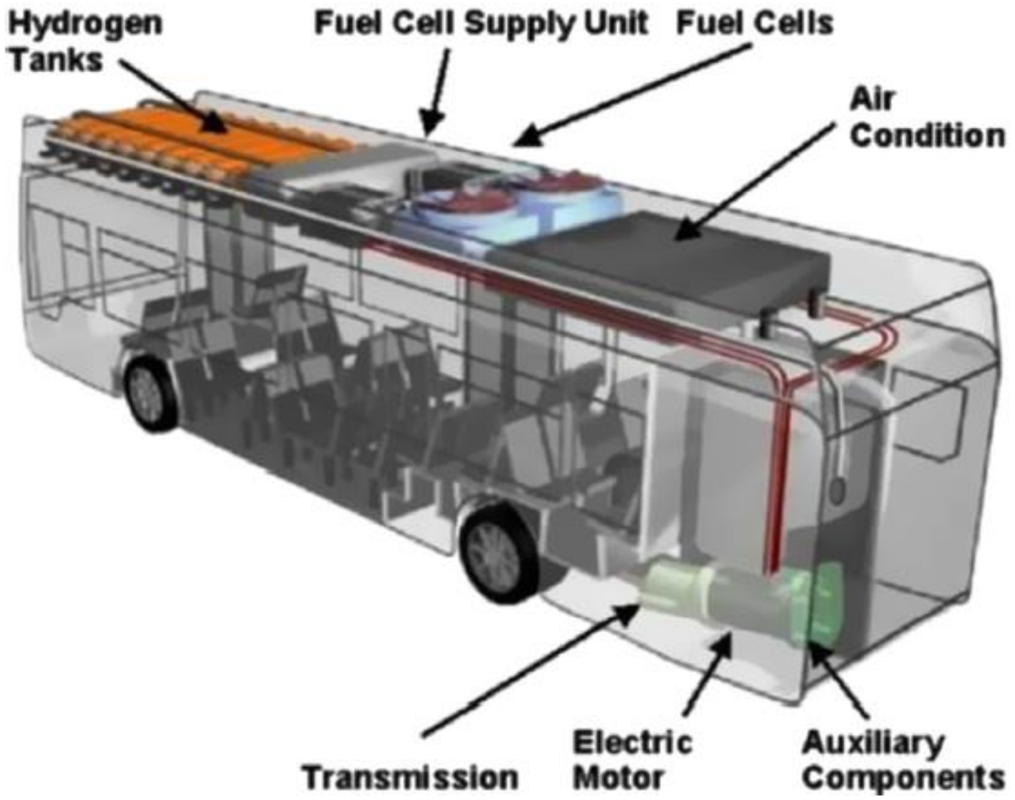
- H-FCEVs: buses, heavy-duty trucks, locomotives, vans, utility trucks, service fleets, etc.
    - FC used for propulsion
- 30+ FC buses currently deployed in Western Europe & 25 in the USA in 2012
    - Fuel cell electric buses (FCEBs) are great public demonstrators in FC transportation industry
- Busses provide more flexible design and packaging (size and weight) & less complex hydrogen infrastructure requirements (fixed bus routes are usually fixed)
    - PEMFCs and PAFCs are the most commonly-used types for bus FC stack
    - High-voltage batteries for regenerative braking energy recovery and better dynamic response

- Heliocentris developing hybrid (diesel engine/FC system) waste disposal heavy-duty truck.
    - Diesel engine used for propulsion
    - FC used for waste collection, management, and disposal.
- For rail vehicles, Guoetal designed and simulated performance of power system for a hybrid switcher locomotive (SOFC power plant + lead-acid batteries + ultracapacitors for propulsion)

LIGHT- VS. HEAVY-DUTY FC VEHICLE CONCEPTS

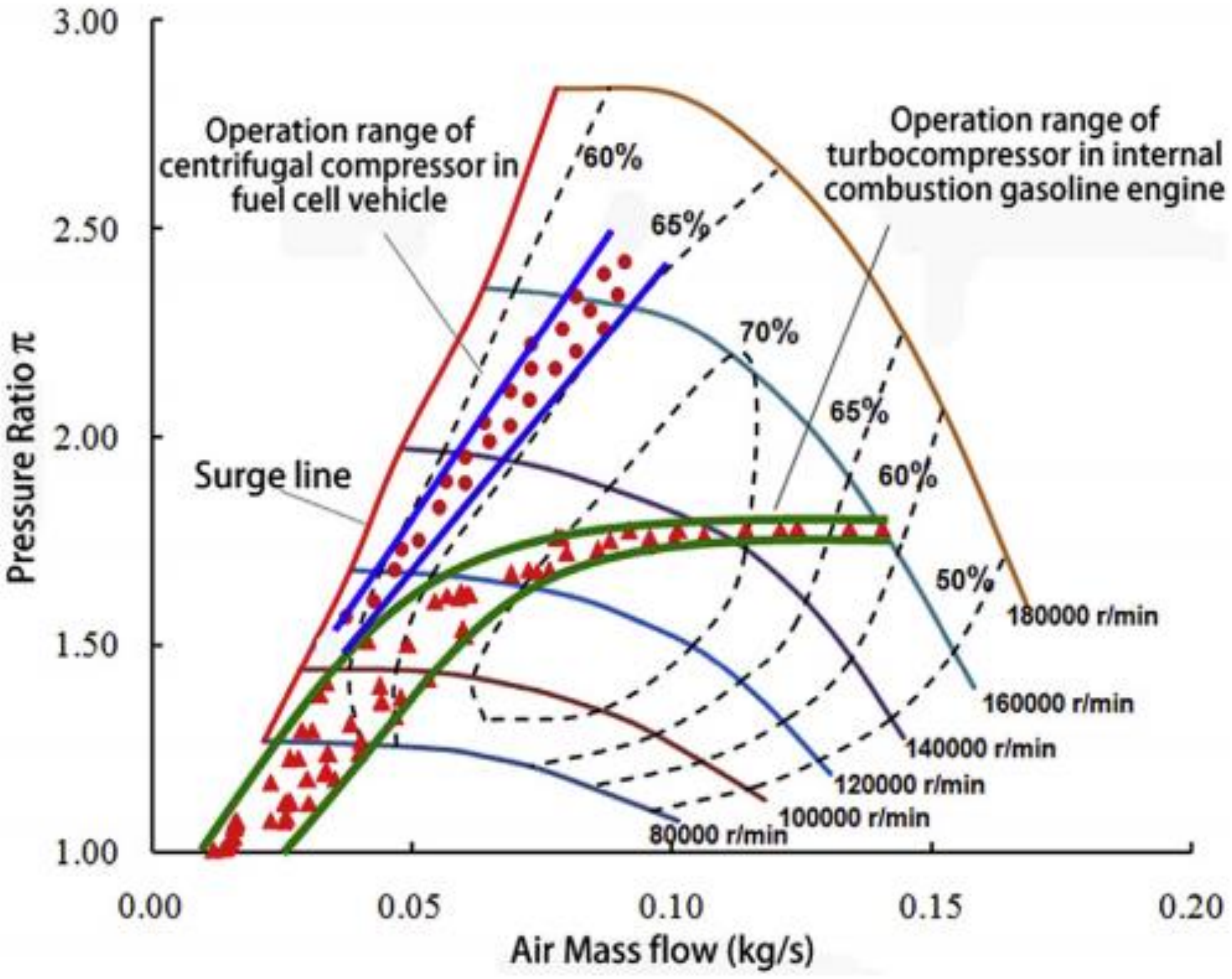


Conceptual design of a future L-FCEV based on the Honda 2005 FCX model - Zorpette G. Supercharged [ultracapacitors]. IEEESpectr 2005; 42:32–7.



Main components in a typical FCEB based on the Mercedes-Benz Citaro Fuel Cell EcoBus – Fuel Cell Application. Murdoch University. ⟨http://www.see.murdoch.edu.au/ resources/info/Applic/Fuelcells/⟩.

OPERATION RANGE



FUEL CELL HEAVY DUTY TRUCKS – A PRESENT DAY REALITY

Hyundai
Hydrogen Mobility
Partnership with H2Energy

H2 service stations in Switzerland

350 bar & 700 bar

● **open**

Hunzenschwil	Coop
St. Gallen	AVIA
Zofingen	Agrola
Rothenburg	Agrola
Rümlang	AVIA
Lausanne	Coop
Geuensee	AVIA
Bern	Coop

● **in preparation**

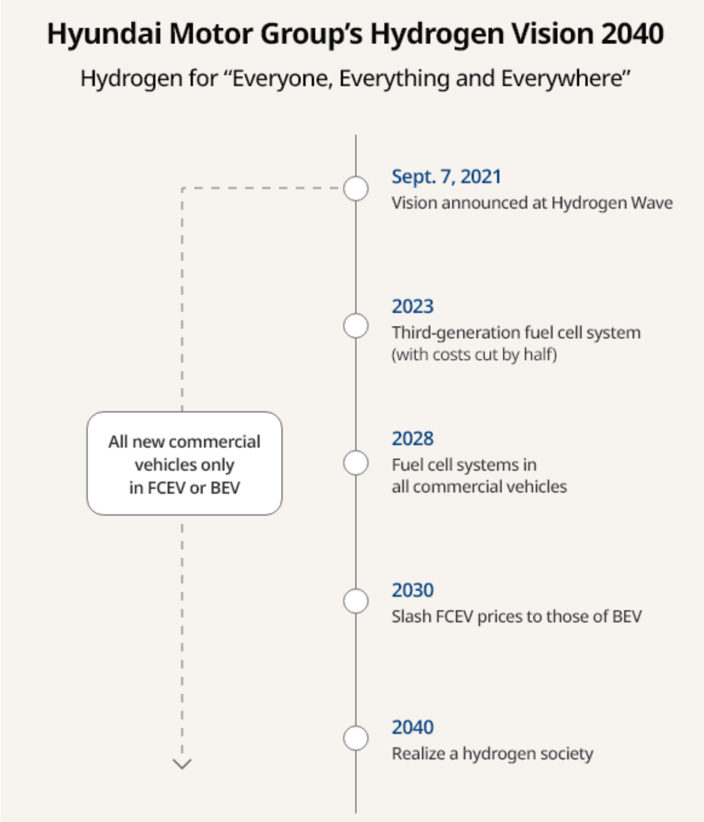
Gossau	AVIA (350 bar)
Müntschemier	Schwab-Guillod

July 2021

Fuel Cell technology

In our fuel cell, hydrogen from green production reacts with oxygen from the air. This produces water, electricity and heat. This electrochemical reaction is also known as "cold combustion" and is particularly efficient. In the first generation of our Xcient Trucks, the Hyundai Nexo's fuel cells, which have proven themselves many times over, are used. We use two fuel cells in parallel, each with an output of 95kW. Together with the high-voltage battery, we can thus ensure that the truck, when fully loaded with a total weight of 36t, has sufficient drive.

CURRENT STATUS OF THE HYDROGEN INDUSTRY & HYDYUNDAI MOTOR GROUP'S VISION



Hyundai Motor Group's Hydrogen Vision 2040

Hydrogen for "Everyone, Everything and Everywhere"

Sept. 7, 2021
Vision announced at Hydrogen Wave

2023
Third-generation fuel cell system
(with costs cut by half)

2028
Fuel cell systems in
all commercial vehicles

All new commercial
vehicles only
in FCEV or BEV

2030
Slash FCEV prices to those of BEV

2040
Realize a hydrogen society

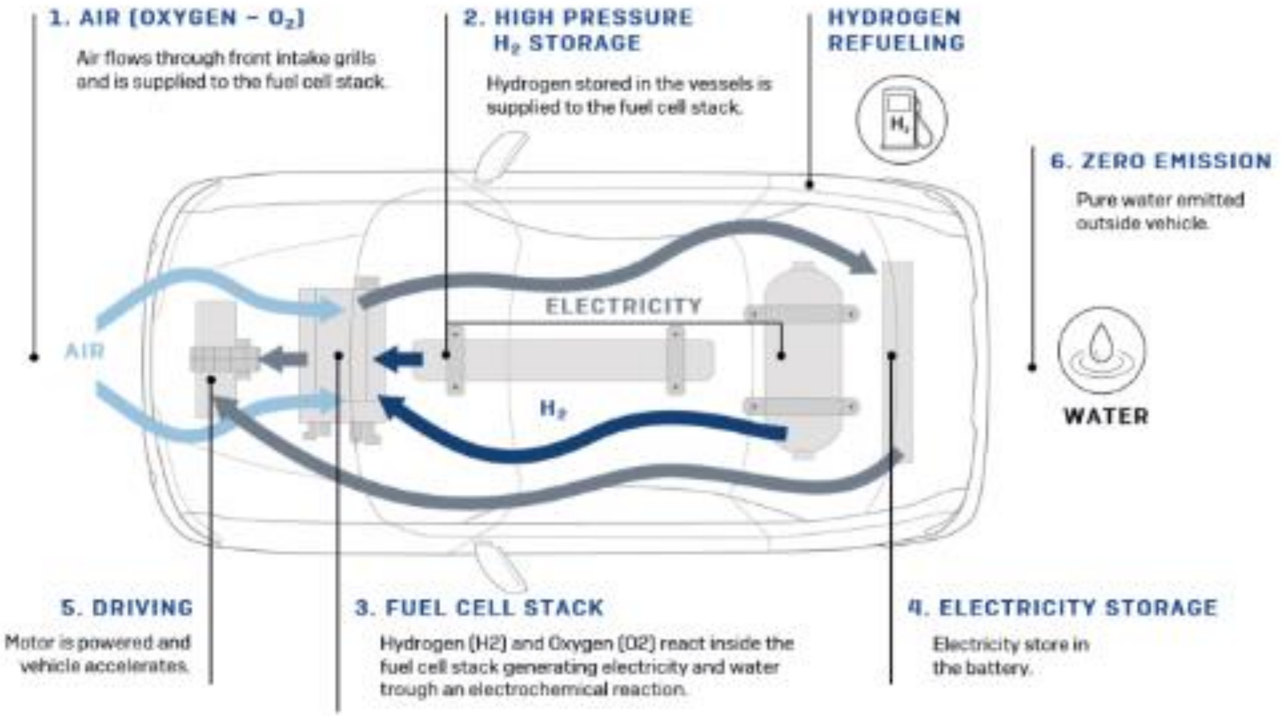
- Hyundai Motor Group (the Group) announces Hydrogen Vision 2040, to popularize hydrogen by 2040 for 'Everyone, Everything and Everywhere' at Hydrogen Wave

- Hydrogen Wave represents the Group's plans for a new 'wave' of hydrogen-based products and technologies toward a hydrogen society

- The Group to introduce next-generation fuel cell system-in 2023 with costs being lowered by more than 50%, total package volume reduced by 30% and power output doubled

HYDROGEN AND FUEL CELL – ZERO EMISSION TECHNOLOGY FOR MOBILITY SOLUTIONS

EKPO FUEL CELL TECHNOLOGIES



1. AIR (OXYGEN – O_2)
Air flows through front intake grills and is supplied to the fuel cell stack.

2. HIGH PRESSURE H_2 STORAGE
Hydrogen stored in the vessels is supplied to the fuel cell stack.

HYDROGEN REFUELING

3. FUEL CELL STACK
Hydrogen (H2) and Oxygen (O2) react inside the fuel cell stack generating electricity and water trough an electrochemical reaction.

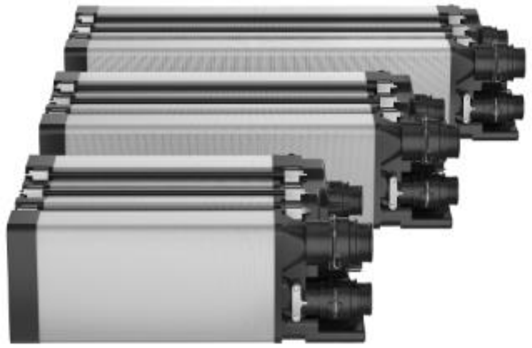
4. ELECTRICITY STORAGE
Electricity store in the battery.

5. DRIVING
Motor is powered and vehicle accelerates.

6. ZERO EMISSION
Pure water emitted outside vehicle.

The mobility turnaround.

Our product portfolio includes both customer-specific developments for each integration stage and high-performance standard solutions. These include PEM fuel cell modules with stack-related peripherals, PEMFC stack modules for integration into customer systems, and various stack components such as metallic bipolar plates or end plates and media modules.



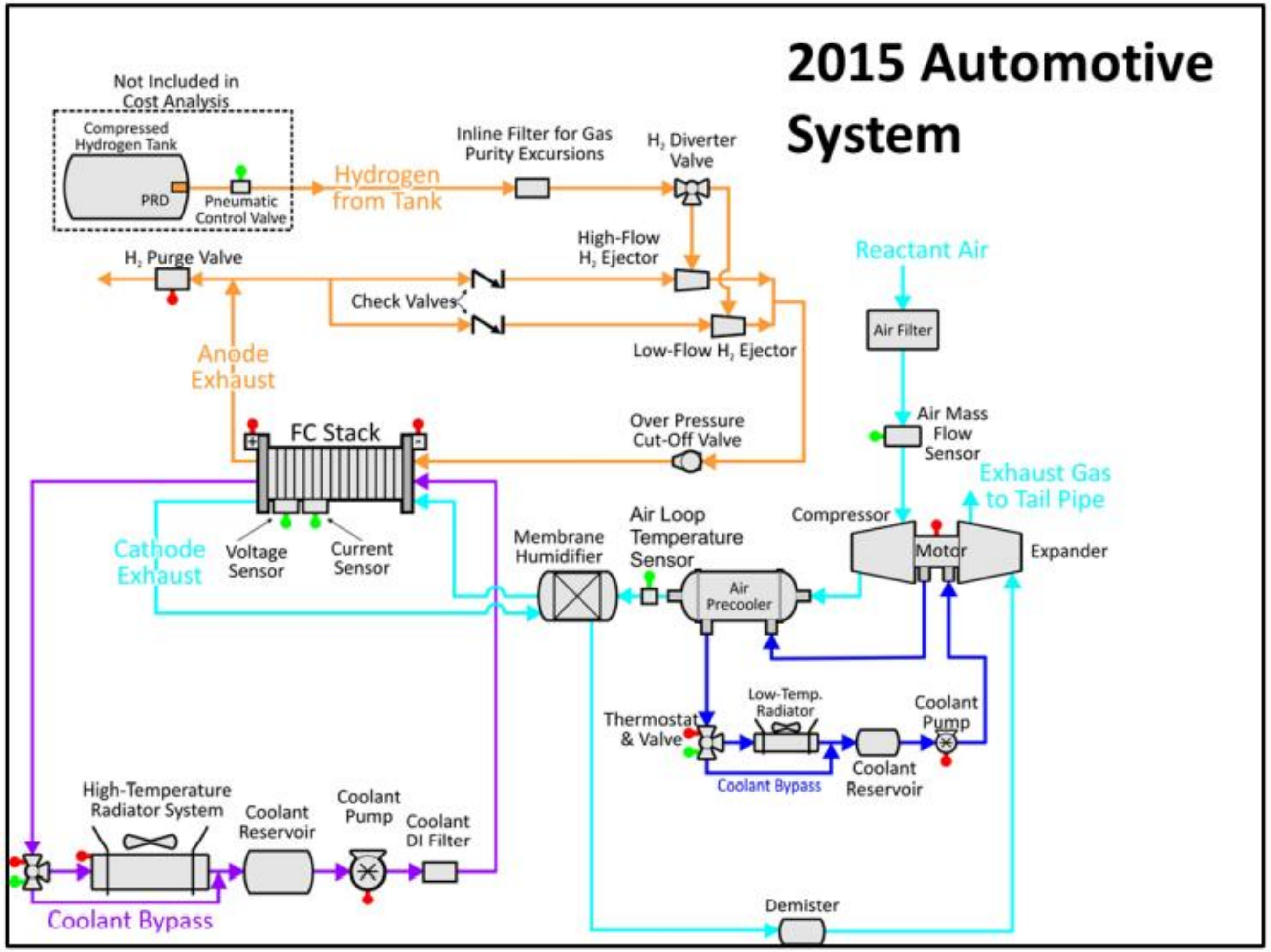
Technology with a future

The PEMFC (Proton Exchange Membrane Fuel Cell) is a low-temperature fuel cell and converts chemical energy into electrical energy using hydrogen and oxygen. This technology can be used advantageously wherever pure hydrogen is available as a fuel and high electrical efficiency is required. If the hydrogen for the low-temperature PEMFC is produced from regeneratively generated electricity by means of electrolysis, completely emission-free mobility is feasible.

In both field and bench tests, PEMFC stacks from EKPO show outstanding performance and durability values.

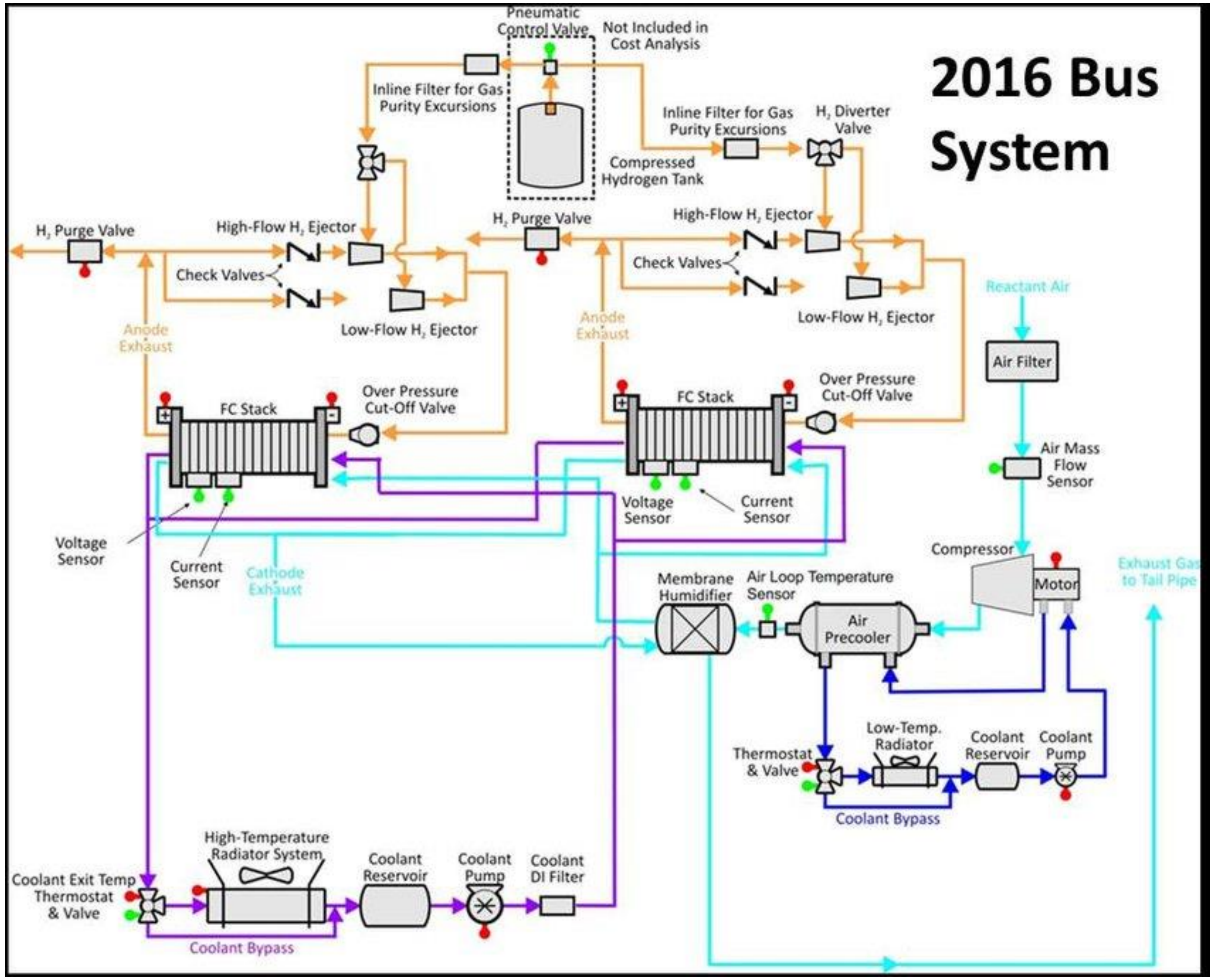
Hydrogen drive – on the way to sustainable mobility

FUEL CELL – EXAMPLE FOR AUTOMOTIVE SYSTEM



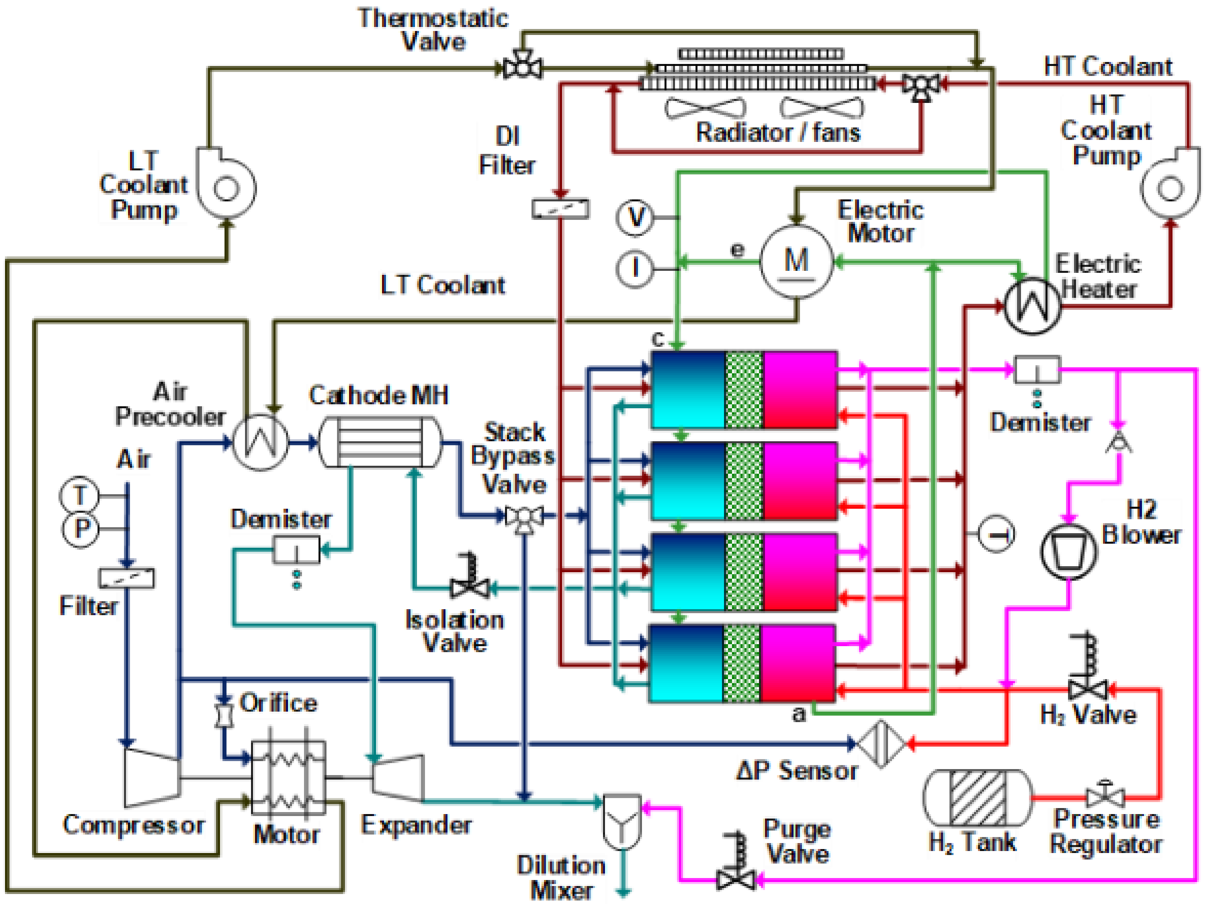
Schematic of an automotive system for a light duty vehicle fuel cell power system - (PDF) Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2015 Update (researchgate.net)

FUEL CELL - BUS SYSTEM



Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications (2016)

FUEL CELL – HEAVY-DURTY TRUCKS

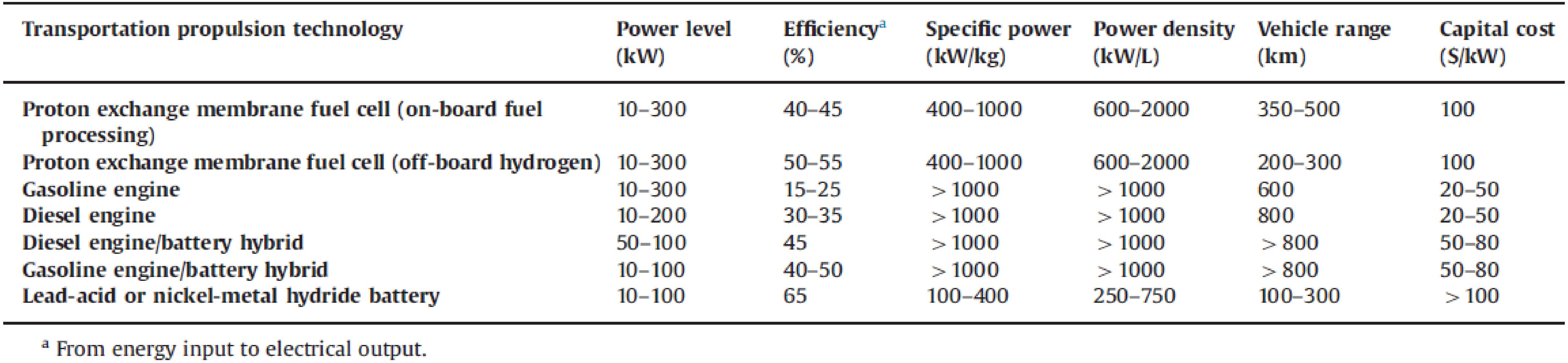


Fuel cell systems for medium- and heavy-duty trucks

Salient Features

- Multiple stacks 2, 3 or 4
- Pt loading Cathode: 0.2 mg/cm^2 Anode: TBD
- Membrane thickness: TBD
- Single air system with expander
- Single anode system with recirculation blower
- No cathode humidification
- Rated power: 2.5 atm, 87^{o}C, 0.7 V
- Control valves for startup/shutdown, cold start and OCV

FC TECHNO-ECONOMIC COMPETITION (TRANSPORTATION)



Transportation propulsion technology	Power level (kW)	Efficiency[a] (%)	Specific power (kW/kg)	Power density (kW/L)	Vehicle range (km)	Capital cost ($/kW)
Proton exchange membrane fuel cell (on-board fuel processing)	10–300	40–45	400–1000	600–2000	350–500	100
Proton exchange membrane fuel cell (off-board hydrogen)	10–300	50–55	400–1000	600–2000	200–300	100
Gasoline engine	10–300	15–25	> 1000	> 1000	600	20–50
Diesel engine	10–200	30–35	> 1000	> 1000	800	20–50
Diesel engine/battery hybrid	50–100	45	> 1000	> 1000	> 800	50–80
Gasoline engine/battery hybrid	10–100	40–50	> 1000	> 1000	> 800	50–80
Lead-acid or nickel-metal hydride battery	10–100	65	100–400	250–750	100–300	> 100

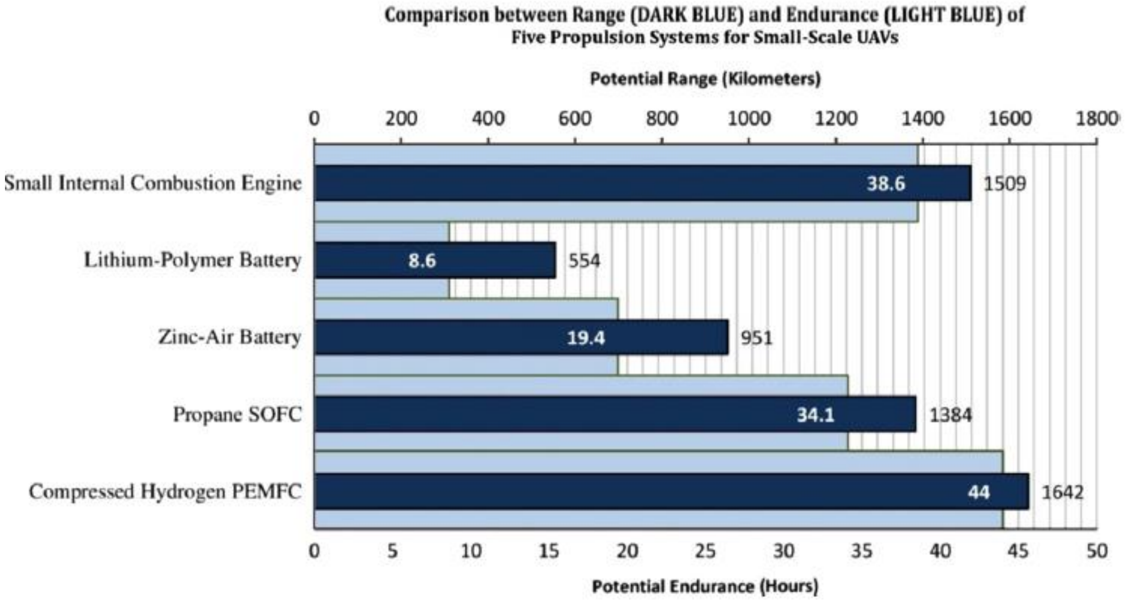
[a] From energy input to electrical output.

Technoeconomic comparison between fuel cells and their competitors in the transportation propulsion sector
O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

3.3 Aerospace

AERIAL PROPULSION

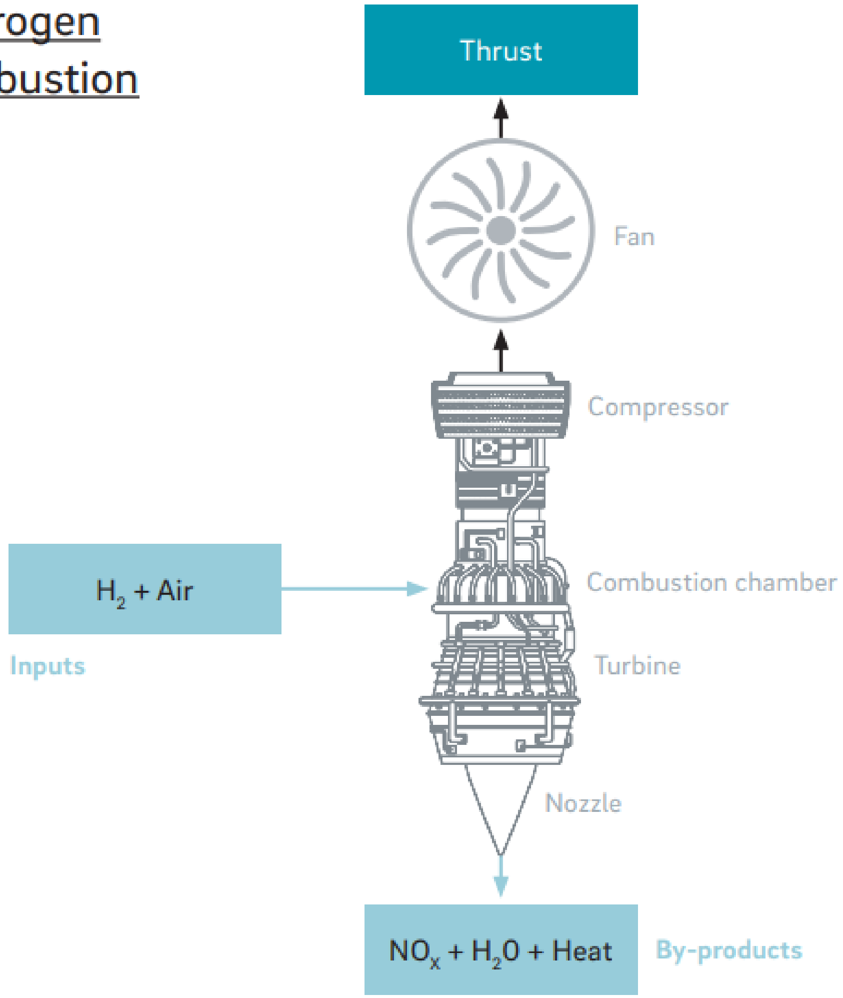
- FCs in <u>aviation</u> industries dominated by small unmanned aerial vehicles (UAVs)
  - UAVs are mainly used for surveying, surveillance, and reconnaissance purposes due to their stealth nature and lack of risk to human life.
  - Ever-increasing interest in UAVs by military authorities and commercial parties
- Mostly PEMFCs with few SOFCs
  - UAV stealth nature facilitated by FC static operation and low heat dissipation vs. dynamic heat engines.
  - FC has advantage over batteries low energy density and large weight (needed for improved mission range and endurance)
- FC modularity promising even for small-scale applications
  - Combustion engines suffer from low efficiencies when designed for small-scale applications
- FCs in <u>space</u> propulsion are attractive for similar reasons
  - Added benefit that produced water is a crucial part of life on and outside of Earth



Comparison between different proposed UAV small-scale propulsion systems – Bradley TH, Moffitt BA, Mavris D, Parekh DE. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009.

MAIN DIRECTIONS OF USES HYDROGEN FUEL IN AVIATION

Hydrogen combustion



Thrust

Fan

Compressor

H_2 + Air

Inputs

Combustion chamber

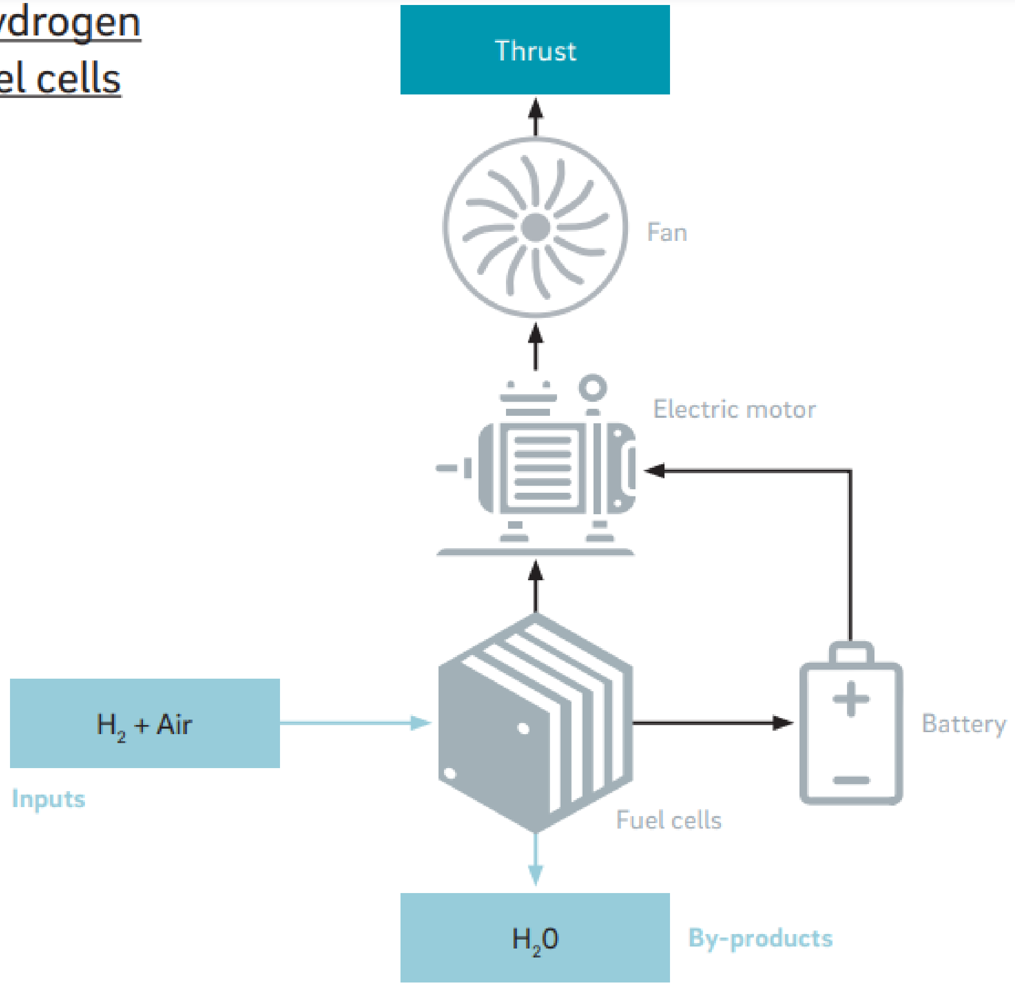
Turbine

Nozzle

$NO_x + H_20$ + Heat

By-products

Hydrogen fuel cells



Thrust

Fan

Electric motor

H_2 + Air

Inputs

Battery

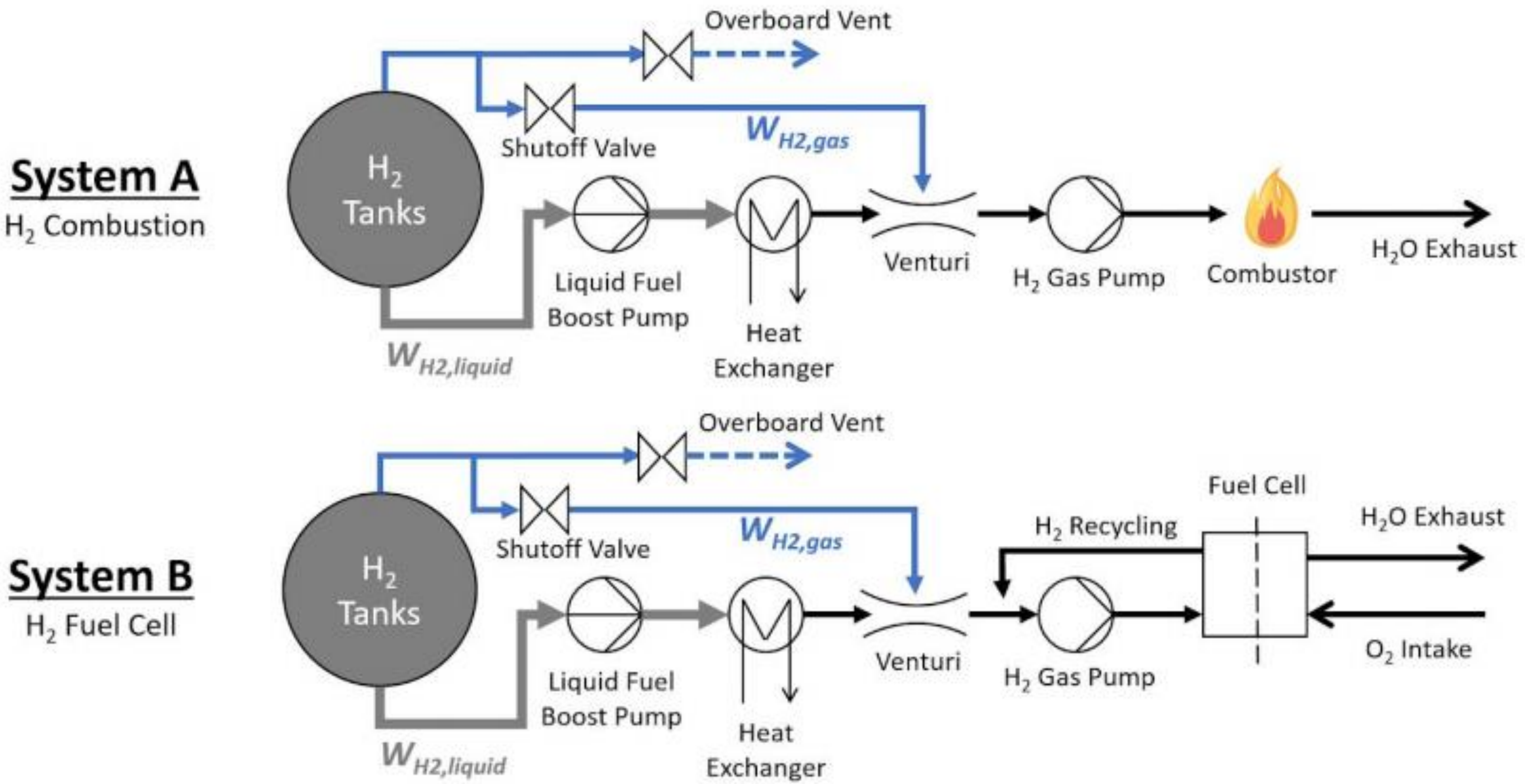
Fuel cells

H_20

By-products

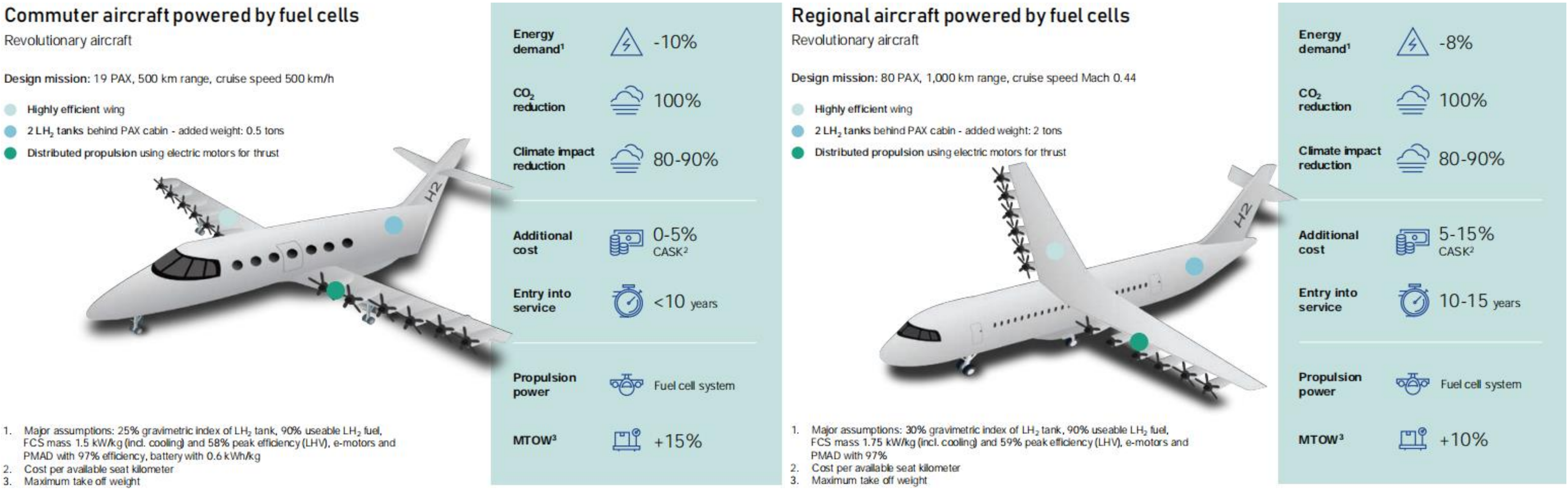
Hydrogen | A future fuel for aviation? R. THOMSON, U. WEICHENHAIN, N. SACHDEVA, M. KAUFMANN. - PUBLISHER:ROLAND BERGER GMBH Sederanger 1 - 80538 Munich Germany. - p 28

VARIANTS OF ONBOARD FUEL DISTRIBUTION



Hydrogen as a Renewable Energy Carrier for Commercial Aircraft.- Caleb Amy, Alex Kunyскую- May 12, 2019. - pp.41

ESTIMATED OPTIONS FOR AIRCRAFT ENGINES DEPENDING ON THE FLIGHT RANGE.



Commuter aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 19 PAX, 500 km range, cruise speed 500 km/h

- ● Highly efficient wing
- ● 2 LH_2 tanks behind PAX cabin - added weight: 0.5 tons
- ● Distributed propulsion using electric motors for thrust

Energy demand[1]	-10%
CO_2 reduction	100%
Climate impact reduction	80-90%
Additional cost	0-5% CASK[2]
Entry into service	<10 years
Propulsion power	Fuel cell system
MTOW[3]	+15%

1. Major assumptions: 25% gravimetric index of LH_2 tank, 90% useable LH_2 fuel, FCS mass 1.5 kW/kg (incl. cooling) and 58% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg
2. Cost per available seat kilometer
3. Maximum take off weight

Regional aircraft powered by fuel cells

Revolutionary aircraft

Design mission: 80 PAX, 1,000 km range, cruise speed Mach 0.44

- ● Highly efficient wing
- ● 2 LH_2 tanks behind PAX cabin - added weight: 2 tons
- ● Distributed propulsion using electric motors for thrust

Energy demand[1]	-8%
CO_2 reduction	100%
Climate impact reduction	80-90%
Additional cost	5-15% CASK[2]
Entry into service	10-15 years
Propulsion power	Fuel cell system
MTOW[3]	+10%

1. Major assumptions: 30% gravimetric index of LH_2 tank, 90% useable LH_2 fuel, FCS mass 1.75 kW/kg (incl. cooling) and 59% peak efficiency (LHV), e-motors and PMAD with 97%
2. Cost per available seat kilometer
3. Maximum take off weight

Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050, May 2020,- Print ISBN 978-92-9246-341-0 doi:10.2843/766989 EG-04-20-214-EN-C

ESTIMATED OPTIONS FOR AIRCRAFT ENGINES DEPENDING ON THE FLIGHT RANGE.

Short-range aircraft powered by hybrid H_2 propulsion

Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

- ● **2 LH_2 tanks** behind PAX cabin -added weight: 4 tons
- ● **Fuel cell system** (11 MW) powering electric motors
- ● **Electric motor** driving main turbine fan shaft during cruise, while H_2 turbine is turned off

Energy demand[1]	-4%
CO_2 reduction	100%
Climate impact reduction	70-80%
Additional cost	20-30% CASK[2]
Entry into service	15 years
Propulsion power	Hybrid
MTOW[3]	+14%

1. Major assumptions: 35% gravimetric index of LH_2 tank, 91% useable LH_2 fuel, FCS mass 2 kW/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg, H_2-turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

Medium-range aircraft powered by H_2 turbines

Evolutionary aircraft

Design mission: 250 PAX, 7,000 km range, cruise speed Mach 0.82

- ● **2 LH_2 tanks** in front and back of PAX cabin - added weight: 29 tons
- ● **H_2 turbines** generating propulsion power

Energy demand[1]	+22%
CO_2 reduction	100%
Climate impact reduction	50-60%
Additional cost	30-40% CASK[2]
Entry into service	20 years
Propulsion power	H_2 turbine
MTOW[3]	+12%

1. Major assumptions: 37% gravimetric index of LH_2 tank, 92% useable LH_2 fuel, 47% H_2 turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

Long-range aircraft powered by H_2 turbines

Evolutionary aircraft

Design mission: 325 PAX, 10,000 km range, cruise speed Mach 0.85

- ● **2 LH_2 tanks** in front and back of PAX cabin - added weight: 52 tons
- ● **H_2 turbines** generating propulsion power

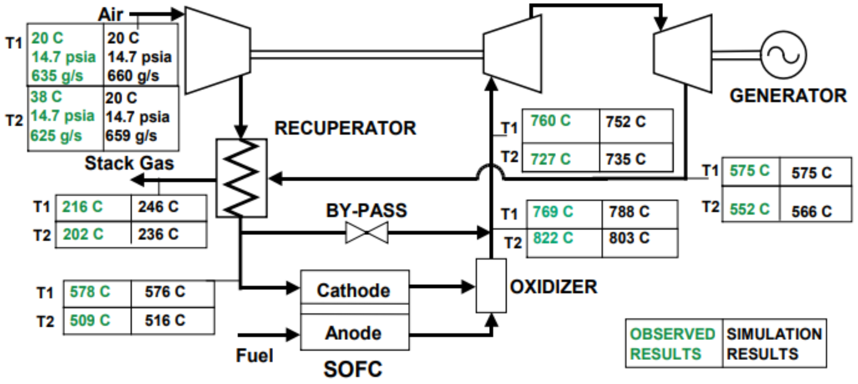
Energy demand[1]	+42%
CO_2 reduction	100%
Climate impact reduction	40-50%
Additional cost	40-50% CASK[2]
Entry into service	20-25 years
Propulsion power	H_2 turbine
MTOW[3]	+23%

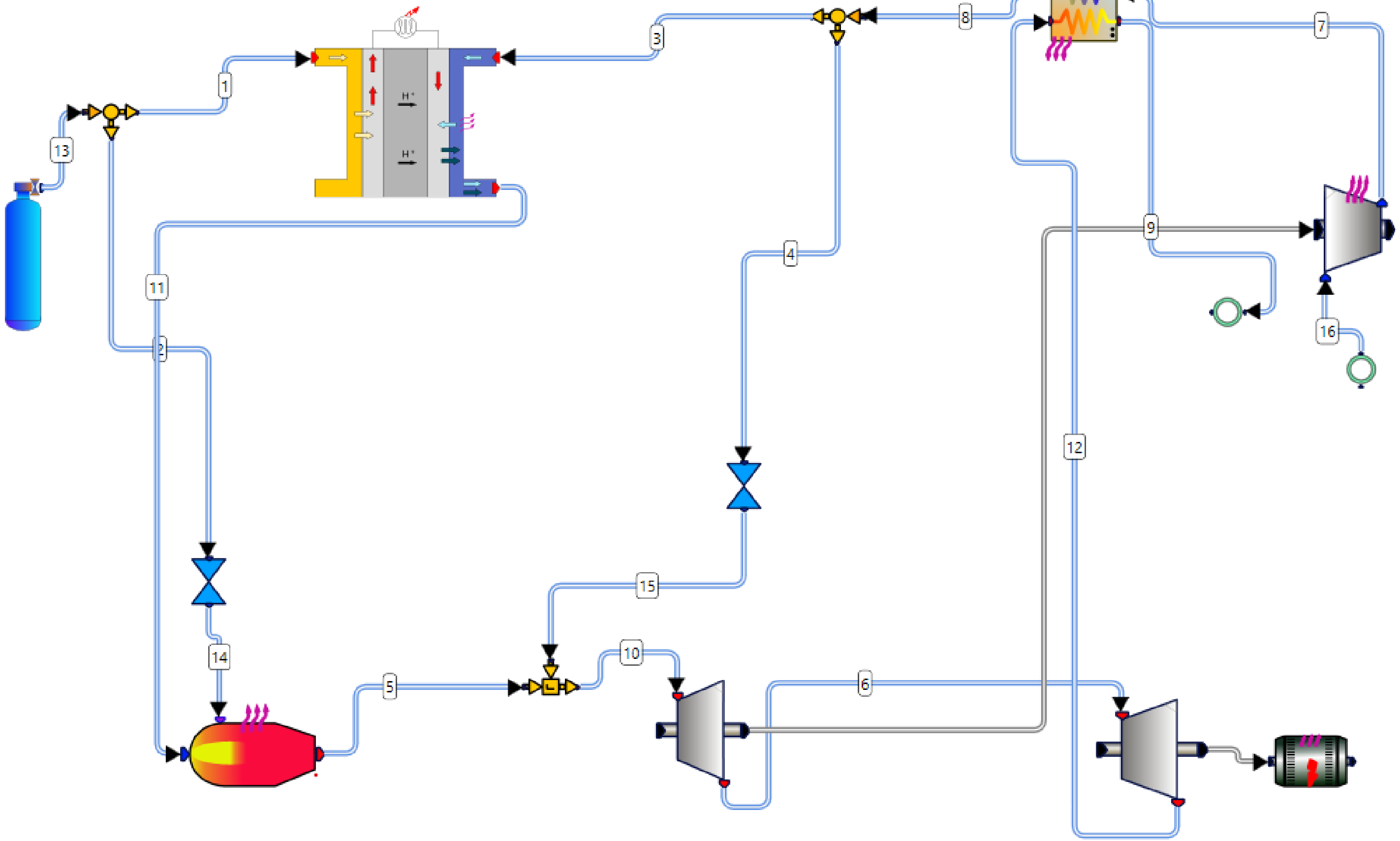
1. Major assumptions: 38% gravimetric index of LH_2 tank, 92% useable LH_2 fuel, 50% H_2 turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050, May 2020,- Print ISBN 978-92-9246-341-0 doi:10.2843/766989 EG-04-20-214-EN-C, -pp.96

HYBRID GAS TURBINE FUEL CELL SYSTEMS

Name	T_1 exp.	T_1 calc.	Relative measurement error %
Compressor	20	20	0
Fuel cell	578	578	0
Burner	769	769	0
Turbine 1	760	758.21	0.24
Turbine 2	575	588	2.2
Stack gas	216	230.761	6.4

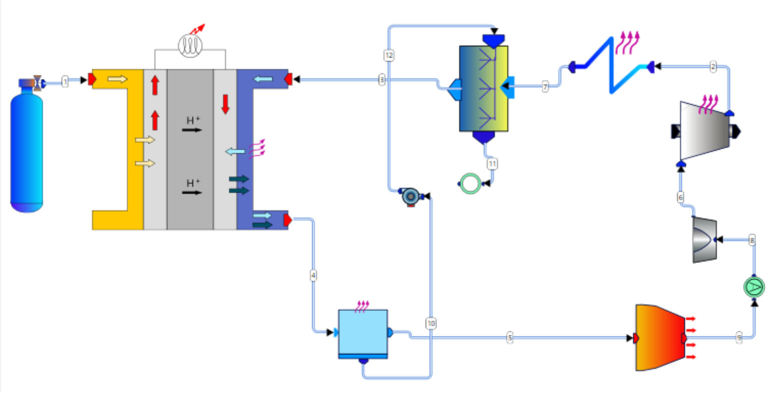




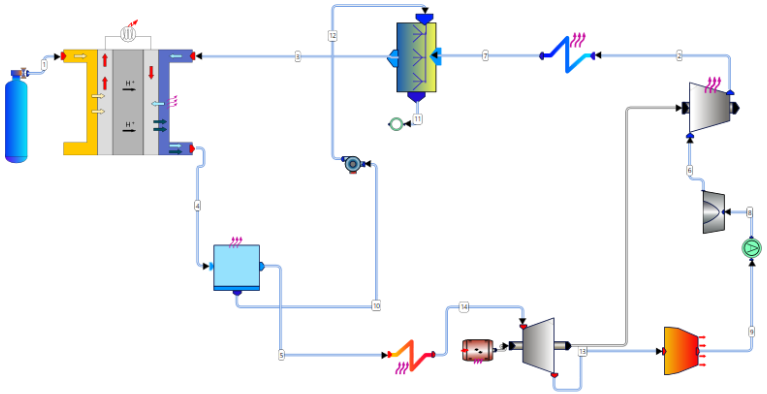
Hybrid Gas Turbine Fuel Cell Systems

SYSTEMS FOR CIVIL AIRCRAFT ONBOARD

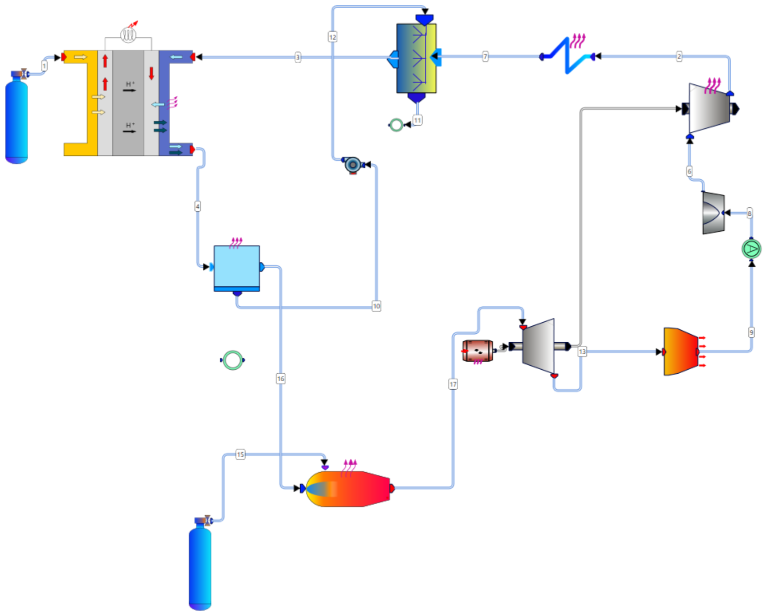
- Different systems using fuel cells were investigated in order to compare their complexity and performances for use in a civil aircraft



Base case arrangement (A)



Case with turbocharger (B)



Case with combustor and turbocharger (C)

FUEL CELL AND HYBRID AIRCRAFT PROTOTYPES

BOEING FUEL CELL DEMONSTRATOR

ENFICA-FC aircraft

AMPERE project by ONERA

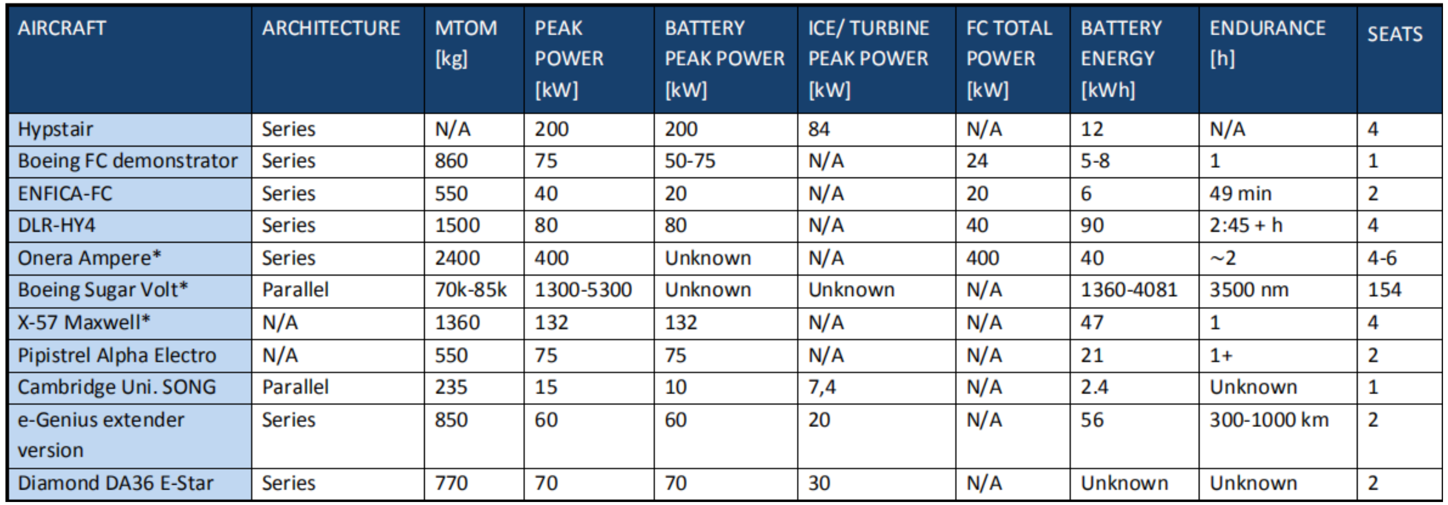
NASA X-57 Maxwell

Pipistrel Alpha Electro

HYPSTAIR PROJECT

DLR - HY4 aircraft

Boeing Sugar Volt



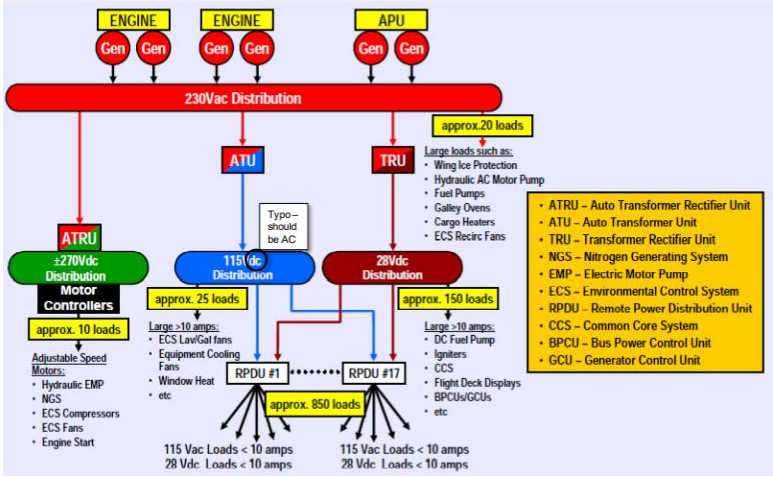
AIRCRAFT	ARCHITECTURE	MTOM [kg]	PEAK POWER [kW]	BATTERY PEAK POWER [kW]	ICE/ TURBINE PEAK POWER [kW]	FC TOTAL POWER [kW]	BATTERY ENERGY [kWh]	ENDURANCE [h]	SEATS
Hypstair	Series	N/A	200	200	84	N/A	12	N/A	4
Boeing FC demonstrator	Series	860	75	50-75	N/A	24	5-8	1	1
ENFICA-FC	Series	550	40	20	N/A	20	6	49 min	2
DLR-HY4	Series	1500	80	80	N/A	40	90	2:45 + h	4
Onera Ampere*	Series	2400	400	Unknown	N/A	400	40	~2	4-6
Boeing Sugar Volt*	Parallel	70k-85k	1300-5300	Unknown	Unknown	N/A	1360-4081	3500 nm	154
X-57 Maxwell*	N/A	1360	132	132	N/A	N/A	47	1	4
Pipistrel Alpha Electro	N/A	550	75	75	N/A	N/A	21	1+	2
Cambridge Uni. SONG	Parallel	235	15	10	7,4	N/A	2.4	Unknown	1
e-Genius extender version	Series	850	60	60	20	N/A	56	300-1000 km	2
Diamond DA36 E-Star	Series	770	70	70	30	N/A	Unknown	Unknown	2

Hybrid-Electric aircraft characteristics

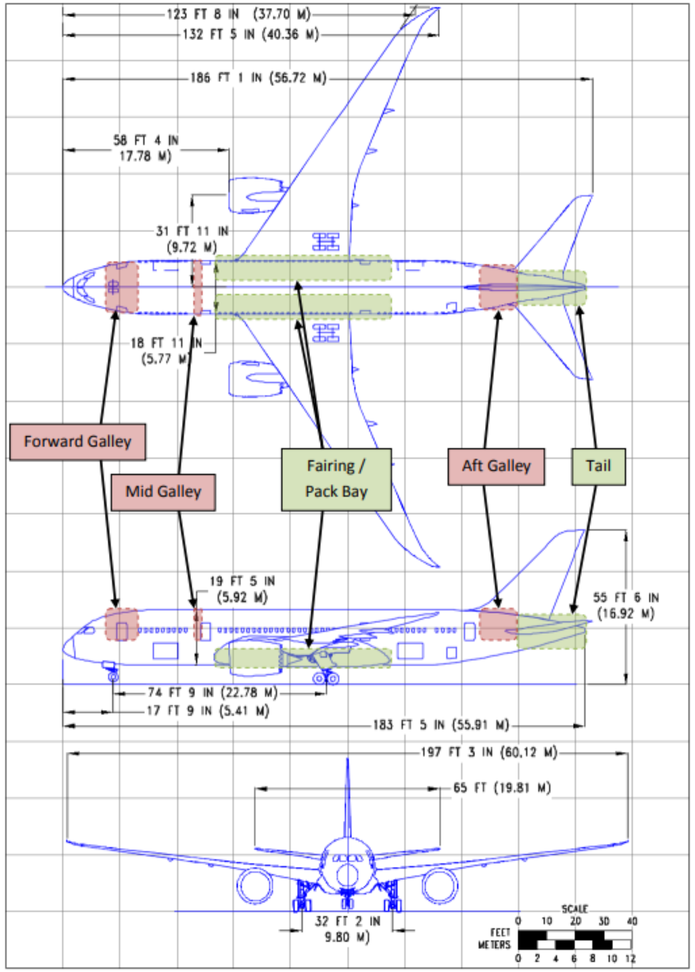
Concept of Modular Architecture for Hybrid Electric Propulsion of Aircraft.-mahepa. - Ref. Ares(2017)5981497 - 06/12/2017. - pp.87 - http://hy4.org/hy4-technology

EXAMPLE OF PROJECT-HYDROGEN FC FOR ON BORD COMMERCIAL AIRPLANE

Boeing 787-8 "more electric airplane" with many conventional systems converted to electric power



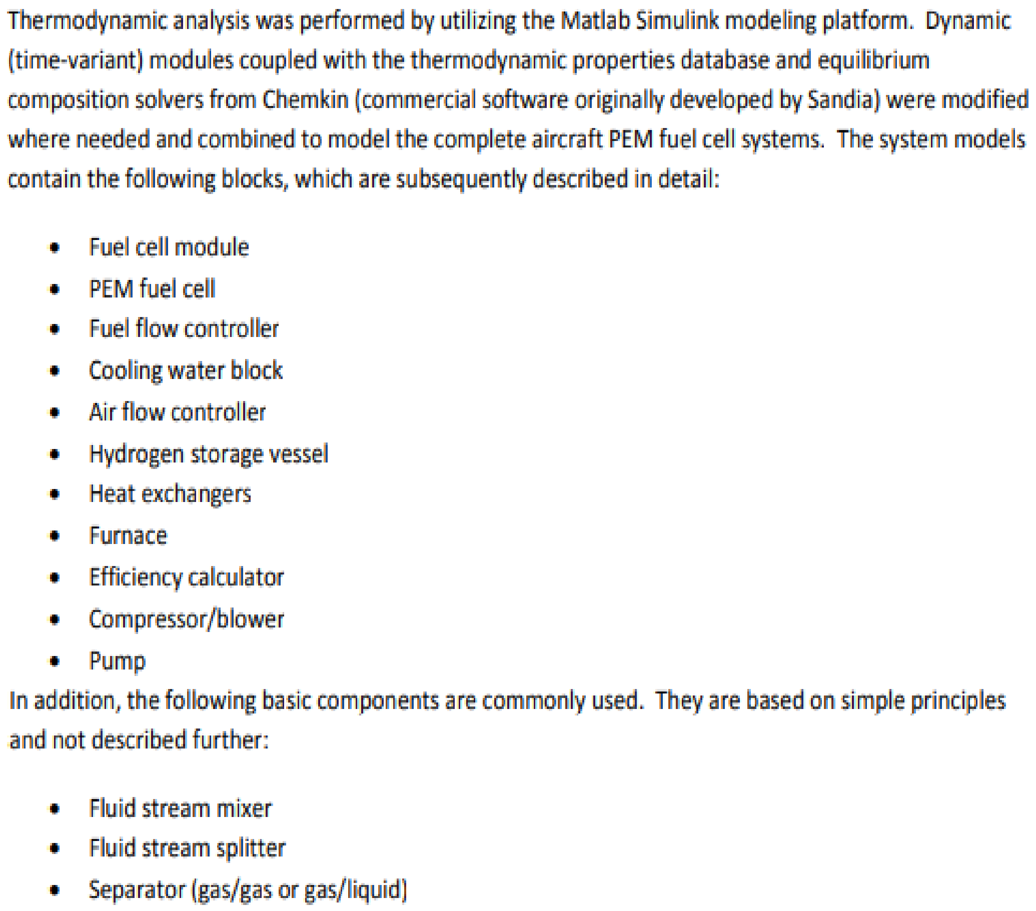
Schematic of Boeing 787 electrical system



Dimensioned outline drawing of 787-8 showing location of loads and options for the fuel cell and hydrogen storage

Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes (energy.gov)

EXAMPLE OF PROJECT-HYDROGEN FC FOR ON BORD COMMERCIAL AIRPLANE

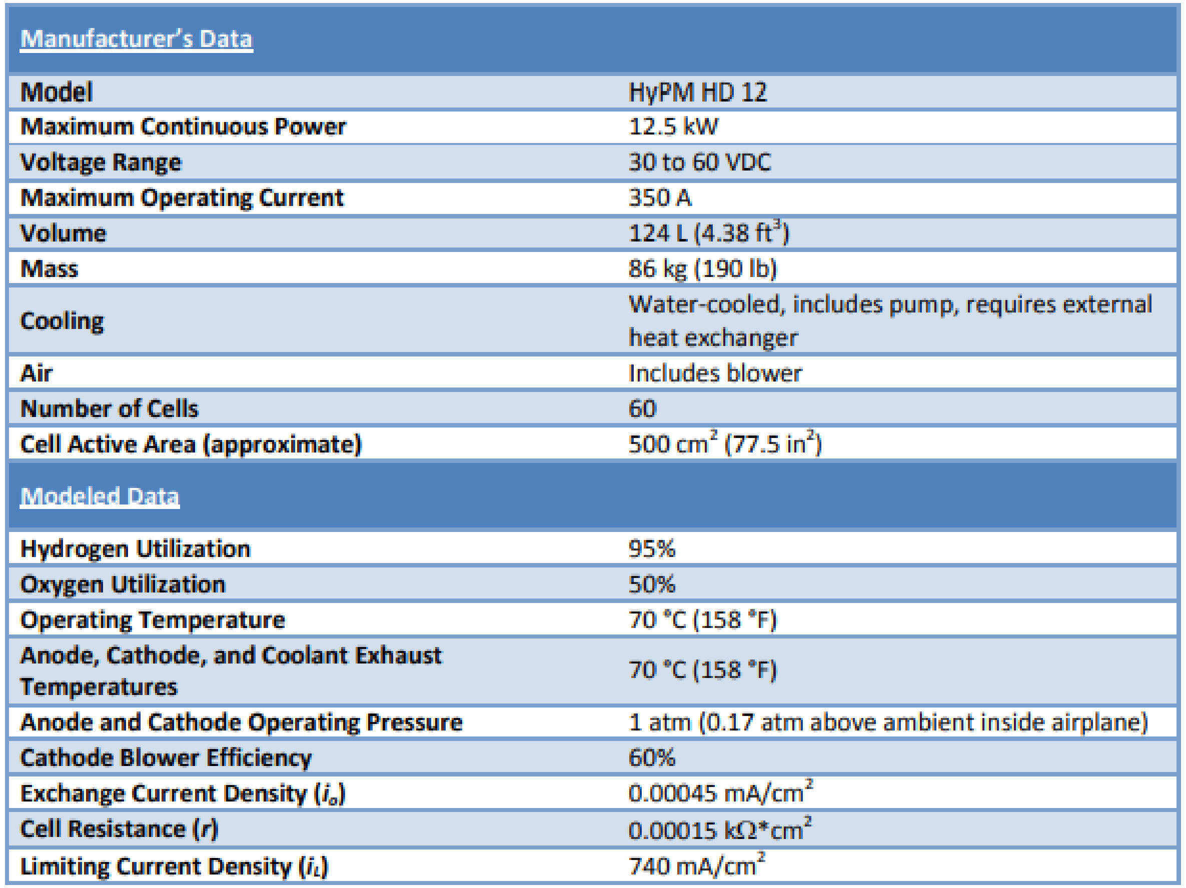


Thermodynamic analysis was performed by utilizing the Matlab Simulink modeling platform. Dynamic (time-variant) modules coupled with the thermodynamic properties database and equilibrium composition solvers from Chemkin (commercial software originally developed by Sandia) were modified where needed and combined to model the complete aircraft PEM fuel cell systems. The system models contain the following blocks, which are subsequently described in detail:

- Fuel cell module
- PEM fuel cell
- Fuel flow controller
- Cooling water block
- Air flow controller
- Hydrogen storage vessel
- Heat exchangers
- Furnace
- Efficiency calculator
- Compressor/blower
- Pump

In addition, the following basic components are commonly used. They are based on simple principles and not described further:

- Fluid stream mixer
- Fluid stream splitter
- Separator (gas/gas or gas/liquid)

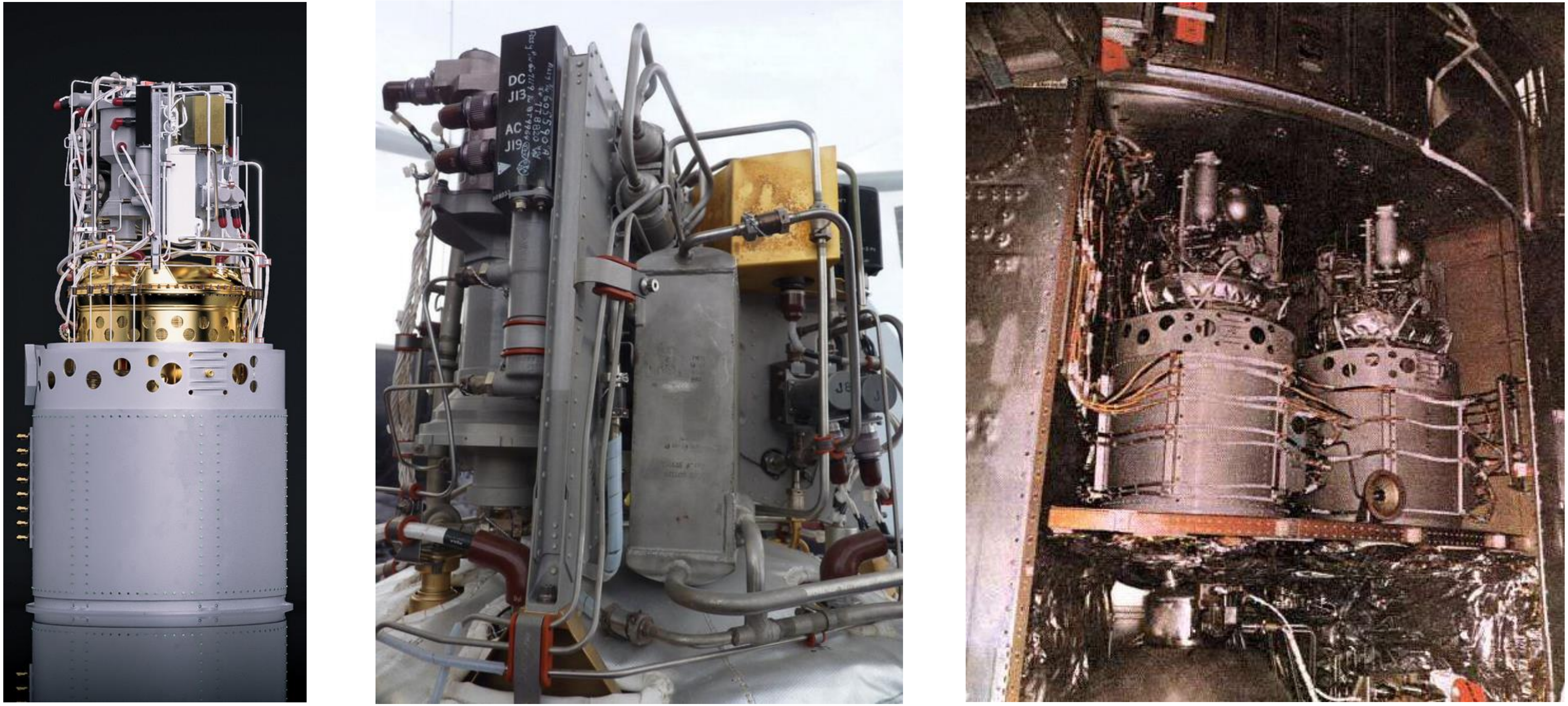


Manufacturer's Data	
Model	HyPM HD 12
Maximum Continuous Power	12.5 kW
Voltage Range	30 to 60 VDC
Maximum Operating Current	350 A
Volume	124 L (4.38 ft^3)
Mass	86 kg (190 lb)
Cooling	Water-cooled, includes pump, requires external heat exchanger
Air	Includes blower
Number of Cells	60
Cell Active Area (approximate)	500 cm^2 (77.5 in^2)
Modeled Data	
Hydrogen Utilization	95%
Oxygen Utilization	50%
Operating Temperature	70 °C (158 °F)
Anode, Cathode, and Coolant Exhaust Temperatures	70 °C (158 °F)
Anode and Cathode Operating Pressure	1 atm (0.17 atm above ambient inside airplane)
Cathode Blower Efficiency	60%
Exchange Current Density (i_o)	0.00045 mA/cm^2
Cell Resistance (r)	0.00015 kΩ*cm^2
Limiting Current Density (i_L)	740 mA/cm^2

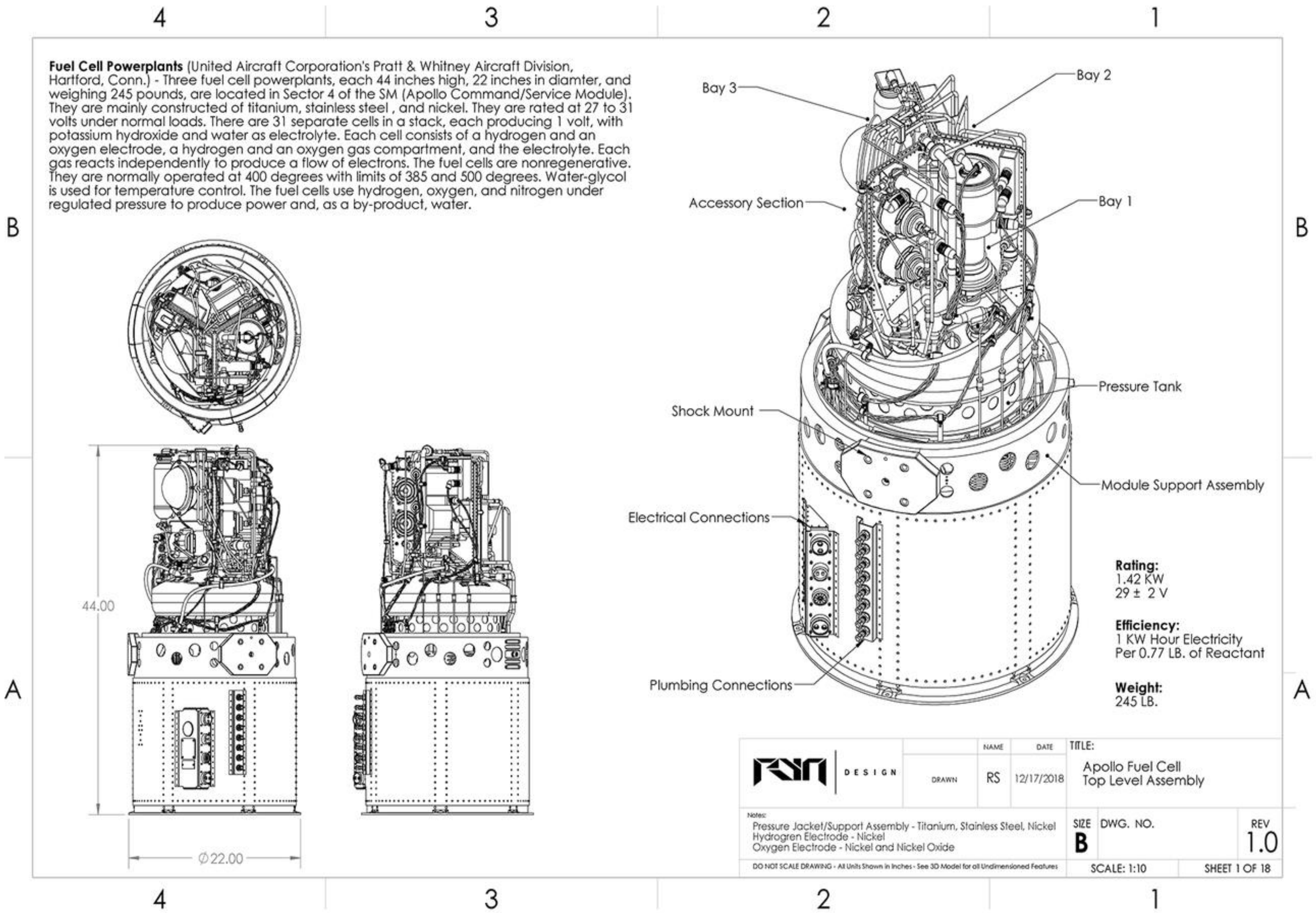
Data for modeled PEMFC

Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes (energy.gov)

APOLLO FUEL CELL



DRAWING OF FUEL CELL MODULE OF APOLLO 13



Fuel Cell Powerplants (United Aircraft Corporation's Pratt & Whitney Aircraft Division, Hartford, Conn.) - Three fuel cell powerplants, each 44 inches high, 22 inches in diamter, and weighing 245 pounds, are located in Sector 4 of the SM (Apollo Command/Service Module). They are mainly constructed of titanium, stainless steel , and nickel. They are rated at 27 to 31 volts under normal loads. There are 31 separate cells in a stack, each producing 1 volt, with potassium hydroxide and water as electrolyte. Each cell consists of a hydrogen and an oxygen electrode, a hydrogen and an oxygen gas compartment, and the electrolyte. Each gas reacts independently to produce a flow of electrons. The fuel cells are nonregenerative. They are normally operated at 400 degrees with limits of 385 and 500 degrees. Water-glycol is used for temperature control. The fuel cells use hydrogen, oxygen, and nitrogen under regulated pressure to produce power and, as a by-product, water.

Rating:
1.42 KW
29 ± 2 V

Efficiency:
1 KW Hour Electricity
Per 0.77 LB. of Reactant

Weight:
245 LB.

DESIGN

	NAME	DATE	TITLE:
DRAWN	RS	12/17/2018	Apollo Fuel Cell Top Level Assembly

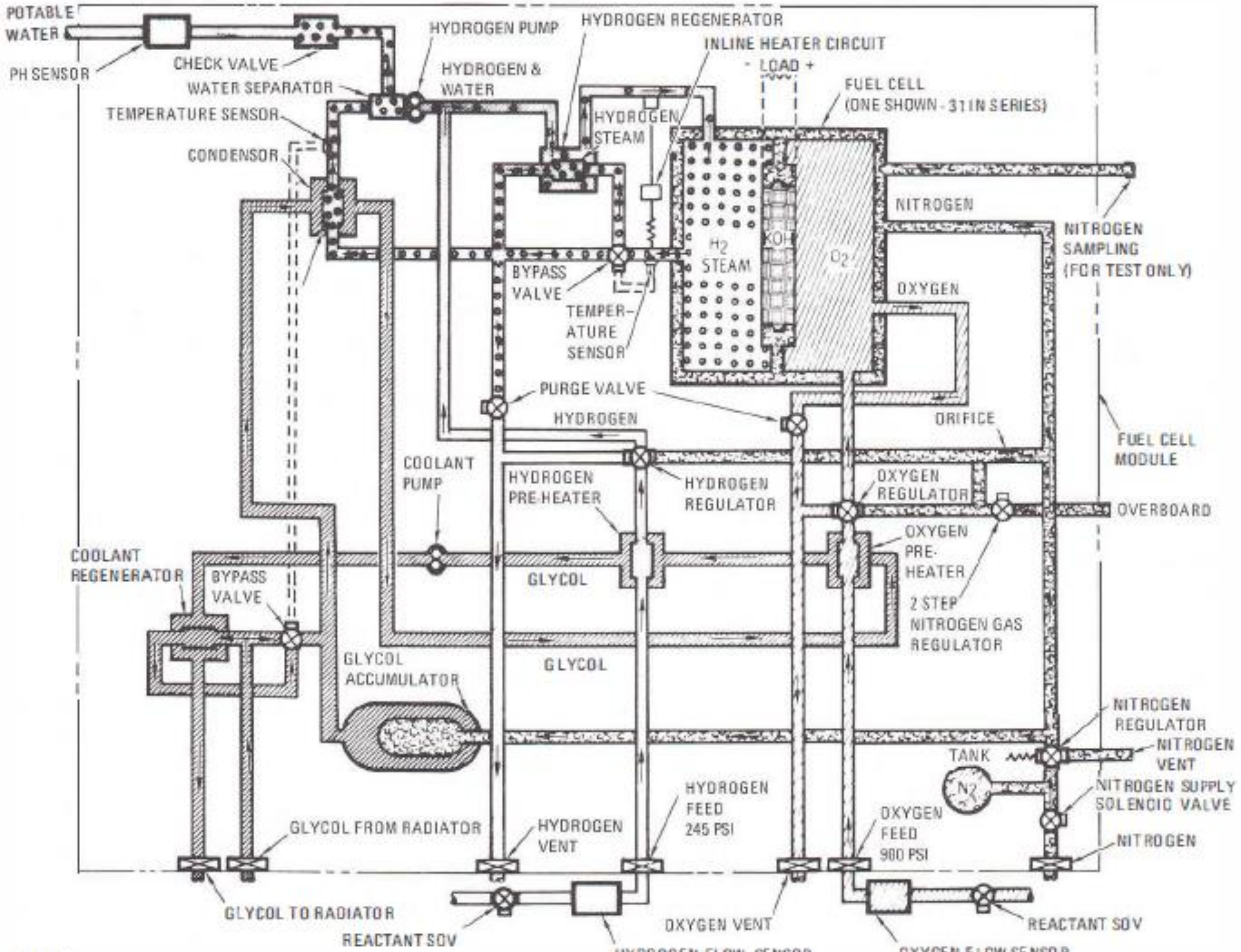
Notes:
Pressure Jacket/Support Assembly - Titanium, Stainless Steel, Nickel
Hydrogren Electrode - Nickel
Oxygen Electrode - Nickel and Nickel Oxide

SIZE	DWG. NO.	REV
B		1.0

DO NOT SCALE DRAWING - All Units Shown in Inches - See 3D Model for all Undimensioned Features

SCALE: 1:10
SHEET 1 OF 18

SCHEMATIC OF FUEL CELL MODULE OF APOLLO 13

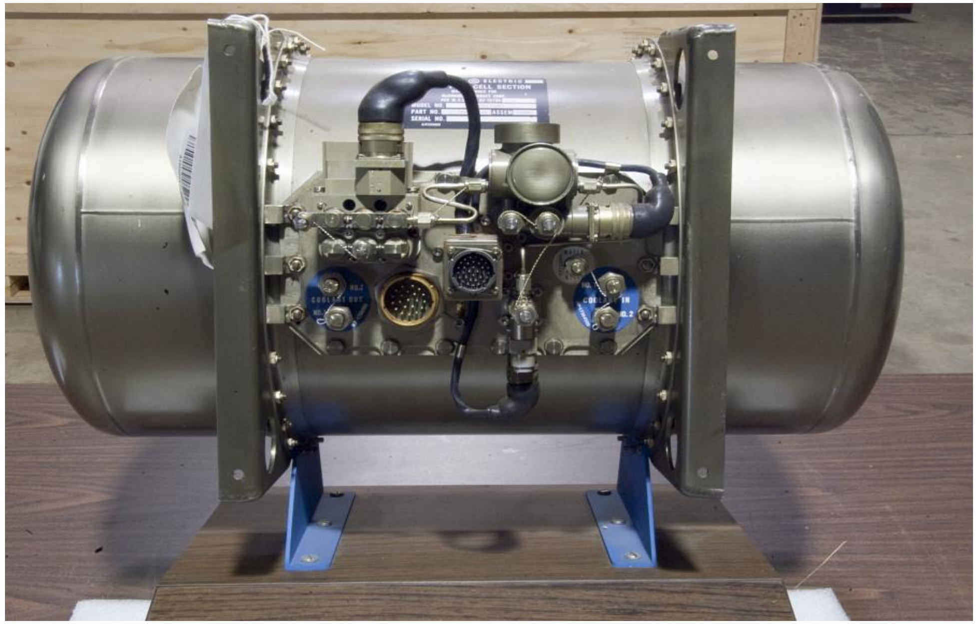


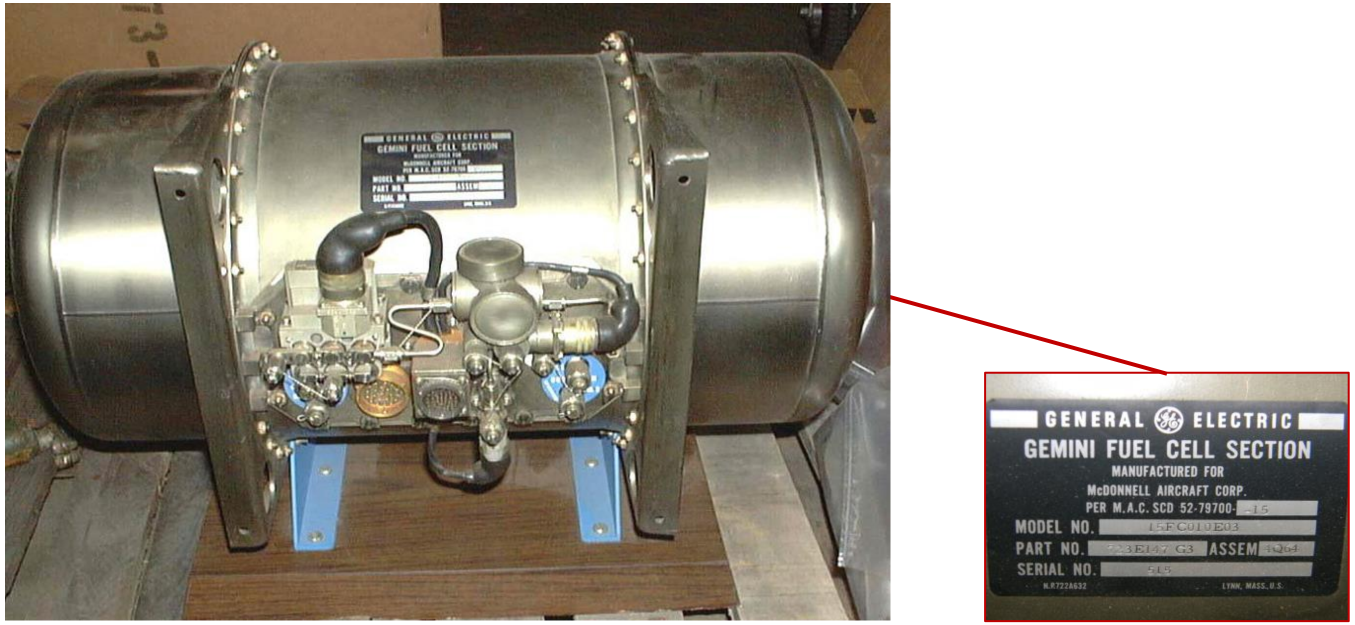
P-153

Schematic of fuel cell module

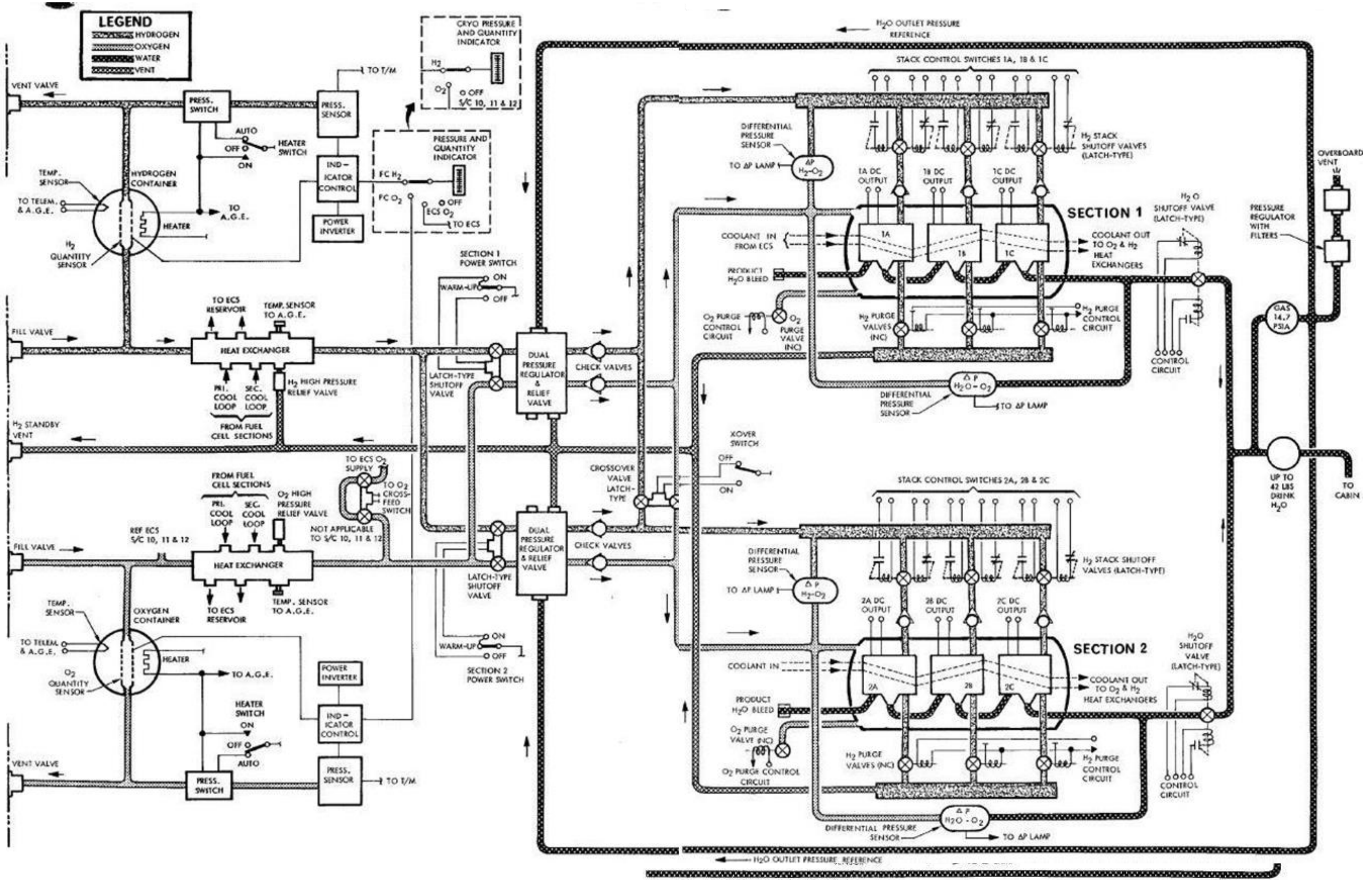
GEMINI FUEL CELL (APOLLO-SOYUZ MISSION)

- Test version of electric-power generating device used during 7 missions in 1965-66.
- Run for 1000+ hours to demonstrate long-duration functioning.
- Gemini PEMFC used liq. oxygen and liq. hydrogen to generate electricity, with water as a byproduct.
- The Gemini program pioneered the use of fuel cells in space
  - Similar technology subsequently used in the Apollo and Space Shuttle programs.



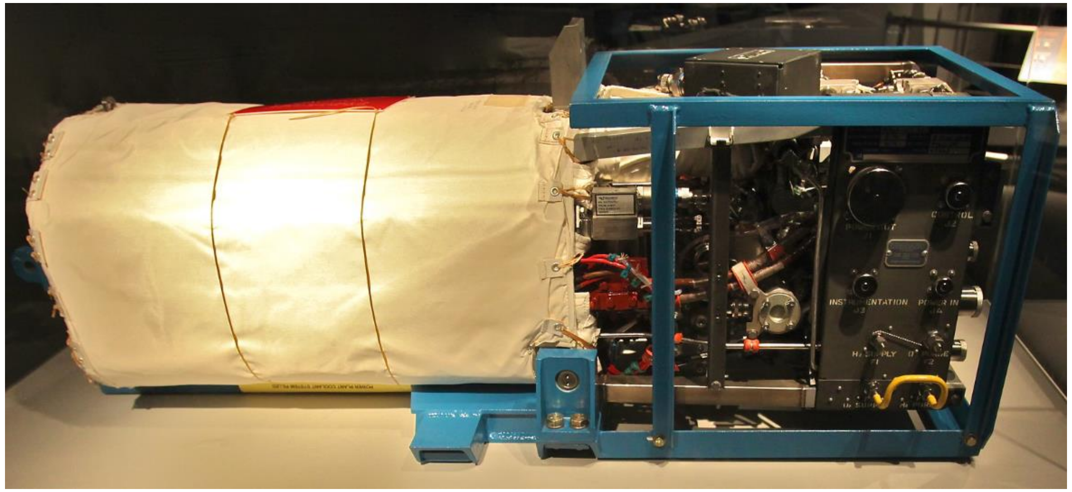


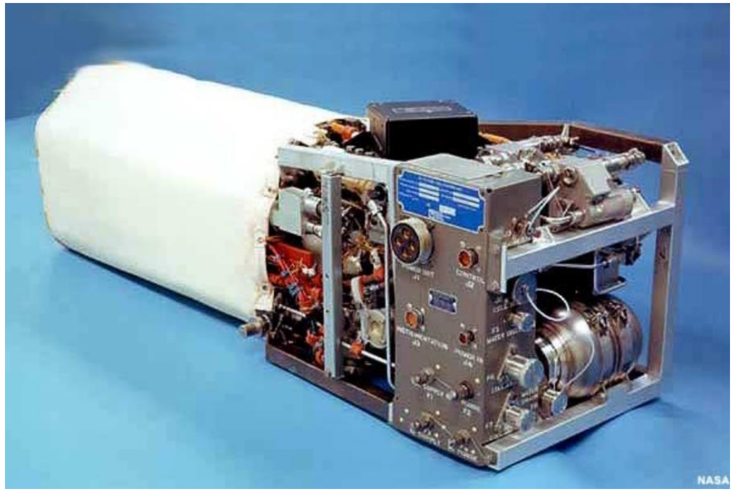
SCHEMATIC ELECTRICAL POWER SYSTEM (GEMINI)



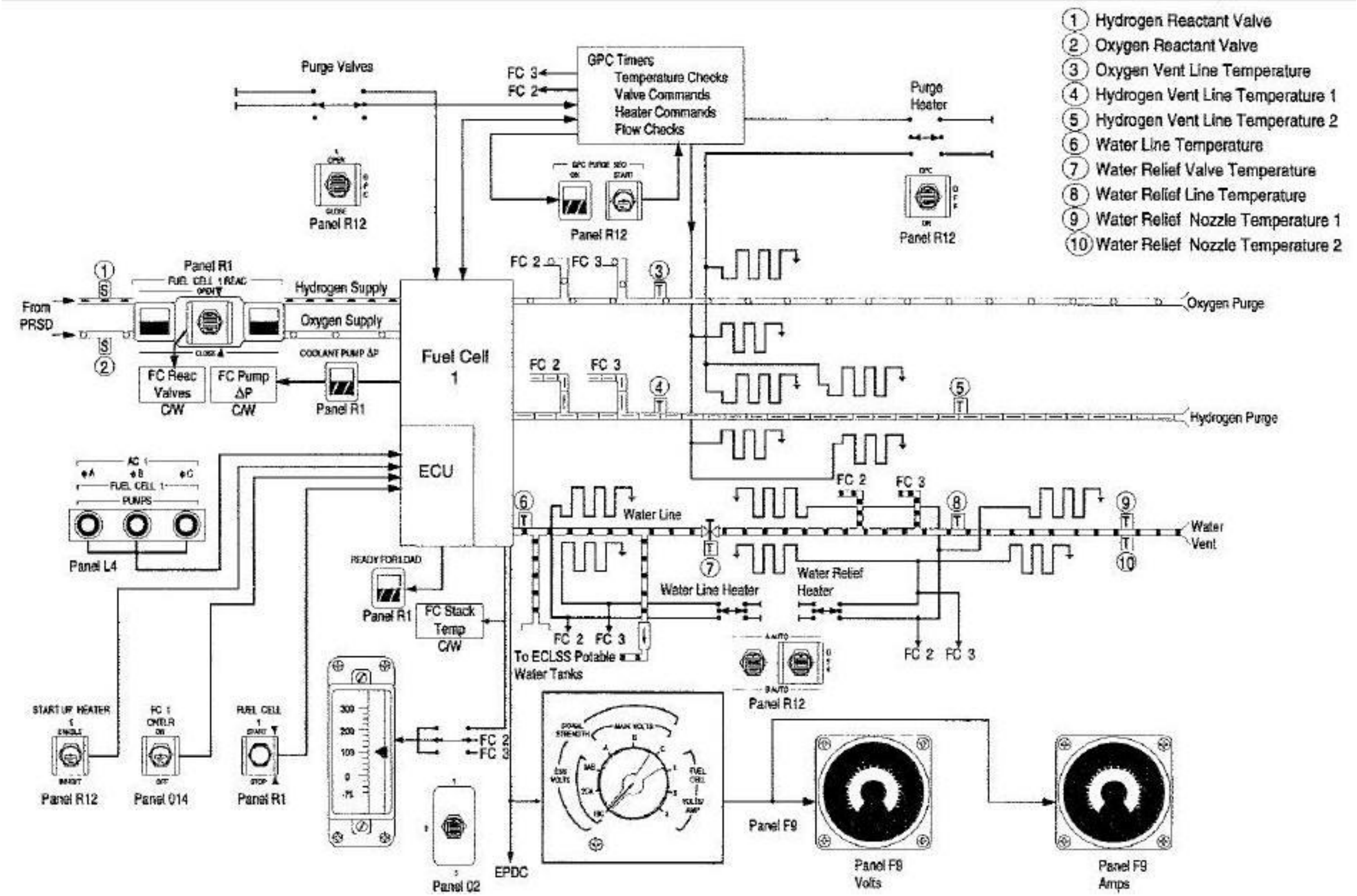
SPACE SHUTTLE FUEL CELL POWER PLANT (NASA)

- 3 FC power plants individually coupled to reactant (H_2 & O_2 stored in nearby cryogenic tanks) distribution subsystem, heat rejection subsystem, potable water storage subsystem, and electrical power distribution and control subsystem.
  - Excess heat directed to fuel cell heat exchangers into Freon coolant loops.
  - Water directed to the potable water storage subsystem.
- 3661 Wh/kg of water formed | Up to 11 L (kg) of water formed per hour of flight
  - Requires 1.12 kg of hydrogen & 8.78 kg of oxygen to produce 40,271 watts of continuous power each hour.
  - Operated at 92°C and 0.40 to 0.44 MPa.

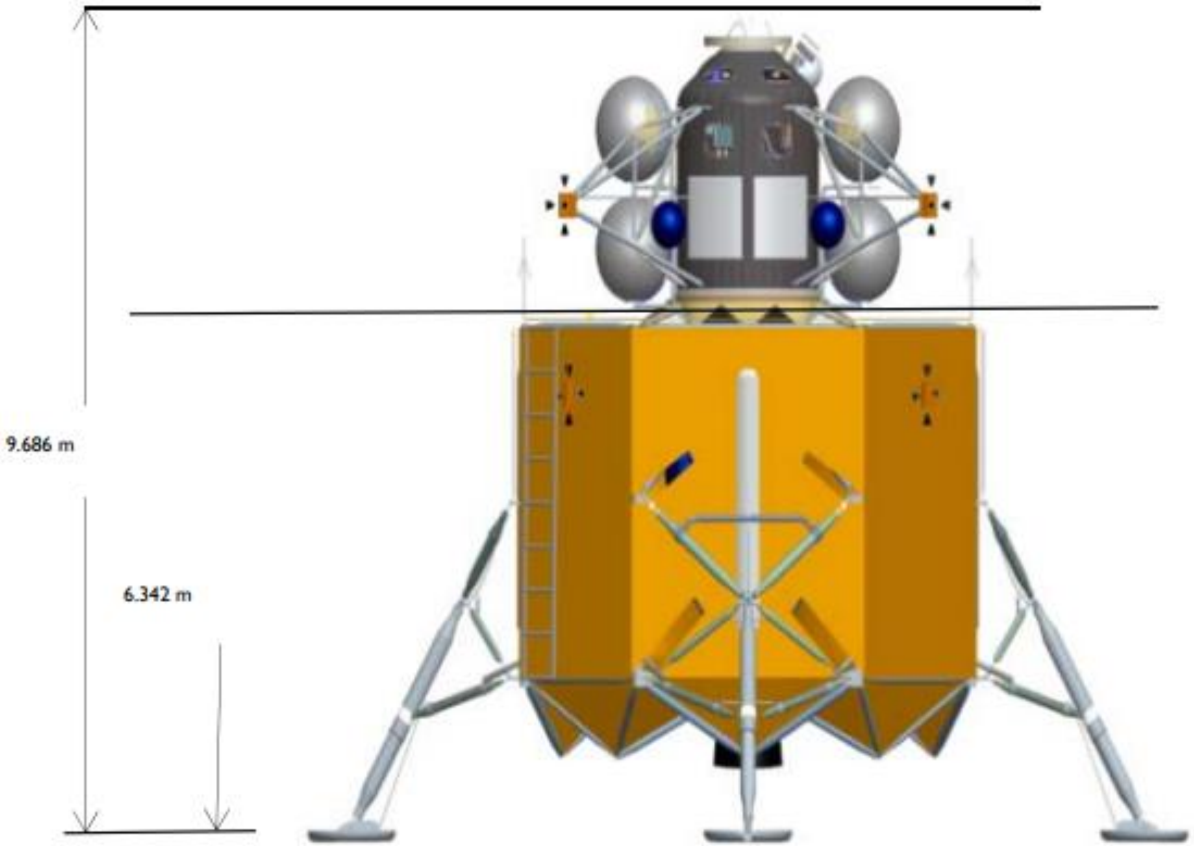




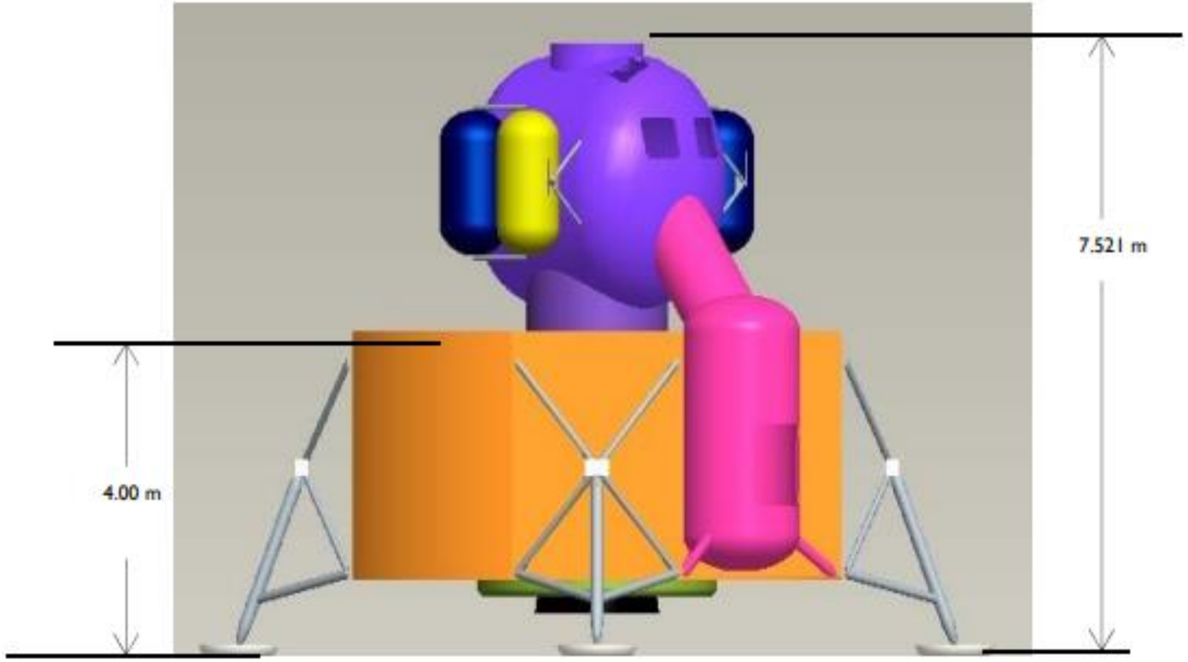
SPACE SHUTTLE ELECTRICAL SYSTEM SCHEMATICS



LANDERS

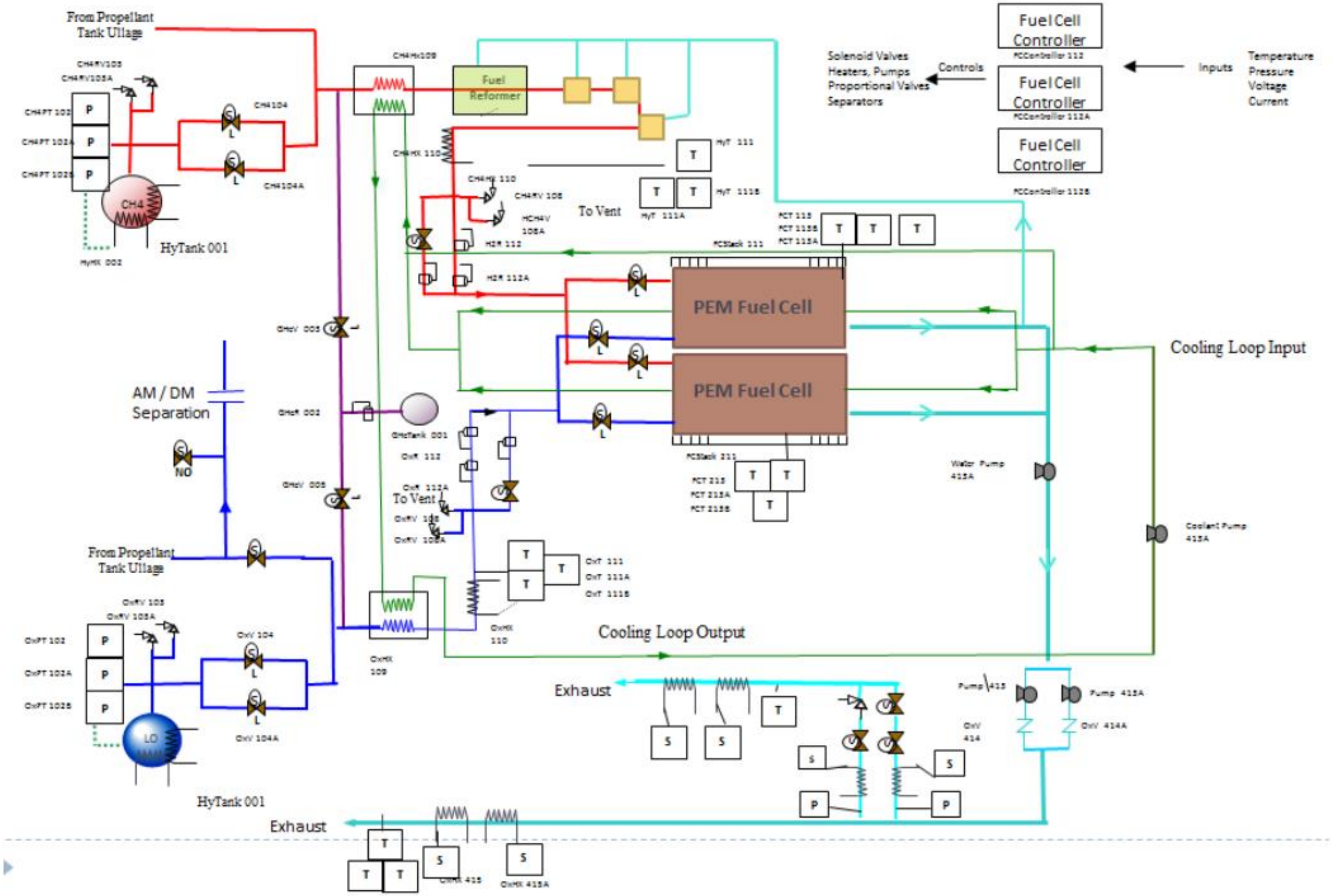


LH2/LO2 Lander Size

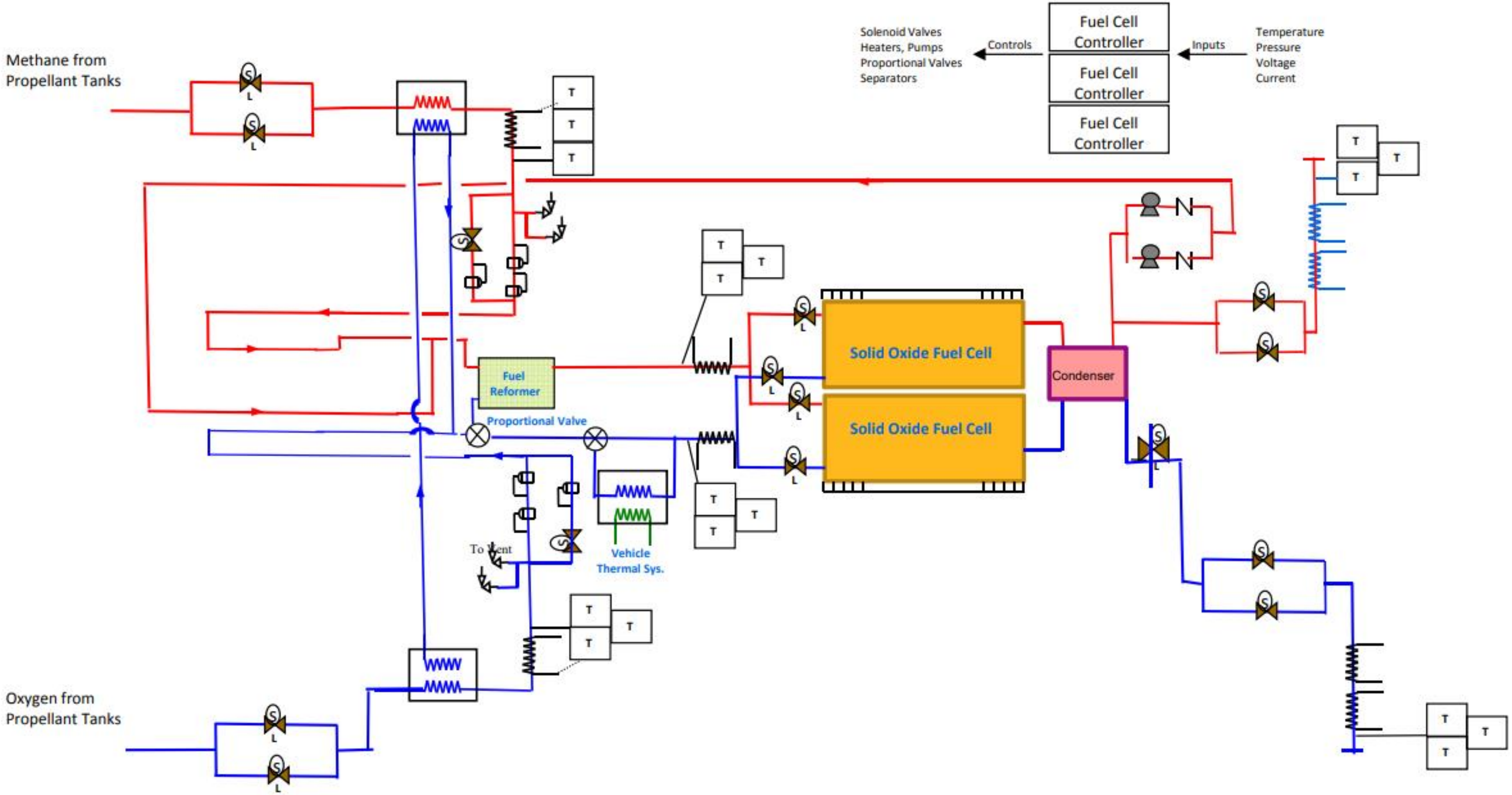


LOX/Methane Lander Size

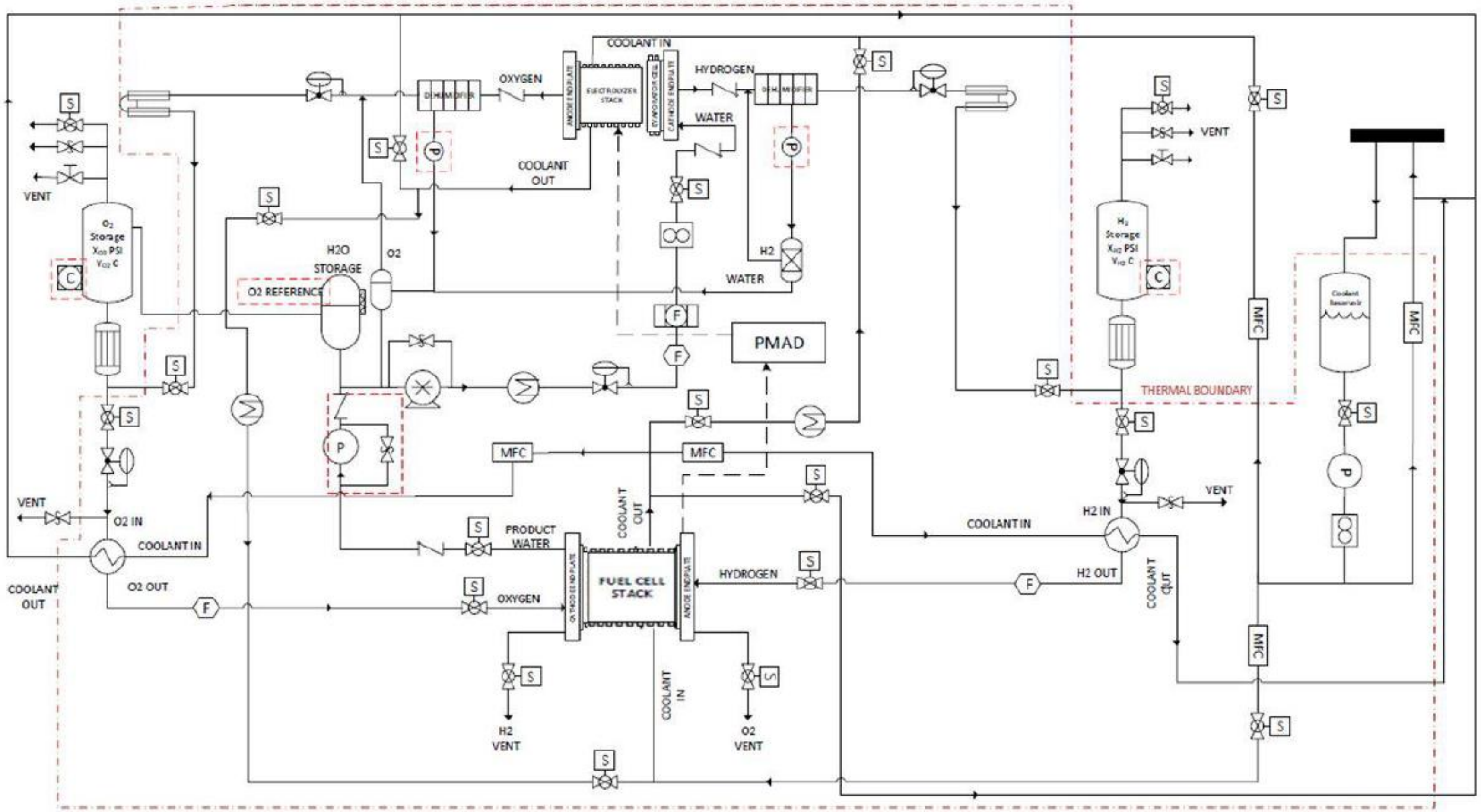
SCHEME OF FUEL CELL OF LANDER (PEM)



SCHEME OF FUEL CELL OF LANDER (SOFC)



REGENERATIVE FUEL CELL POWER SYSTEMS FOR LUNAR AND MARTIAN SURFACE EXPLORATION



PEM FC-based RFC piping and instrumentation diagram (P&ID) - Monica C. Guzik1, Ian J. Jakupca2, Ryan P. Gilligan3, William R. Bennett4, Phillip J. Smith5, and James Fincannon6 (National Aeronautics and Space Administration, John H. Glenn Research Center, Cleveland, OH, 44135)

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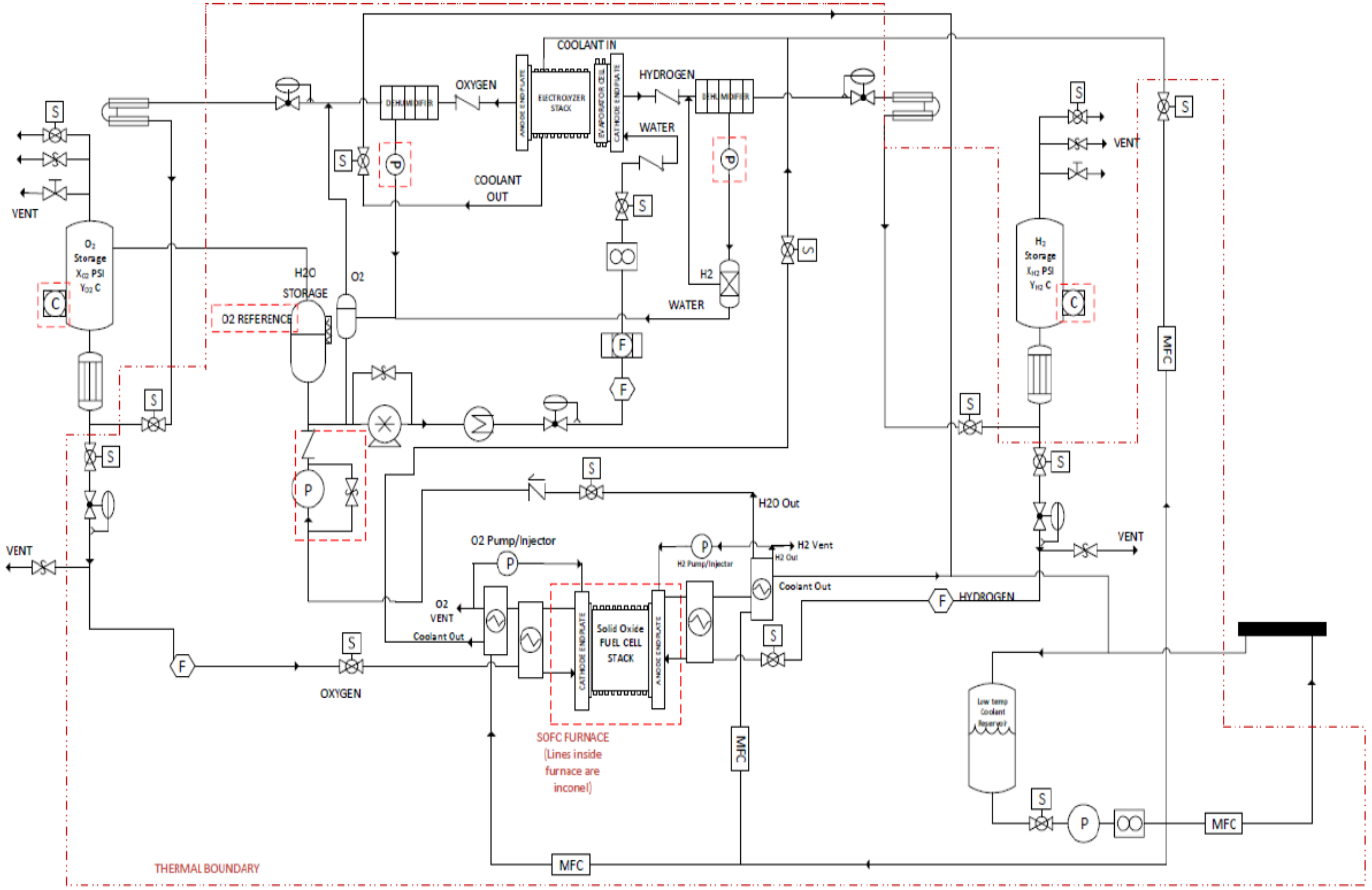


SOFC-based RFC piping and instrumentation diagram (P&ID) - Monica C. Guzik1, Ian J. Jakupca2, Ryan P. Gilligan3, William R. Bennett4, Phillip J. Smith5, and James Fincannon6 (National Aeronautics and Space Administration, John H. Glenn Research Center, Cleveland, OH, 44135)

3.4 Misc. Applications

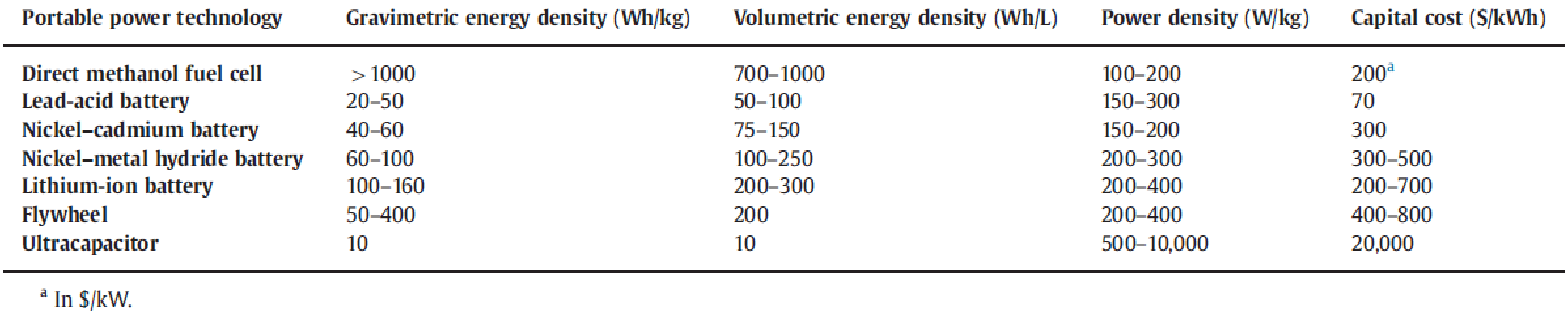
PORTABLE POWER GENERATION

- Portable applications for FCs mainly focused on two main markets.
  - Portable power generators designed for
    - Light outdoor personal uses: Camping and climbing
    - Light commercial applications: Portable signage and surveillance, and emergency relief efforts power
  - Consumer electronic devices: Laptops, cell phones, radios, camcorders, and any electronic device traditionally running on a battery.
- On a MW-level, portable sector accounts is <1% of worldwide FC shipments in 2008–2011
  - Portable FCs ~5-500W

- Advantages for future portable personal electronics: Modularity and high energy density of FC (5–10x higher vs. typical rechargeable battery)
- Advantages for portable military equipment (direct methanol fuel cells (DMFCs), reformed methanol fuel cells (RMFCs), and PEMFCs): Silent operation, high power and energy density, and low weight

- Challenges to resolve for that market:
  - Heat dissipation | Emissions dissipation | Noise | Integrated fuel storage and delivery | Shock and vibrations endurance | Response time to sharp and repeated demand fluctuations | Operation under various operation conditions | Tolerance to air impurities | Reusability and recyclability of fuel containers and area exposed to oxygenated air

FC TECHNO-ECONOMIC COMPETITION (PORTABLE POWER)



Portable power technology	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Power density (W/kg)	Capital cost ($/kWh)
Direct methanol fuel cell	> 1000	700–1000	100–200	200[a]
Lead-acid battery	20–50	50–100	150–300	70
Nickel–cadmium battery	40–60	75–150	150–200	300
Nickel–metal hydride battery	60–100	100–250	200–300	300–500
Lithium-ion battery	100–160	200–300	200–400	200–700
Flywheel	50–400	200	200–400	400–800
Ultracapacitor	10	10	500–10,000	20,000

[a] In $/kW.

Technoeconomic comparison between fuel cells and their competitors in the portable power sector
O.Z. Sharaf, M.F. Orhan, Renewable and Sustainable Energy Revies 32 (2014) 810-853

MARINE PROPULSION

- Most common FC use in marine industry as APUs on-board of boats and yachts
- Promising future marine FC propulsion markets in submarines, ferries, underwater vehicles, boats, yachts, and even cargo ships.
  - Technical challenges related to reliability, lifetime, shock resistance, and tolerance to sea air salt content
  - PEMFCs, SOFCs, and MCFCs as most promising

- First yacht with certified hybrid PEMFCs/lead-gel batteries system for both propulsion and APU successfully demonstrated in Germany in 2003.
- World's first commercial passenger ship running on a hybrid PEMFCs/lead-gel battery system put into service in Germany in 2008
  - Capacity of 100 passengers with twice efficiency of conventional diesel-based ship

- Remarkable advantages of FC-based submarines: Stay underwater without surfacing for refueling much longer when compared to a conventional diesel electric submarine
  - German submarines can stay underwater for weeks using stored oxygen and hydrogen vs. ~2 two days for purely diesel-based propulsion
  - High efficiencies (~70%) due to usage of pure oxygen instead of air
  - Lower heat and magnetic signatures vs. nuclear-or diesel-based submarines
  - Almost no noise due to the static operation of the fuel cell.

CONCLUSIONS

- Fuel cells represent a very promising yet challenging path to a cleaner future across a very wide range of industries
- Different FC types provide different benefits that can be exploited based on the system of interest
- Basic unit cell understanding involves multi-disciplinary engineering which gets more complex as the stack is considered and even more so when the full system (including Balance of Power equipment) is included
  - Improvements in BoP sub-systems are expected to make FCs even more attractive
    - Turbomachinery components and related systems play a significant role in this!
- Power density curve provides indication of flexibility of output power produced by FC stack. Polarization curve, in combination with the power density curve, is used to determine optimum operation points in terms of voltage, current, and power.
- General public acceptance linked to hydrogen remains a major hurdle to overcome
  - Demonstrators (busses, forklifts, etc.) should facilitate this aspect

SOME POTENTIALS FUEL CELL R&D IMPROVEMENTS

- New electrolyte materials
- Cost reduction
- Contamination minimization
- Dealing with ultra cold and hot conditions
- Seals for high-temperature FCs
- Stack water management optimization
- Chemical and temperature sensors cost reduction and improved reliability and durability in stationary applications
- Reduce packaging, cost and performance requirements for air management systems
- Minimize parasitic loads (air management, humidifiers, etc.)
- New non-toxic coolants
- Increase performance of humidifiers in transportation applications
- Develop fuel flexibility in reformers and minimize cost
- Etc.

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