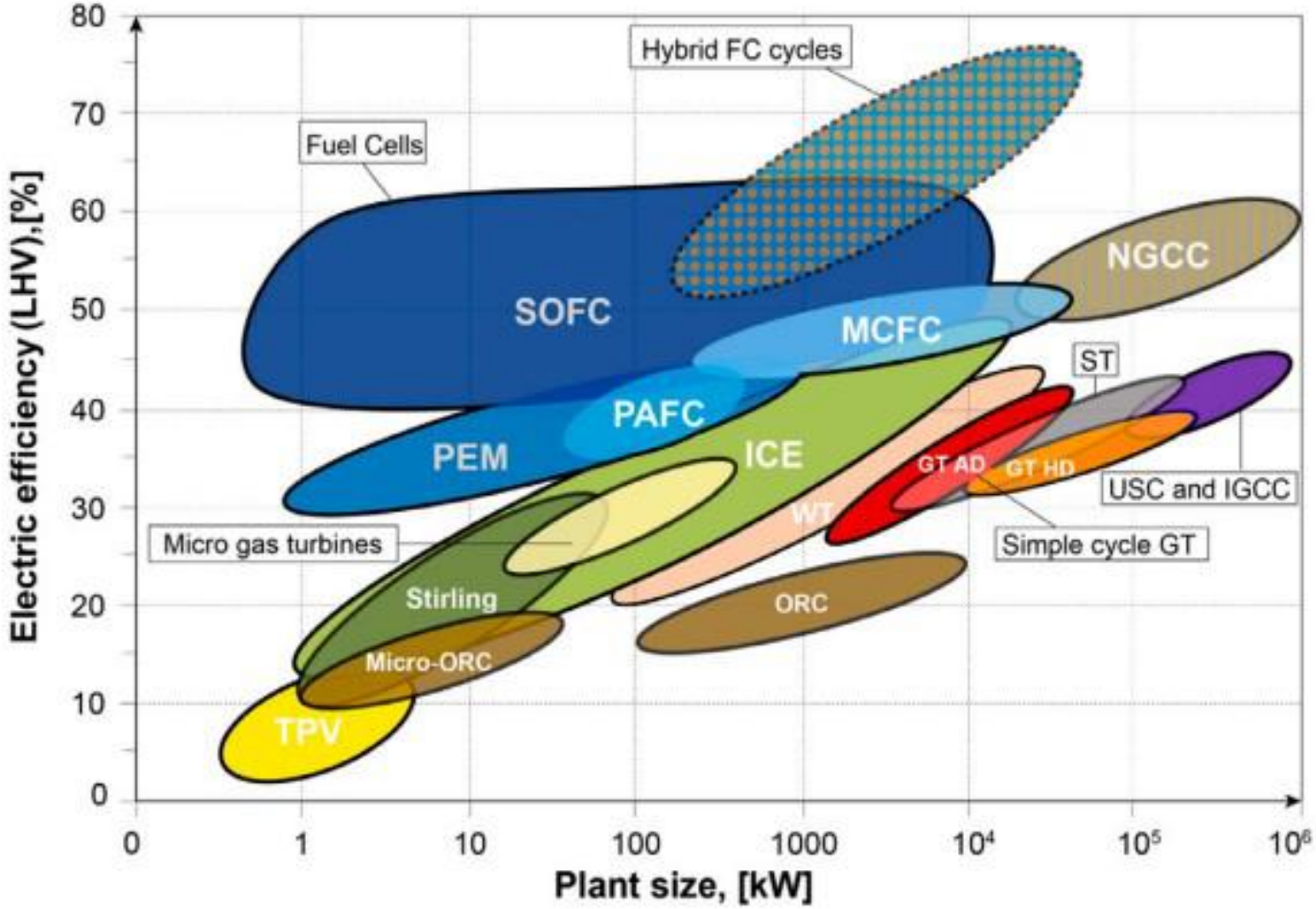
- 7 May Polidoro. H_2 in boilers
- 14 May Fincantieri: H_2 for maritime transport
- Visit to DISC lab on SOFC

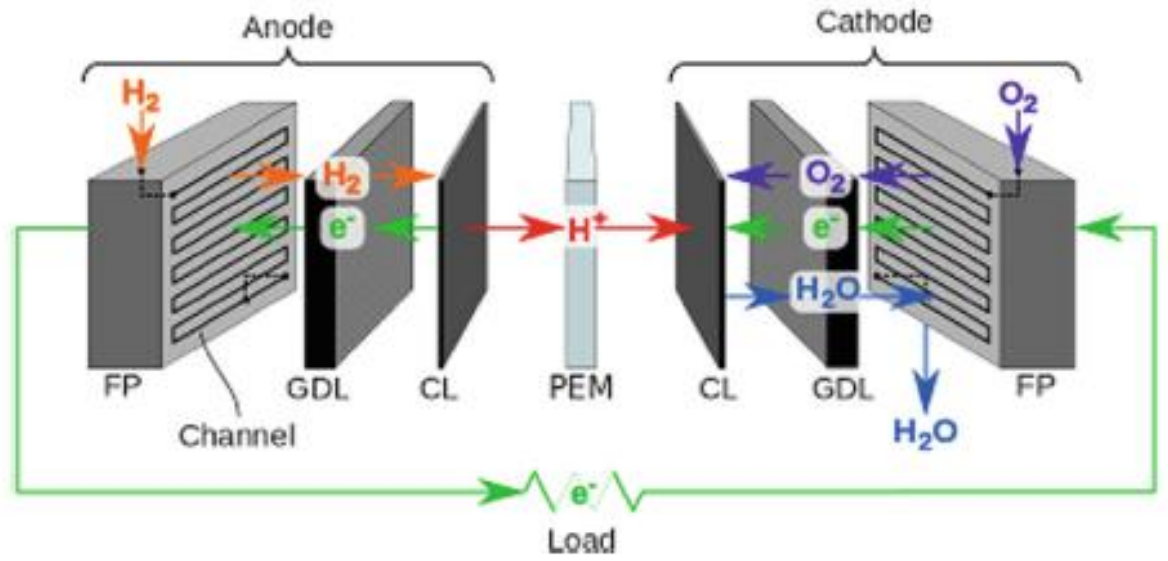
Hydrogen use as energy vector

FUEL CELLS


Electric efficiency (LHV),[%]
80
70
60
50
40
30
20
10
0
0
1
10
100
1000
10⁴
10⁵
10⁶
Plant size, [kW]
Hybrid FC cycles
Fuel Cells
SOFC
MCFC
NGCC
ST
PAFC
PEM
ICE
GT AD
GT HD
USC and IGCC
WT
Micro gas turbines
Simple cycle GT
Stirling
ORC
Micro-ORC
TPV

Characteristics	PEMFCs	DMFCs	SOFCs	AFCs	PAFCs	MCFCs
Operating temperature (°C)	60–110	70–130	500–1000	60–250	150–210	500–700
System efficiency (%)	40–55	40	40–60	60–70	40–50	50–60
Combined heat and power efficiency (%)	70–90	80	<90	>80	>85	>80
Stack power (kW)	1–100	0.001–100	0.5–2.000	1–100	100–400	300–3.000,000
Energy density (kW hr/m^3)	112.2–770	29.9–274	172–462.09	—	—	25–40
Power density (kW/m^3)	3.8–6.5	~0.6	4.20–19.25	~1	0.8–1.9	1.5–2.6
Lifespan (hr)	2.000–3.000	1.000–4500	1.000	8.000	>50,000	7.000–8.000
Cell voltage (V)	1.1	0.2–0.4	0.8–1.0	1.0	1.1	0.7–1.0
Nominal current density (A/cm^2)	0.5–1	0.15–0.3	—	0.1–0.3	0.15	0.14–0.16
Electrolyte	Polymer membrane	—	Yttria-stabilized zirconia (YSZ)	KOH	Phosphoric acid (H_3PO_4)	Molten carbonate
Fuel type	Hydrogen	Methanol	Hydrogen, natural gas biogas coal gas	Hydrogen ammonia	Hydrogen methanol	Natural gas biogas coal gas
Startup time	<1 min	—	60 min	<1 min	—	10 min
Advantages	(1) Small size (2) Lightweight (3) Quick startup time and load response (4) Low temperature	(1) Low cost of fuel methanol, low operational temperature, and pressure (2) High power density	(1) High efficiency (2) Fuel flexibility. (3) Solid electrolyte (4) Suitable for CHP (5) Hybrid/gas turbine cycle	(1) A wider range of stable materials allows components to be priced lower (2) Low temperature (3) Quick startup	(1) Suitable for CHP (2) Increased tolerance to fuel impurities	(1) Fuel variety (2) High efficiency
Disadvantages	(1) Sensitivity to low temperature, humidity, salinity, and fuel impurities	(1) Low reaction kinetics (2) Methanol is very toxic and highly flammable	(1) High temperature (2) Long startup time (3) Limited number of shutdowns (4) Intensive heat	(1) Sensitive to CO_2 in fuel and air (2) Electrolyte management (aqueous) (3) Electrolyte conductivity (polymer)	(1) Expensive catalysts (2) Long startup time (3) Sulfur sensitivity	(1) Slow response time (2) Highly corrosive (3) Low power density
Applications	(1) Transportation, portable power, unmanned aerial vehicles (UAVs)	(1) Transportation, portable power, unmanned aerial vehicles (UAVs)	(1) UAVs, transportation, power plant (2) Auxiliary power units	(1) Transport, military, auxiliary power units, aerospace (2) Off-grid telecom	(1) Building (2) Utilities (3) Distributed generation	(1) Distributed generation, Utilities

PEM- Proton Exchange Membrane Fuel Cell (Polymer Electrolyte Membrane Fuel Cell)



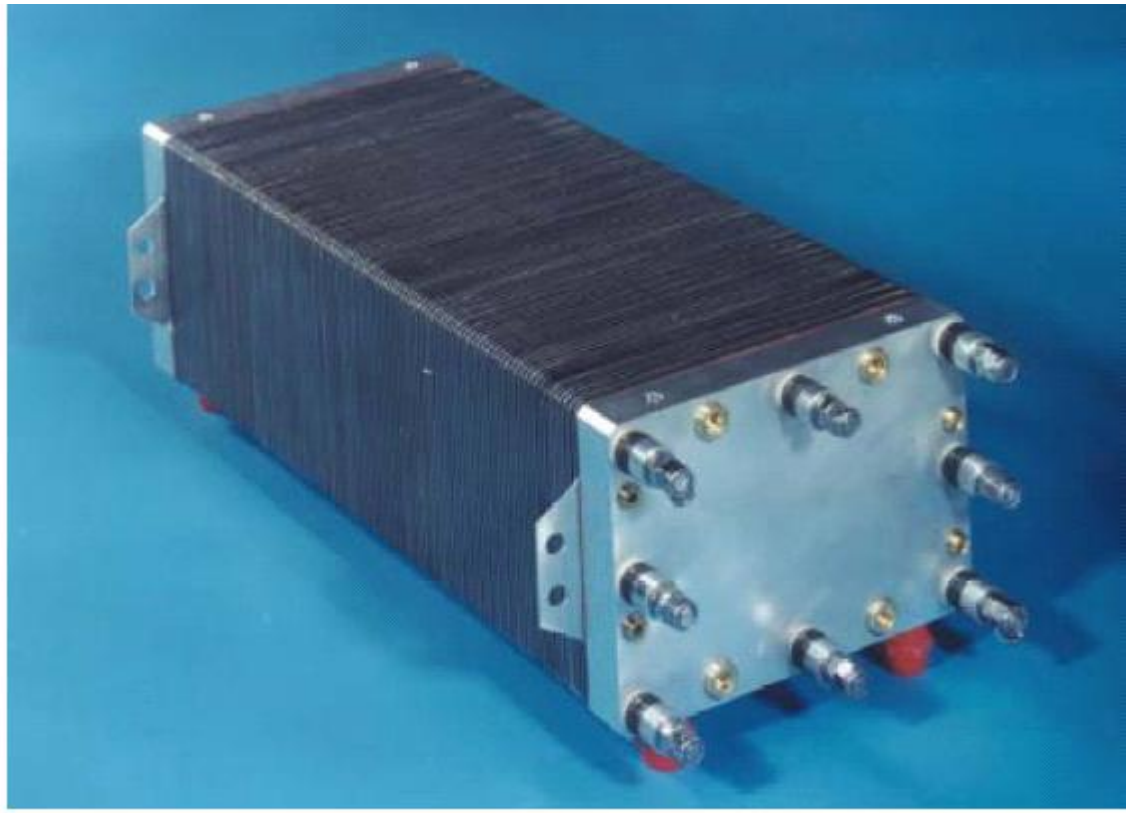
60-80°C

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $2H^+ + ½\ O_2 + 2e^- \rightarrow H_2O$


Quality exchange membrane/nafion membrane
ood corrosion resistance, acid and alkali corrosion resistance
1102591691

Nafion ®

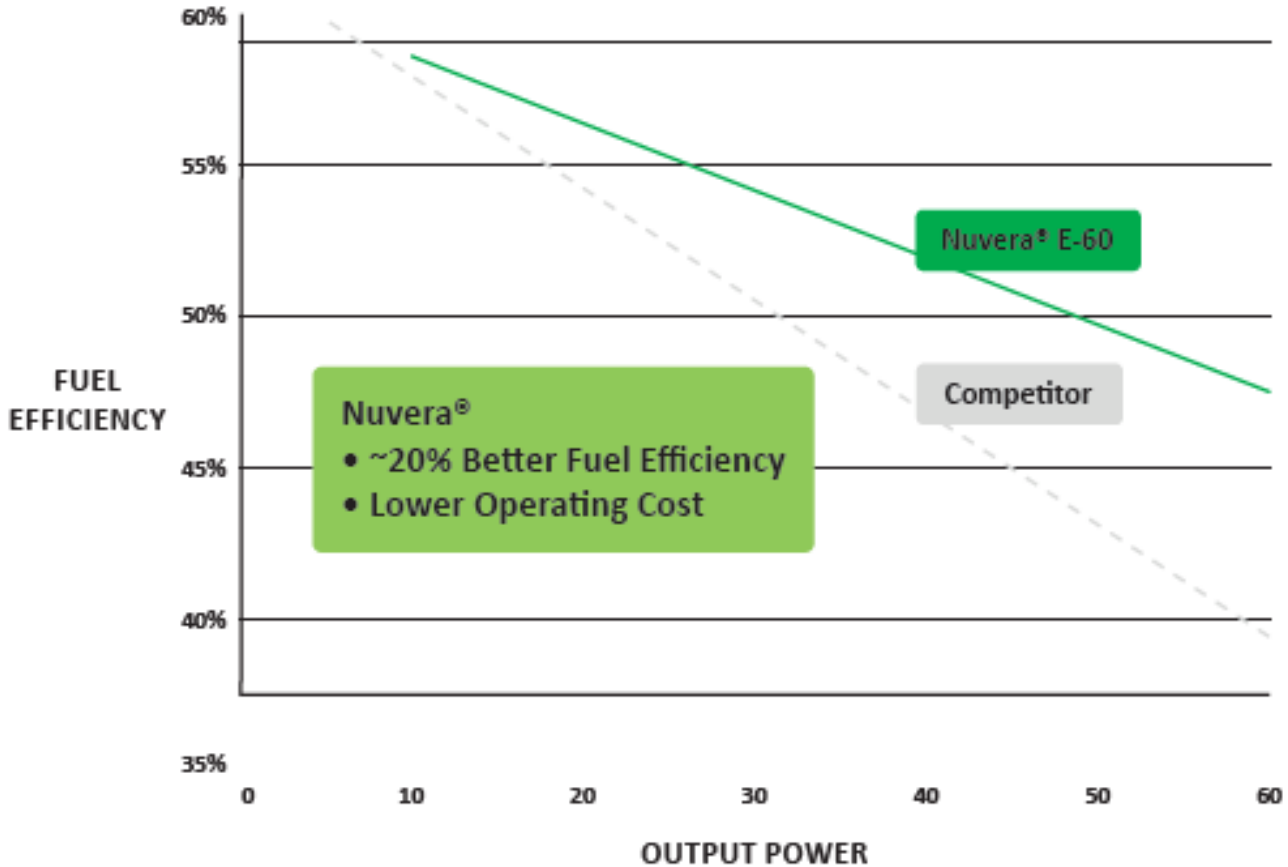


Nuvera® E-Series Fuel Cell Engine

- Fuel Efficiency
- Reliability
- Proven Performance

Product Specification	E-45	E-60
PERFORMANCE*		
Net output power**	47 kW	59 kW
Operating voltage	150-255 VDC	175–290 VDC
Maximum operating current	375 A	
Peak efficiency	58%	
PHYSICAL		
Dimensions (L x W x H)	1000 x 600 x 500 mm	
Mass	188 kg	190 kg
OPERATION		
Ambient operating / starting temperature	-30°C to 45°C	
Coolant	De-ionized water: fuel cell glycol mix	
Oxidant	Air	
Fuel quality	SAE J2719, ISO 14687-2	
Air supply pressure	0.70–1.05 bara	
Fuel supply pressure	12.5–15.0 bara	
Input power for balance-of-plant	1.2 kW at 27 VDC 4.0 kW at 375 VDC	1.2 kW at 27 VDC 8.0 kW at 375 VDC
Input power -30°C freeze start module†	3.5 kW	
Vehicle communication	CAN 2.0B	
STANDARDS		
Nuvera certifications	ISO-9001, ISO-14001, ISO-45001	
Regulatory conformance	2006/42/EC, 2011/65/EU, 2014/30/EU IEC 62282-2, GB/T 29838, GB/T 33978, CE- Declaration of Incorporation	
Functional safety	ISO 13849-1:2015	

Nuvera® E-60 Fuel Cell Engine



Impurity Limits : SAE J-2719 as compared to commercial practice

THE LINDE GROUP

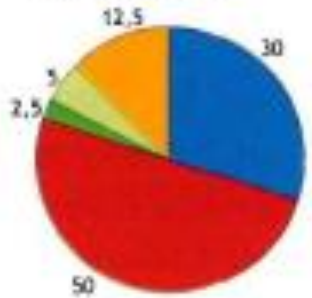
Linde

Constituent	Chemical Formula	Limits (ppm)	Linde-EU Grade 5.0*	CGA G-4.3 Grade 4.5
Total non hydrogen components	Grade 99.97	300	<50*	<50
Total non-hydrogen, non-helium	Grade 99.99	100	<10	<10
Water	H_2O	5	<5	<5
Total Hydrocarbons	CH_4, C_xH_y,	2	<1	<1
Oxygen	O_2	5	<2	<2
Helium (*not included in assay)	He	300	<50*	<50
Inerts (Nitrogen and Argon)	N_2 + Ar	100	<10	<10
Carbon Dioxide	CO_2	1	<1	<1
Carbon Monoxide	CO	0.1	ND/ <0.1	ND/ <0.1
Total Sulfur	Includes: H_2S, COS, CS_2	0.001	ND / <0.001	ND / <0.001
Formic Acid	CHOOH	0.2	ND/ <0.1	ND/ <0.1
Amonia	NH_3	0.1	ND/ <0.1	ND/ <0.1

SAE J-2719 and ISO/PDTS 14687-2 define the minimum purity level of fuel cell grade hydrogen as 99.99% (99.97% if we consider Helium)

	Total % hydrogen	Total impurities (ppmv)	Total impurities (ppb)
Grade 3	99.9 %	1000	1,000,000
Grade 4	99.99 %	100	100,000
Grade 5	99.999 %	10	10,000
Grade 6	99.9999 %	1	1000

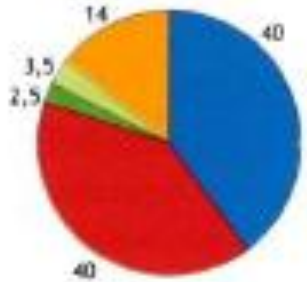
Bilancio energetico PEM
taglia 1-10 kWel



- Calore di scarto
- Ausiliari
- Perdite DC/AC
- Calore recuperato
- Energia elettrica

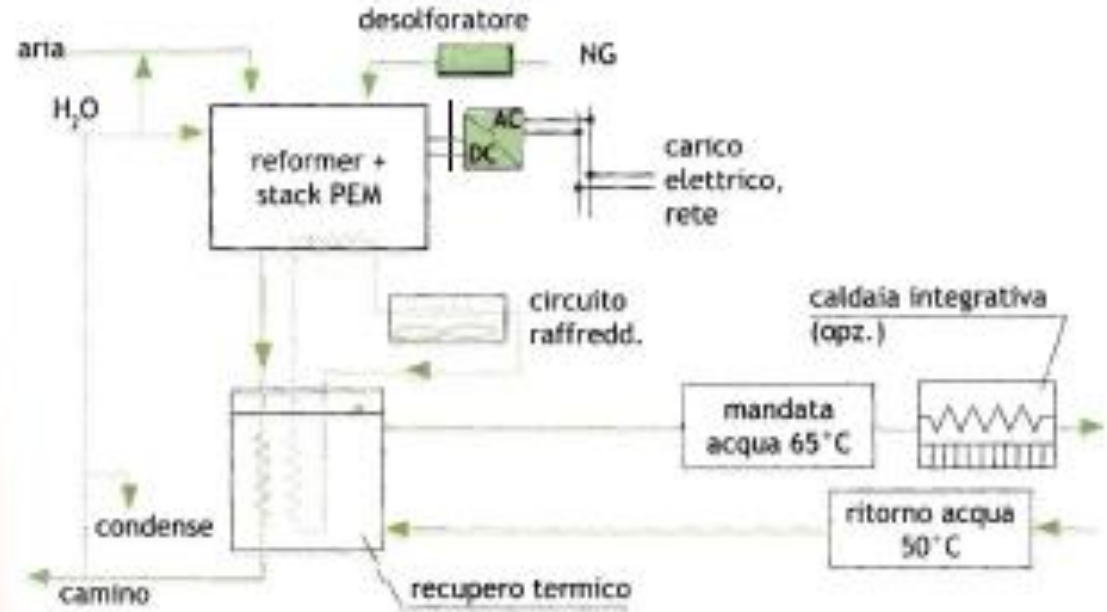
(Combustibile in ingresso = 100; riferimento PCI)

Bilancio energetico PEM
taglia 100-300 kWel

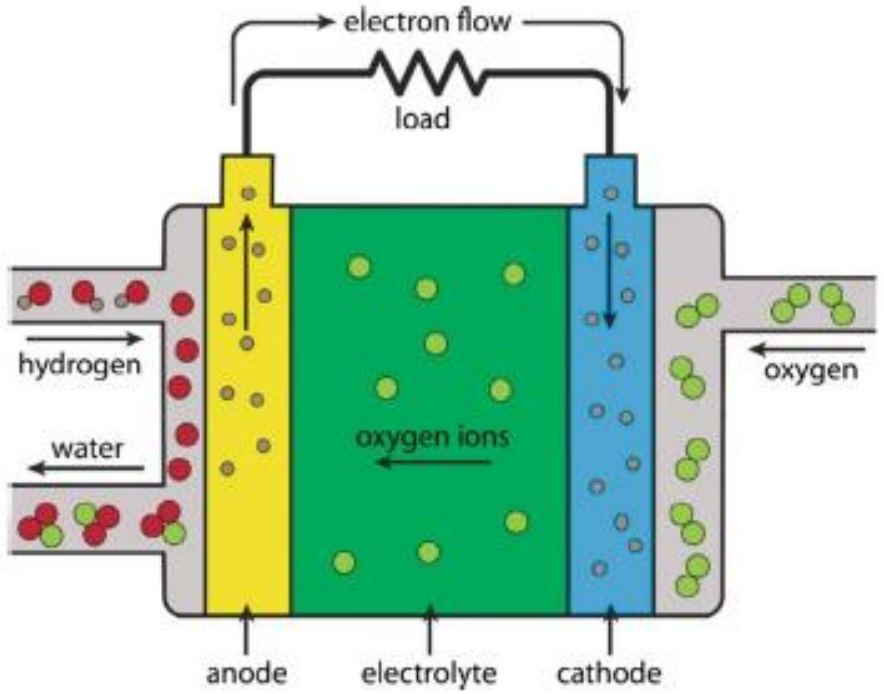


- Calore di scarto
- Ausiliari
- Perdite DC/AC
- Calore recuperato
- Energia elettrica

(Combustibile in ingresso = 100; riferimento PCI)



SOFC- Solid Oxide Fuel Cells



Anode: $H_2 + O^{2-} \rightarrow 2H_2O + 2e^-$

Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow O_2^{2-}$

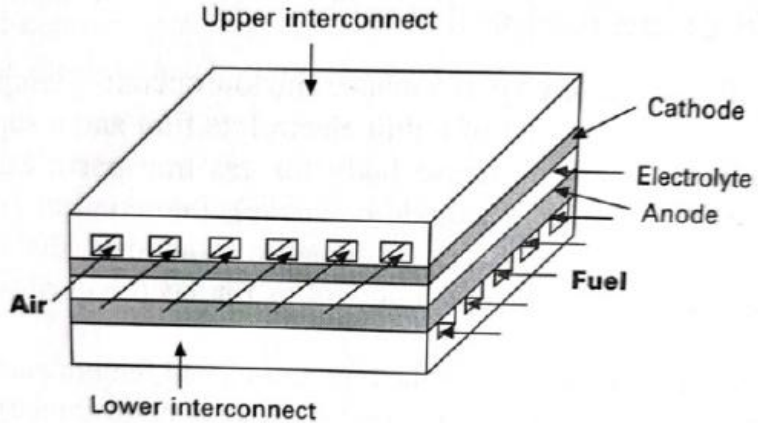
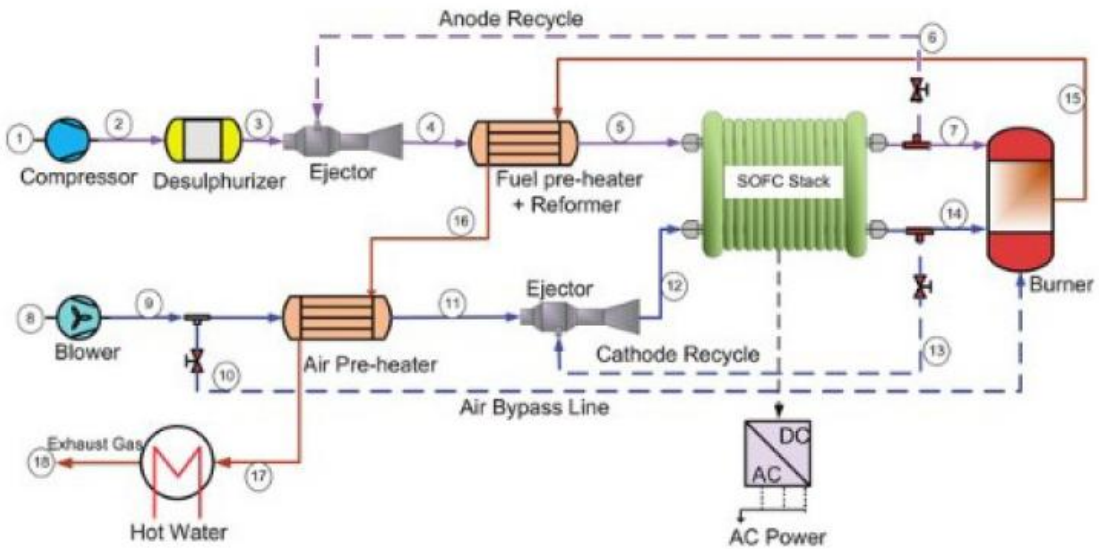
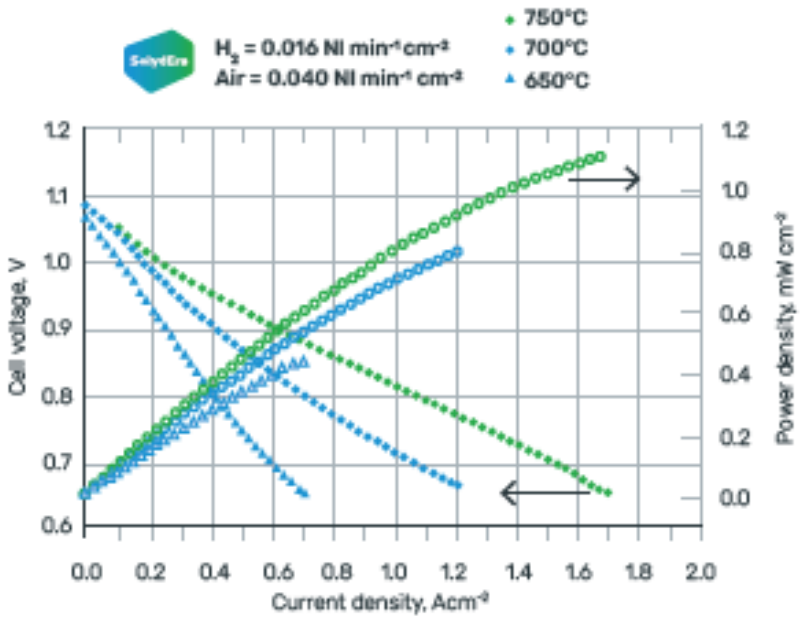


Figure 14 - schematic of an anode-supported planar SOFC stack [15]



Performance



Voltage & Power vs current characteristics in SOFC-mode

Technical data

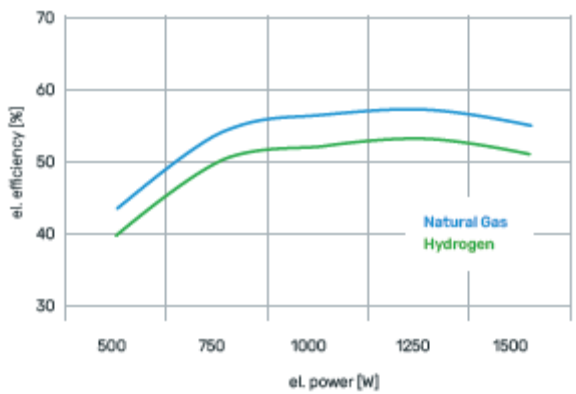
Physical data

Stack	G8
Number of cells	70
Size (w-h-d)	399 x 878 x 456 mm
Weight	83.8 kg
Fuels	Desulphurized natural gas (EN437) natural gas blends, Hydrogen, Biogas

Performance data

	Natural Gas
Max. Power	1.7 kW DC
El. Efficiency	Up to 58 %
Voltage at rated power	56V
Current at rated power	30A
Modulation	30 - 100 %
Operating Stack temperature	750-780
Degradation	< 0.3%/kh
Steam to carbon	> 1.8
Exhaust temperature	120-140°C
Exhaust mass	3-5 g/s
Life time	5 - 7 years

Performance



SolydEra Power Module PM-X

Technical data

The main technical data of the Power Module are reported in the table below.

PM-X MODULE		
Nominal Power (DC, BoL)	kW	9.6
Peak Power (DC, BoL)	kW	10
Power Modulation Range	%	30-100
output Voltage	VDC	710-810
HeatUp Time	h	<24
El. efficiency (DC, LHV) @ nominal power	%	Up to 63
Total efficiency @ 30°C in / 40°C out	%	>100
Total efficiency @ 50°C in / 60°C out	%	>90
Exhaust temperatures	°C	<200
Steam to Carbon	-	>1.8
Water consumption (deionized)	l/h	2.3*
Water condensed at 70°C	l/h	>2.3
Input Voltage	V	230V – 50Hz
Max Input Power	W	350
Physical		
Width	mm	600
Depth	mm	750
Height	mm	1900
Specific Power (net DC)	kW/m2	21
Weight	kg	<520
Fuels		
Natural Gas (desulphurized)	--	Yes
Hydrogen	--	Yes **
Serviceability		
Hotswap capability	--	Yes, with proper electrical protection at system level
Service access	--	single side, front

** Up to 70 °C the amount of condensed water exceeds the water consumption: no external tap water is required*

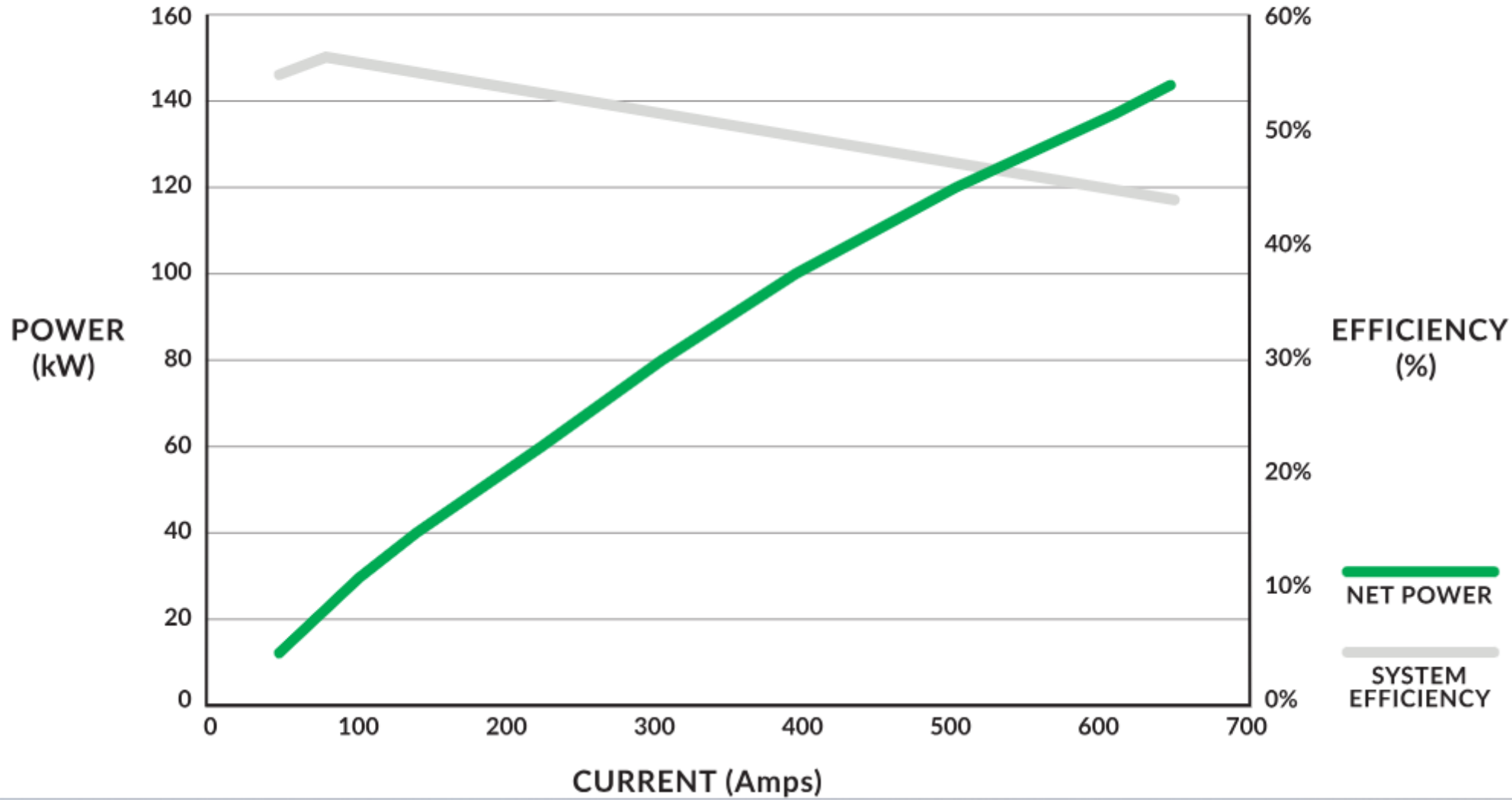
*** Electrical power reduction up to 20%*

Technical data

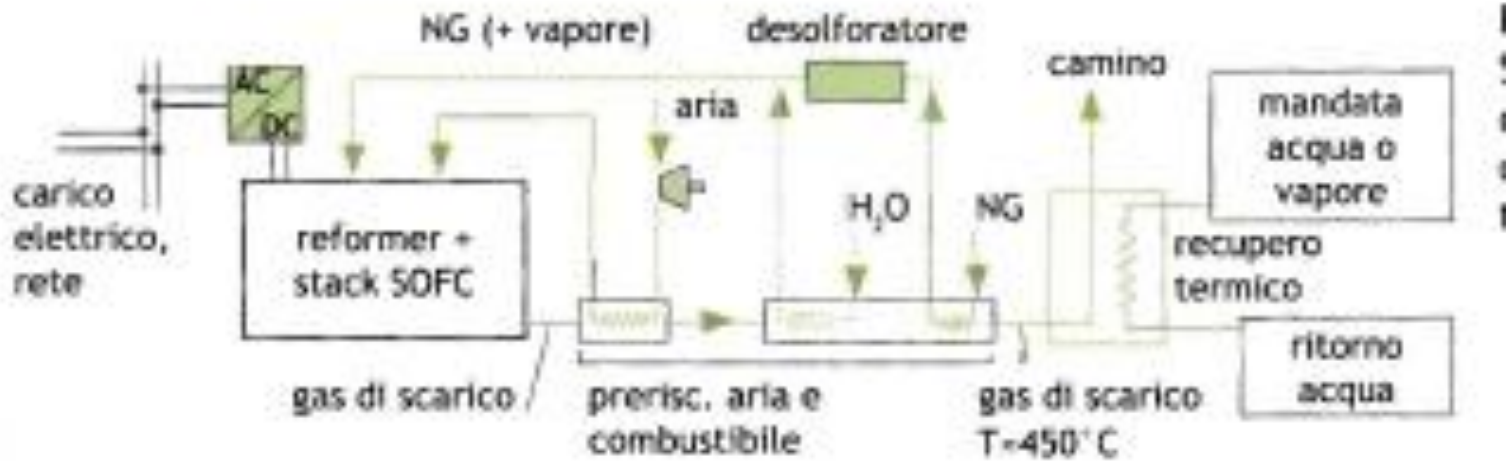
BG-15

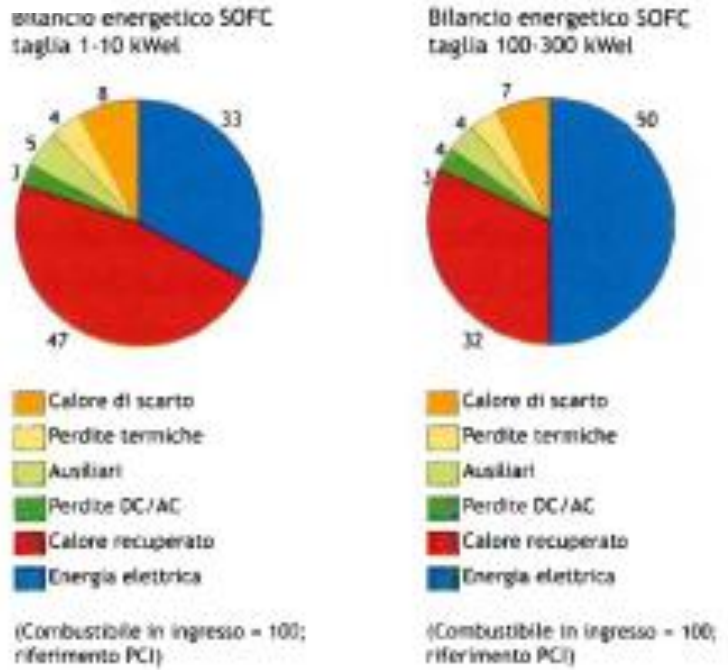
Application fields	Electrical energy generator with heat recovery for single-family homes, multi-family homes, companies, public and commercial buildings
Operating mode	All year round (approx. 8,700 hours)
Monitoring	Remote monitoring available 24 hours via app online/smartphone
Fuel	Natural gas, natural gas with up 20% hydrogen admixture, bio-methane, synthetic natural gas
Fuel cell type	Solid Oxide Fuel Cell (SOFC)
Overall efficiency	Up to 89%
Electrical efficiency	Up to 57%
Electrical energy	Min. 0.5 kW - max. 1.5 kW
Thermal power	Up to 0.85 kW
Electrical energy generated/year	Up to 13,000 kWh
Weight	250 kg
Height x width x depth	1,200 mm x 550 mm x 1014 mm
Noise level	47 db (A)
Service interval	12 months

EN-125 System Power + Efficiency



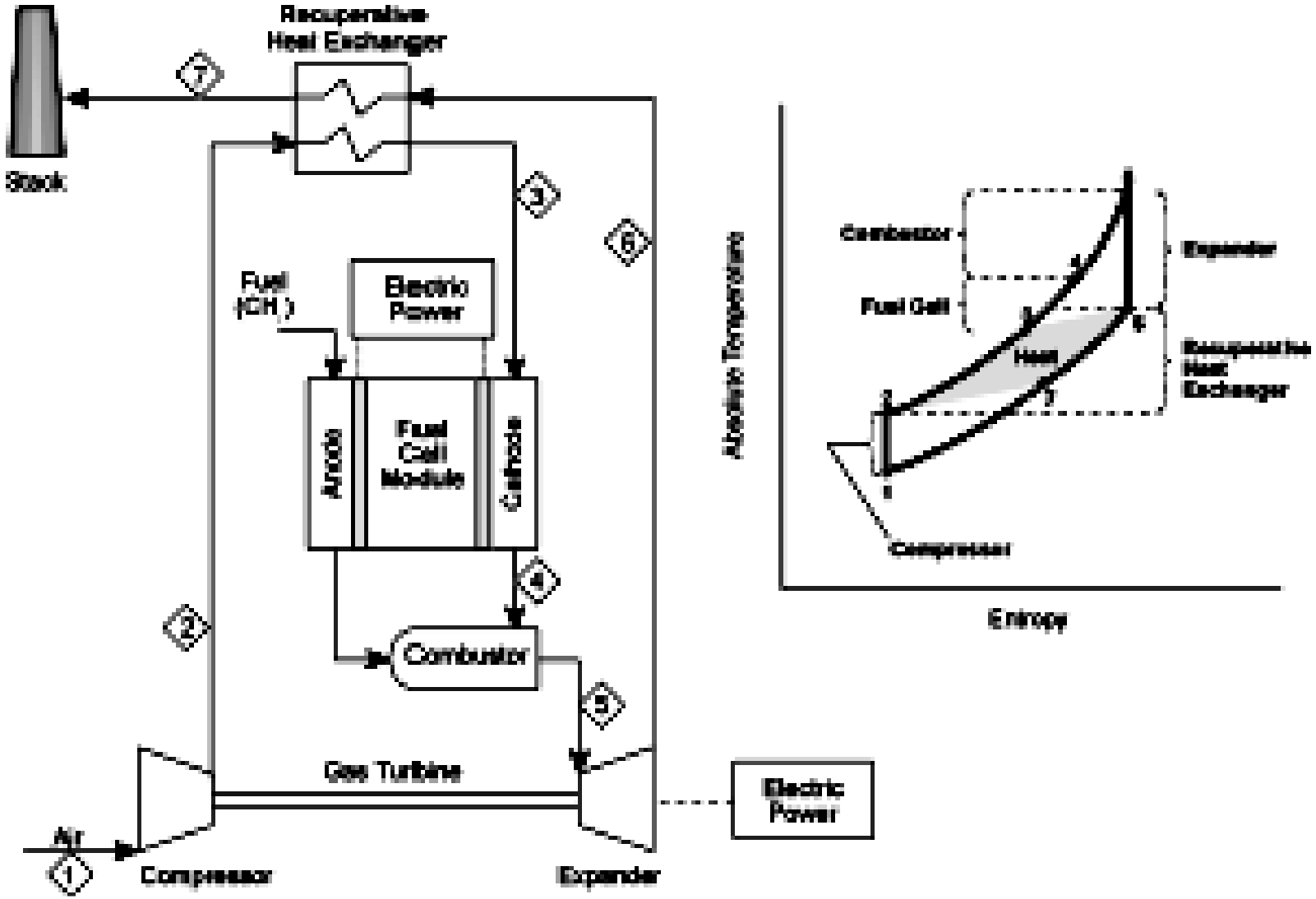
per applicazioni cogenerative:





Characteristics	PEMFCs	DMFCs	SOFCs	AFCs	PAFCs	MCFCs
Operating temperature (°C)	60–110	70–130	500–1000	60–250	150–210	500–700
System efficiency (%)	40–55	40	40–60	60–70	40–50	50–60
Combined heat and power efficiency (%)	70–90	80	<90	>80	>85	>80
Stack power (kW)	1–100	0.001–100	0.5–2.000	1–100	100–400	300–3.000,000
Energy density (kW hr/m^3)	112.2–770	29.9–274	172–462.09	—	—	25–40
Power density (kW/m^3)	3.8–6.5	~0.6	4.20–19.25	~1	0.8–1.9	1.5–2.6
Lifespan (hr)	2.000–3.000	1.000–4500	1.000	8.000	>50,000	7.000–8.000
Cell voltage (V)	1.1	0.2–0.4	0.8–1.0	1.0	1.1	0.7–1.0
Nominal current density (A/cm^2)	0.5–1	0.15–0.3	—	0.1–0.3	0.15	0.14–0.16
Electrolyte	Polymer membrane	—	Yttria-stabilized zirconia (YSZ)	KOH	Phosphoric acid (H_3PO_4)	Molten carbonate
Fuel type	Hydrogen	Methanol	Hydrogen, natural gas biogas coal gas	Hydrogen ammonia	Hydrogen methanol	Natural gas biogas coal gas
Startup time	<1 min	—	60 min	<1 min	—	10 min
Advantages	(1) Small size (2) Lightweight (3) Quick startup time and load response (4) Low temperature	(1) Low cost of fuel methanol, low operational temperature, and pressure (2) High power density	(1) High efficiency (2) Fuel flexibility. (3) Solid electrolyte (4) Suitable for CHP (5) Hybrid/gas turbine cycle	(1) A wider range of stable materials allows components to be priced lower (2) Low temperature (3) Quick startup	(1) Suitable for CHP (2) Increased tolerance to fuel impurities	(1) Fuel variety (2) High efficiency
Disadvantages	(1) Sensitivity to low temperature, humidity, salinity, and fuel impurities	(1) Low reaction kinetics (2) Methanol is very toxic and highly flammable	(1) High temperature (2) Long startup time (3) Limited number of shutdowns (4) Intensive heat	(1) Sensitive to CO_2 in fuel and air (2) Electrolyte management (aqueous) (3) Electrolyte conductivity (polymer)	(1) Expensive catalysts (2) Long startup time (3) Sulfur sensitivity	(1) Slow response time (2) Highly corrosive (3) Low power density
Applications	(1) Transportation, portable power, unmanned aerial vehicles (UAVs)	(1) Transportation, portable power, unmanned aerial vehicles (UAVs)	(1) UAVs, transportation, power plant (2) Auxiliary power units	(1) Transport, military, auxiliary power units, aerospace (2) Off-grid telecom	(1) Building (2) Utilities (3) Distributed generation	(1) Distributed generation, Utilities

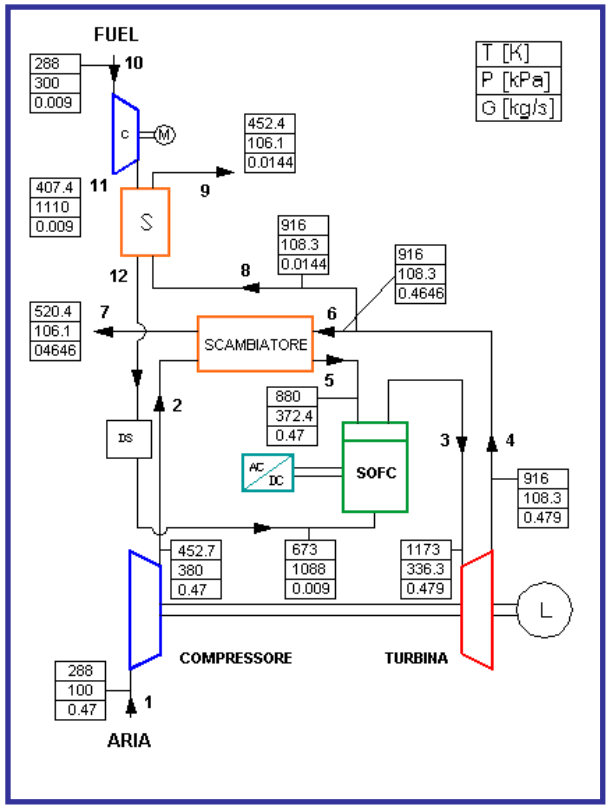
FC+TG


Recuperative
Heat Exchanger
Stack
Fuel
(CH)
Electric
Power
Anode
Fuel
Cell
Module
Cathode
Combustor
Gas Turbine
Air
Compressor
Expander
Electric
Power
Absolute Temperature
Combustor
Fuel Cell
Heat
Compressor
Expander
Recuperative
Heat
Exchanger
Entropy

SOFC+TG

- SOFC substitutes the traditional combustion chamber;
- CO ed NO_X are very lower due to the absence of combustion
- The GT can be cogenerative;
- $P_{FC} = 4P_{MGT}$

η>60%

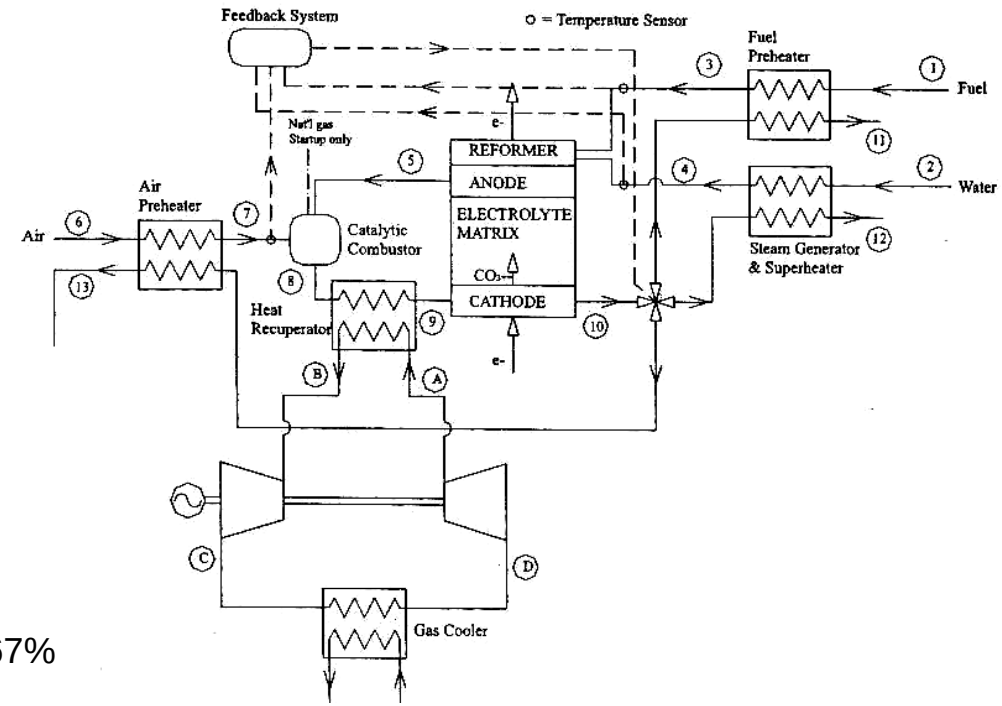


EXAMPLES

- University of California, Irvine
- Essen, Germania
- Milano, Edison S.p.A.
- Sinetta Marengo, Alessandria

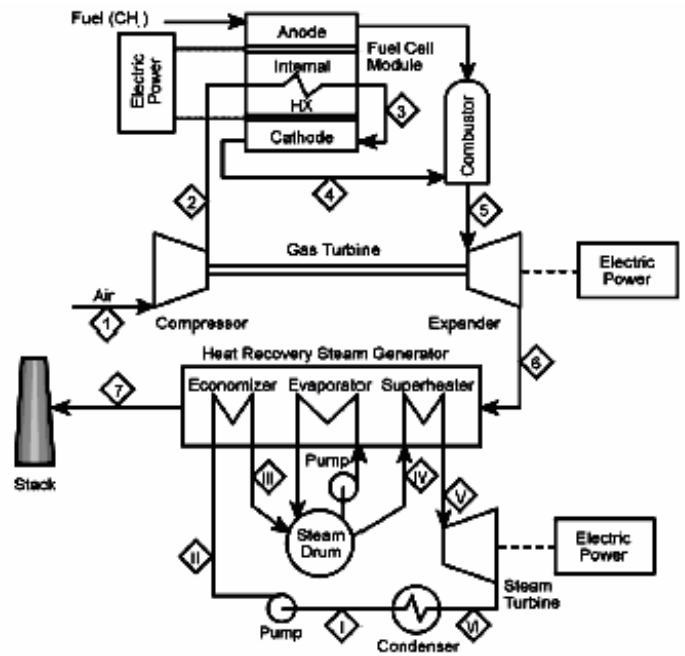
SOFC-MGT 220 kW

MCFC+TG

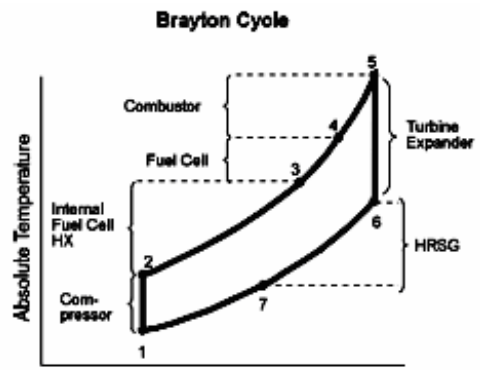

Feedback System
o = Temperature Sensor
Fuel Preheater
Fuel
Water
Nat'l gas Startup only
e-
REFORMER
ANODE
ELECTROLYTE MATRIX
CO3=
CATHODE
Air Preheater
Air
Catalytic Combustor
Heat Recuperator
Steam Generator & Superheater
Gas Cooler
1
2
3
4
5
6
7
8
9
10
11
12
13
A
B
C
D

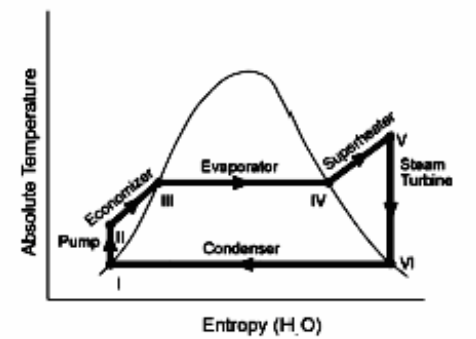
η=67%

FC+CCGT

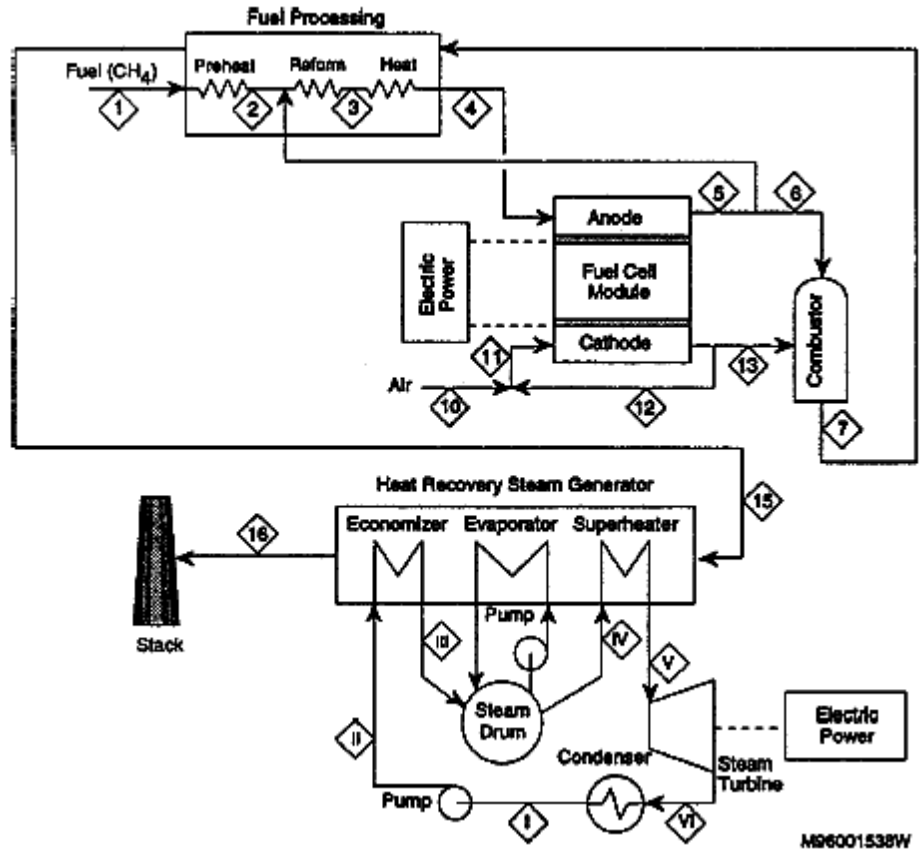


η=75%

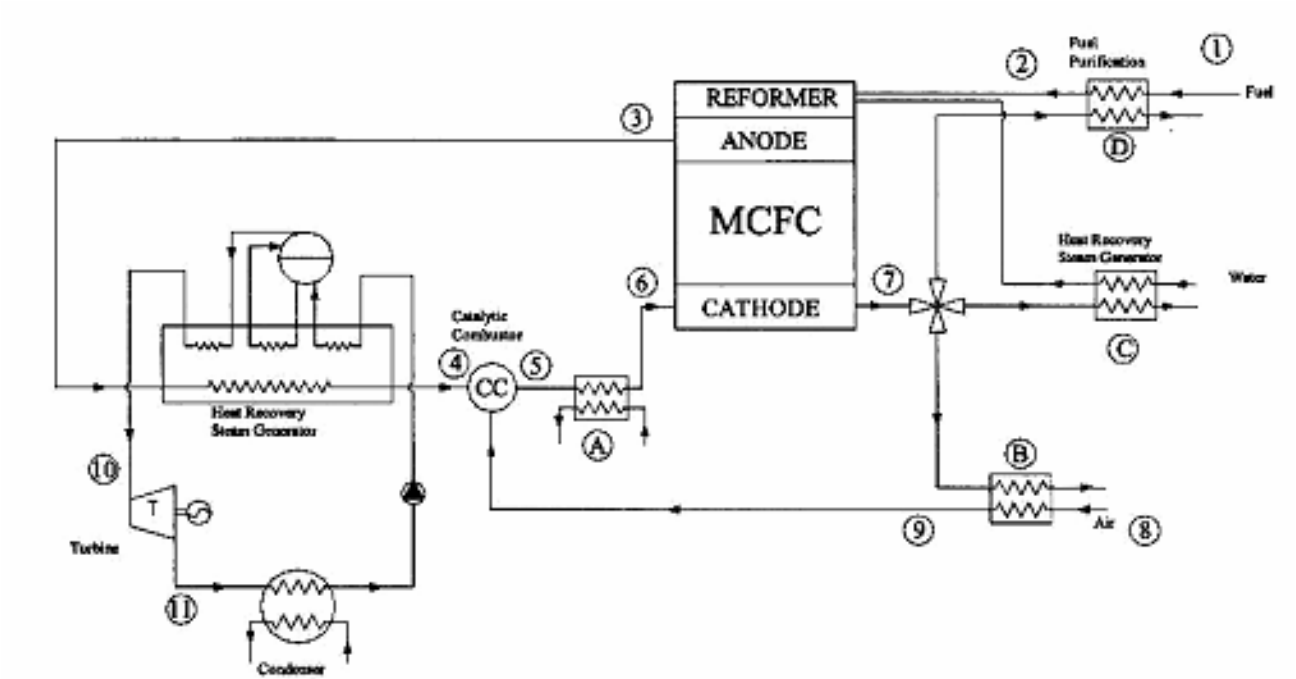




FC+ST

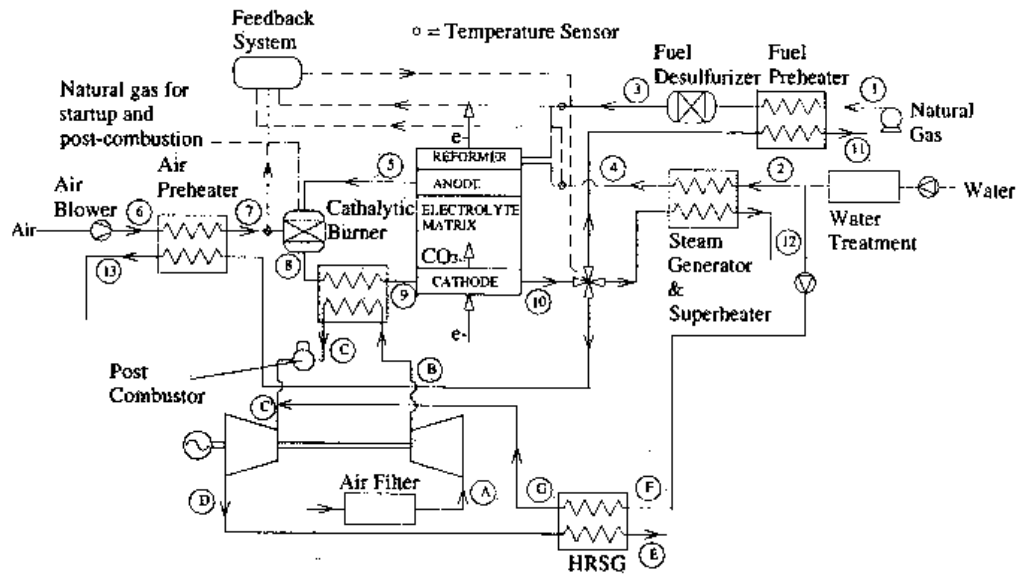

Fuel Processing
Fuel (CH_4)
Preheat
Reform
Heat
1
2
3
4
5
6
Anode
Fuel Cell Module
Cathode
Electric Power
Combustor
7
11
13
Air
10
12
Heat Recovery Steam Generator
15
16
Economizer
Evaporator
Superheater
Stack
Pump
III
IV
V
Steam Drum
II
Condenser
Steam Turbine
Electric Power
Pump
I
VI
M960015388W

MCFC+ST


REFORMER
ANODE
MCFC
CATHODE
Fuel Purification
Fuel
Heat Recovery Steam Generator
Water
Catalytic Combustor
CC
Heat Recovery Steam Generator
Turbine
Air
Condenser
1
2
3
4
5
6
7
8
9
10
11
A
B
C
D

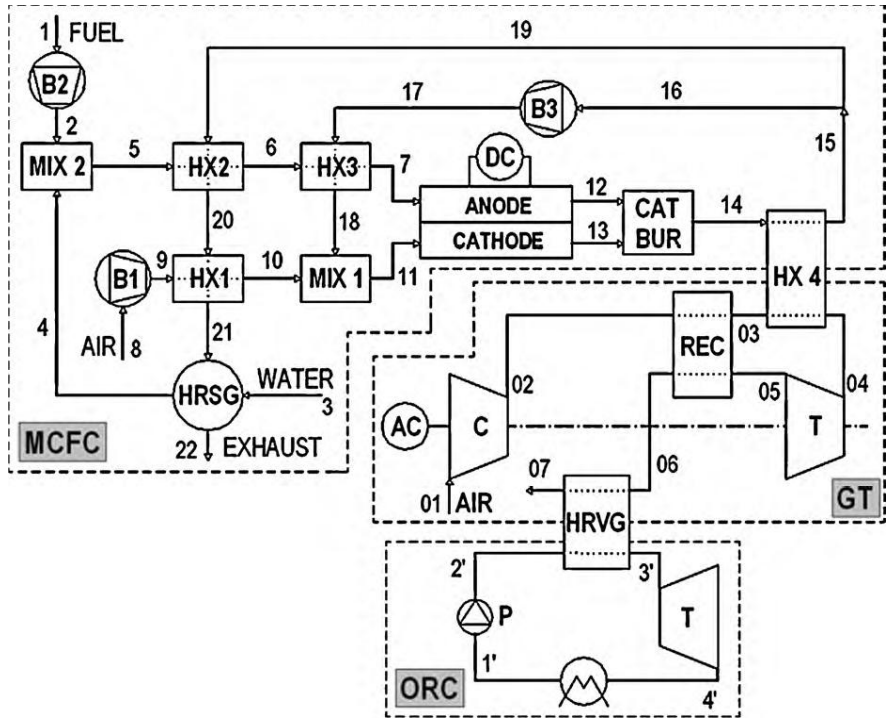
η=63%

MCFC+STIG



η=69%

FC+GT+ORC


1 FUEL
19
B2
17
B3
16
2
MIX 2
5
HX2
6
HX3
7
DC
15
ANODE
CATHODE
12
13
CAT
BUR
14
HX 4
20
18
B1
9
HX1
10
MIX 1
11
4
AIR
8
21
REC
03
HRSG
WATER
3
02
05
04
AC
C
T
MCFC
22 EXHAUST
07
06
01 AIR
HRVG
GT
2'
3'
P
T
1'
ORC
4'

FCs's competitors

	MCI	**TG**	**MTG**	**FC**
Size	50kW - 5MW	500kW - 25MW	25 - 150 kW	3kW - 10MW
Electric efficiency	30-45 %	23-35 %	20-30 %	30-50 %
Fuel	Natural gas, diesel, biogas, syngas	Natural gas, liquid fuels,	Natural gas, propane	Hydrogen, (natural gas, methanol)
NO_X emissions	>1.4 g/kWh	0.3-0.5 g/kWh	0.2-0.65 g/kWh	< 0.02 g/kWh
SO_X emissions	3.6-5.4 g/kWh	3.6-7.3 g/kWh	5-5.9 g/kWh	< 0.01 g/kWh
CO_2 emissions	420-640 g/kWh	450-850 g/kWh	590-720 g/kWh	330-510 g/kWh
Exhaust gas temperature	400-600°C	450-550°C	200-300°C	80-1000°C

Types	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Perfluorosulfonic acid type proton exchange membrane	Potassium hydroxide and other alkaline aqueous solution	Phosphoric acid aqueous solution	Molten carbonate	Yttrium oxide stabilized zirconia
Reaction temperature	50–100 °C	90–100 °C	150–200 °C	600–700 °C	700–800 °C
Power	1–100 kW	10–100 kW	50–1 MW	300–3 MW	1–2 MW
efficiency	45%–60%	60%	40%	>40%	60%
Application	Backup power/ portable power generation	Space/ Military	Distributed power generation	Electric utility companies	Auxiliary power/ electric utility companies
Advantage	High power density/low temperature	Low cost/ quickstart/ reliable performance	Long lifespan/ advanced technology	Wide fuel compatibility/ high waste heat utilization efficiency	Solid-state/ high waste heat utilization value
Disadvantage	High catalyst cost	Durability/ difficult electrolyte management	Long startup time/low waste heat recovery efficiency	Corrosive electrolyte/ short lifespan/ long startup time	High cost/ stringent material selection/ high operating temperature