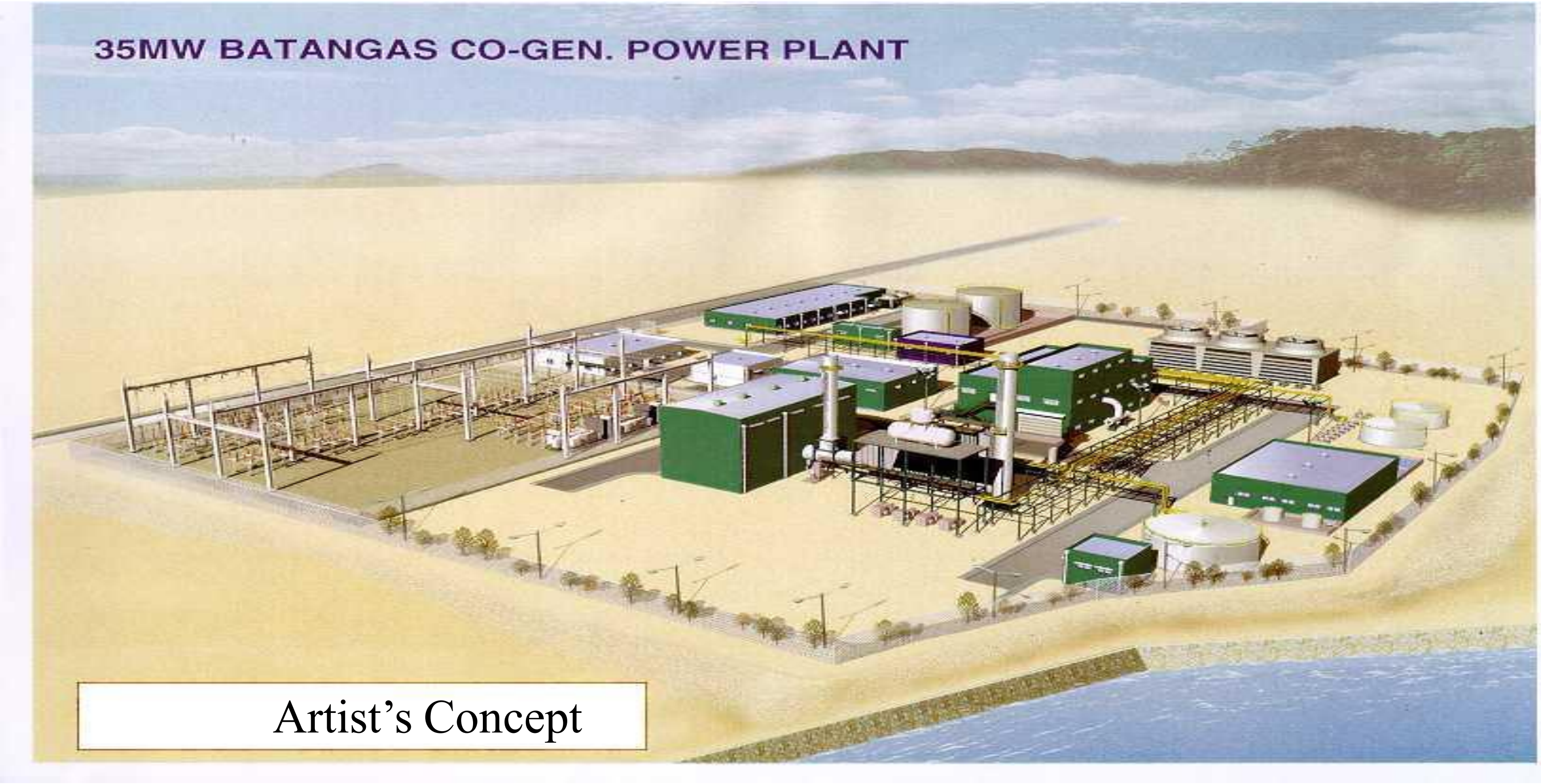
Combined Heat & Power (Cogeneration)



Artist’s Concept

Topics – Combined Heat & Power

- Combined Heat & Power, Its Uses and History
- Basic Principle of Combined Heat & Power (CHP)
- CHP or Cogeneration Plant Efficiency
- Efficiency of Separate Generation
- Types of Cogeneration Cycles
- Other CHP Technologies
- Opportunities for CHP
- Cost of CHP (Capital, O&M, Levelized)
- Applicability, Advantages, Disadvantages
- Environmental Impact & Risks

What is CHP or Cogeneration?

- **Combined Heat and Power (CHP) –** is the simultaneous generation of electricity and steam (or heat) in a single power plant. It has been long used by industries and municipalities that need process steam or heat as well as electricity. CHP or cogeneration is not usually used by large utilities which tend to produce electricity only. It is advisable only for industries and municipalities if they can produce electricity cheaper or more conveniently; otherwise, buy from the utility instead.

- In theory, CHP provides the **most efficient use of energy** resources, often utilizing up to 90% of the heat energy of the fossil fuel. In practice, while the efficiency of entire process is recognized, its application has been limited.

History of Cogeneration

- **End of 19th century –** Potential for combining the generation of electricity and heat was recognized by the power industry, and schemes in the US and UK for combining the distribution of steam across district heating networks with electricity for lighting were conceived.

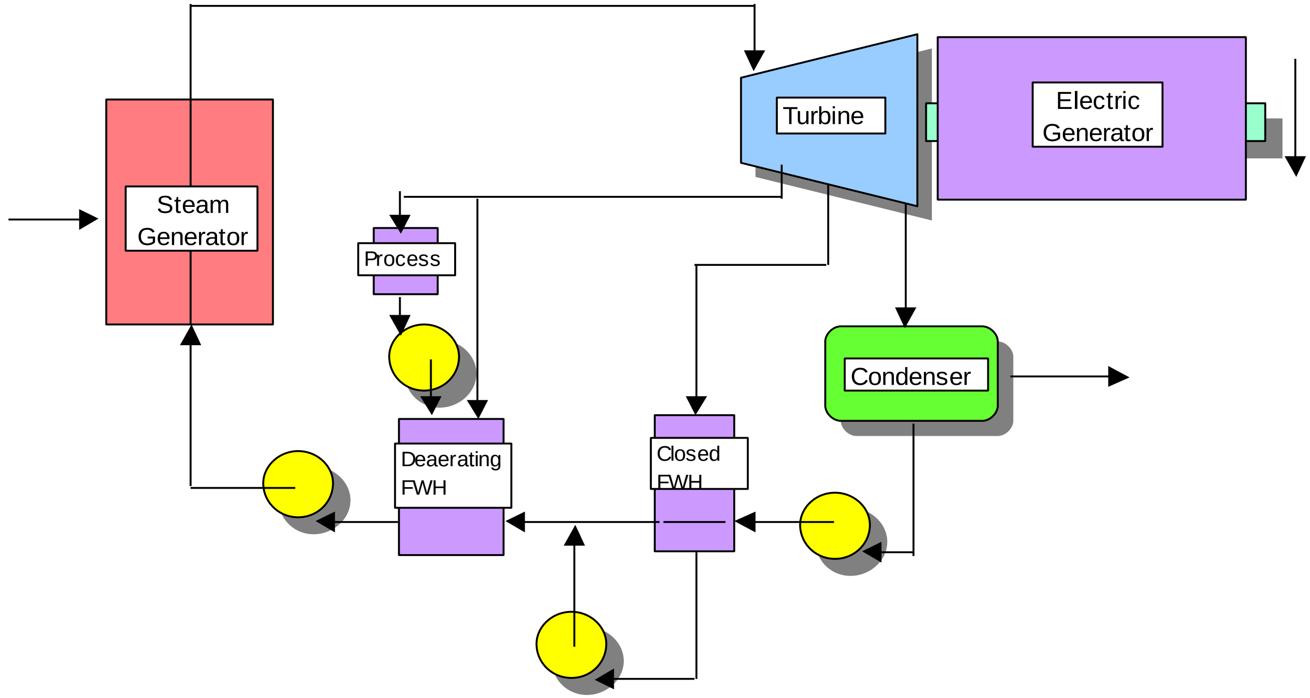
- **1920s to 1930s –** Advantages of combining power and heat generation attracted more attention during the depression, but take-up was low.

- **1950s –** District heating systems were established in some cities in the US, Germany, Russia and Scandinavia; very little impact in UK.

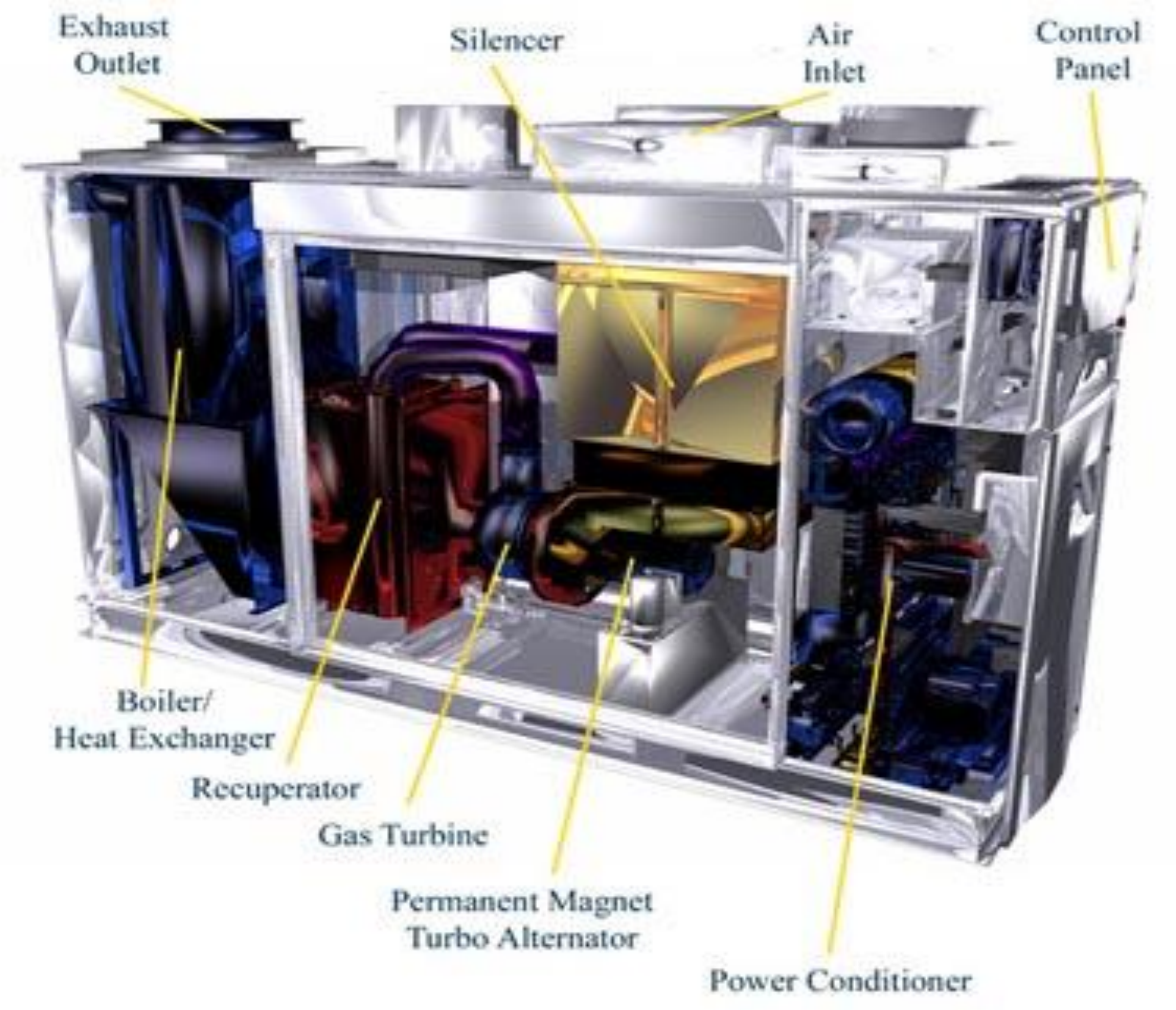
- **1980s –** South Korean government embarked on large-scale utilization of cogeneration for district heating for commercial and domestic use. In **Finland** over 90% of the buildings in the major cities were linked to district heating systems and over 25% of electricity is generated in district heating plants.

Basic Cogeneration Plant Extraction-Condensing Turbine

Figure 2-27 Schematic of Basic Cogeneration Plant with Extraction-Condensing Turbine



CHP GT with waste heat recovery boiler for heat and electrical power.



Cogeneration Plant Efficiency

- From an energy resource point of view, cogeneration is beneficial only if it saves on primary energy when compared to separate generation of electricity and steam.

- The *cogeneration plant efficiency* η_{co} is given by

$$\eta_{co} = (\mathbf{E} + \mathbf{\Delta H_s}) \,/\, \mathbf{Q_a}$$

Where: **E** = electricity generated, kW

$\mathbf{\Delta H_s}$ **=** heat energy in process steam, kJ/s

= (enthalpy of steam entering process) -

(enthalpy of process condensate returning to plant)

$\mathbf{Q_a}$ **=** heat added to plant (coal, oil, gas, nuclear, etc.), kJ/s

Efficiency for Separate Generation

- The *combined efficiency* η_c *for separate generation* is given by

$$\eta_c = \mathbf{1} / \{ [\mathbf{e} / \eta_e] + [(\mathbf{1} - e) / \eta_h] \}$$

Where: **e** = electrical fraction of total energy output

$$= \mathbf{E / (E + \Delta H_s)}$$

η_e **=** electric plant efficiency

η_h **=** steam or heat plant efficiency

- Cogeneration is beneficial only if the efficiency of the cogeneration plant exceeds that of the combined efficiency for separate generation:

$$\eta_{co} >> \eta_c$$

Types of Cogeneration

There are two broad categories of cogeneration:

- 1) ***Topping* cycle –** primary heat at the higher temperature end of the Rankine Cycle is used go generate high pressure and temperature steam and electricity in the usual manner. Depending on process requirements, the process steam at low-pressure and low temperature and pressure either goes to:

  a) ***Extracting* turbine -** extracted from the turbine at an intermediate stage (like feed-water heating), or

  b) ***Back pressure* turbine -** taken at the turbine exhaust.

- 2) ***Bottoming* cycle –** primary heat is used at high temperature directly for process requirements (high-temperature cement kilns) and the low temperature waste heat is used to generated electricity, obviously at a low efficiency. The bottoming cycle has an efficiency below $\boldsymbol{\eta_c}$ for separate generation and is therefore of little thermodynamic and economic interest.

Topping Cycles

Only the topping cycle can provide true savings in primary energy and most process applications require low grade (temperature, pressure) steam. Their applicability are as follows:

(a) Steam-electric power plant with a **back pressure turbine –** most suitable when electric demand is low compared to process heat demand

(b) Steam-electric power plant with steam extraction from a **condensing turbine –** applicable to a wide range of ratios

(c) Gas-turbine power plant with **heat recovery steam generator (HRSG) –** lies in between (a) and (d)

(d) **Combined cycle gas turbine** (CCGT) power plant – when electric demand is high, about comparable to heat demand or much higher

Other CHP Technologies

- **Diesel engines –** waste heat from jacket water cooling, engine exhaust and lubricating oil cooling are recovered for space heating
- **Gas turbine plants with waste heat boilers –** (already discussed)
- **Combined cycle gas turbine (CCGT) power plant –** (already discussed)
- **Oil, gas, coal and biomass-fired boilers and nuclear plants –** combination of back-pressure and condensing turbines to supply heat and electricity.
- **Fuels cells –** when H_2 and O_2 combines to produce electricity and the CO is likewise burned to keep the proper operating temperature, a great deal of heat is wasted that could be recovered from this electro-chemical cycle.
- **Fuel cell-gas turbine and IGCC hybrids –** achieves 50-58% or even 60% net efficiencies (LHV) by combining the fuel cell to electro-chemically generate power from H_2 and O_2 and using the exhaust to drive turbine. Fuel derived from gasification of coal or biomass is used by the fuel cell.

Opportunities for CHP

Utilizing the 45-65% wasted heat is where CHP comes in.

Power Generation Technology	Stand-Alone Efficiency, %	Heat Lost for Recovery, %	CHP Efficiency, %	Remarks Application (in addition to power)
Piston Engine (Diesel)	36	64	80 - 90	Space heating: office, house, hospital, school
Oil-Gas Steam	38 - 45	55 - 62	63 - 67	District heating
Pulverized Coal	38 - 47	53 - 62	63 - 68	District heating
Atmospheric CFB	45	55	67	District heating
Pressurized FBC	45 - 50	50 - 55	67 - 70	District heating
IGCC	45	55	67	District heating
Nuclear (advanced) - GT-MHR	48	52	69	Same principle as oil/gas/coal-fired plant
Simple GT				
Aero-derivative GT	38 - 42	58 - 62	63 - 65	Space Heating: office, house, hospital, school
Heavy-frame GT	30 - 35	65 - 70	58 - 61	District heating, process steam, hot water
Combined Cycle GT	50 - 55	45 - 50	70 - 73	District heating, seawater desalination
Geothermal				District heating
Solar Thermal				
Solar trough	16 - 18	82 - 84	50 - 51	District heating
Solar dish	24 - 35	65 - 76	54 - 61	District heating
Fuel Cells				
Phosphoric PAFC	36	64	45	Like diesel CHP: space heating
Proton PEM	35	65	45	Like diesel CHP: space heating
Molten MCFC	47	53	60	Like diesel CHP: space heating
Solid oxide SOFC	47	53	65	Like diesel CHP: space heating
Biomass				
Direct combustion	23	77	54	District heating, pulp & paper mill
Co-firing with coal	34 - 42	58 - 66	60 - 65	
Biomass gasification	35	65	61	District heating
Municipal Waste				
Ocean Thermal	2 - 6	Flash evaporator (open cycle)		Cogeneration of power and fresh water
Ocean Wave (OWC)	6 - 40	Excess power for H2 as CHP fuel		Cogeneration of power and fresh water
Tidal Power	27.5	Excess power for H2 as CHP fuel		Cogeneration of power and fresh water

ASSUMPTION: Waste heat to be recovered = 50%, Efficiency of recovery system = 80%

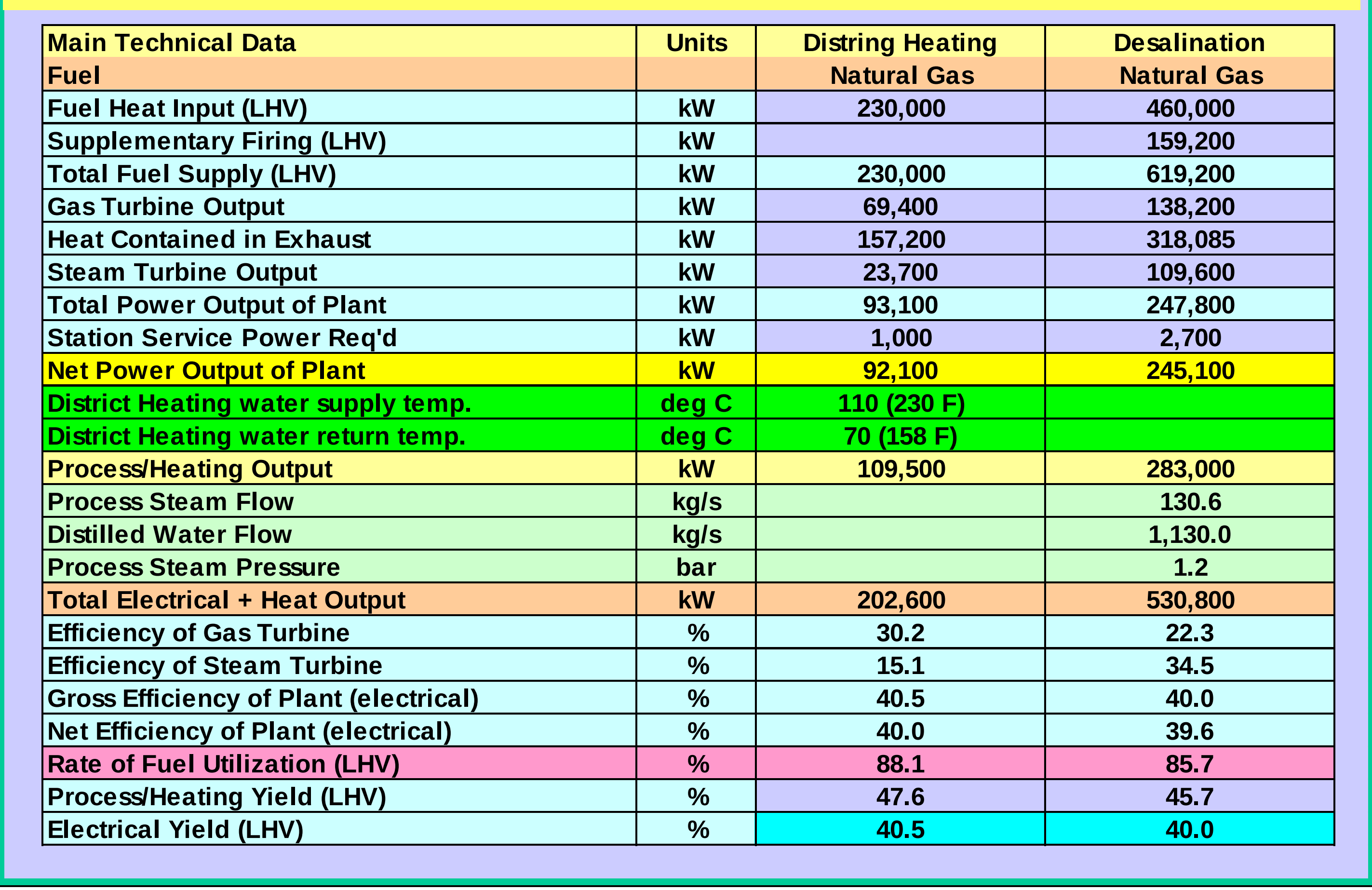
Cost of CHP and Distributed Generation Technologies

Cost of CHP and Distributed Generation Technlogies

Type of Plant	Capacity Range kW	Efficiency % HHV	Genset Package Cost, $/kW	Turnkey Cost No HR, $/kW	Heat Recovery Cost, $/kW	O&M Cost $/kWh
Spark Ignition RE	50 - 5,000+	28 - 42	250 - 600	600 - 1,000	75 - 150	0.007 - 0.015
Compression Ignition RE	20 - 10,000	36 - 43	125 - 300	350 - 500	n.a.	0.005 - 0.010
Rotary Engine	150 - 1,800	28 - 38	250 - 500	500 - 700	75 - 150	0.007 - 0.015
Micro Turbine	30 - 200	25 - 30	350 - 750	600 - 1,100	75 - 350	0.005 - 0.010
Fuel Cell	50 - 1,000	35 - 54	1,500 - 3,000	1,900 - 3,500	included	0.005 - 0.010
Simple Gas Turbine	1,000+	21 - 40	300 - 600	650 - 900	100 - 200	0.003 - 0.008
Combined Cycle GT	UK Pounds		500 - 700			0.2 - 0.7
Back-Pressure ST	UK Pounds		600 - 2,000			0.1
Extraction ST	UK Pounds		600 - 2,000			0.1

CCGT for District Heating and Sea Water Desalination

Thru CHP, the efficiency is raised from 40-88% and 40-86% for district heating and sea water desalination, respectively.



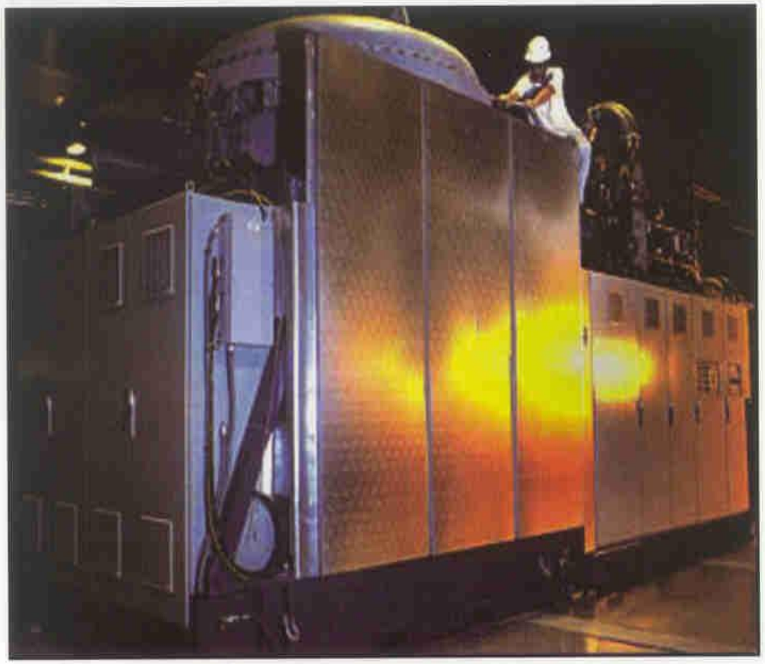
Main Technical Data	Units	Distring Heating	Desalination
Fuel		Natural Gas	Natural Gas
Fuel Heat Input (LHV)	kW	230,000	460,000
Supplementary Firing (LHV)	kW		159,200
Total Fuel Supply (LHV)	kW	230,000	619,200
Gas Turbine Output	kW	69,400	138,200
Heat Contained in Exhaust	kW	157,200	318,085
Steam Turbine Output	kW	23,700	109,600
Total Power Output of Plant	kW	93,100	247,800
Station Service Power Req'd	kW	1,000	2,700
Net Power Output of Plant	kW	92,100	245,100
District Heating water supply temp.	deg C	110 (230 F)	
District Heating water return temp.	deg C	70 (158 F)	
Process/Heating Output	kW	109,500	283,000
Process Steam Flow	kg/s		130.6
Distilled Water Flow	kg/s		1,130.0
Process Steam Pressure	bar		1.2
Total Electrical + Heat Output	kW	202,600	530,800
Efficiency of Gas Turbine	%	30.2	22.3
Efficiency of Steam Turbine	%	15.1	34.5
Gross Efficiency of Plant (electrical)	%	40.5	40.0
Net Efficiency of Plant (electrical)	%	40.0	39.6
Rate of Fuel Utilization (LHV)	%	88.1	85.7
Process/Heating Yield (LHV)	%	47.6	45.7
Electrical Yield (LHV)	%	40.5	40.0

Fuel Cells for CHP

Type of Fuel Cell	Electrolyte	Operating Temp., C	Fuel	Overall Efficiency, %	Power Range Applications
Proton PEM	Solid polymer (Nafion)	50-100	Pure H_2 tolerates CO_2	35 (45)	Automotive, CHP (5-250 kW) portable
Acid (PAFC)	Phosphoric Acid	~ 220	Pure H_2 tol. CO_2, 1% CO	< 45 36	CHP (200 kW) 200 kW (ONSI)
Molten Carbonate	Lithium & Potassium	~ 650	H_2, CO, CH_4, etc. tol. CO_2	47 (60)	200 kW-2 MW CHP, stand alone
Solid Oxide	Stabilized Zirconia	~ 1000	H_2, CO, CH_4, etc. tol. CO_2	47 (65)	2-1000 kW, CHP stand alone

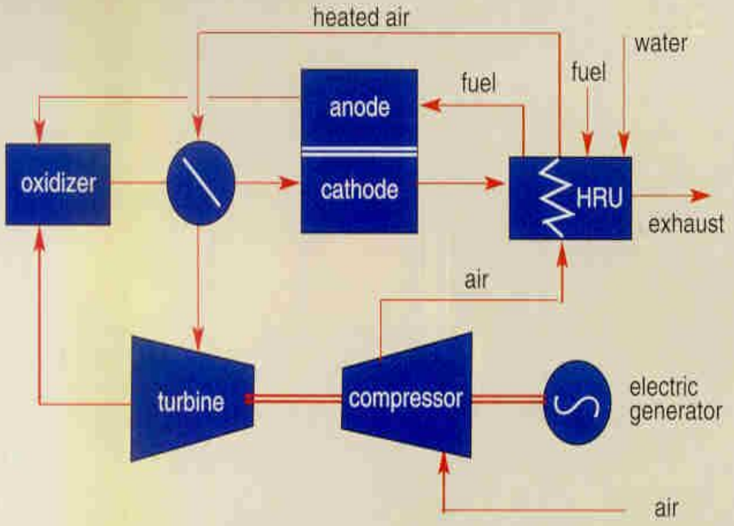
Renewable Energy World, "Renewable Fuel Cell Power from Biogas", Nov-Dec 2001

Fuel Cell-IGCC Hybrid



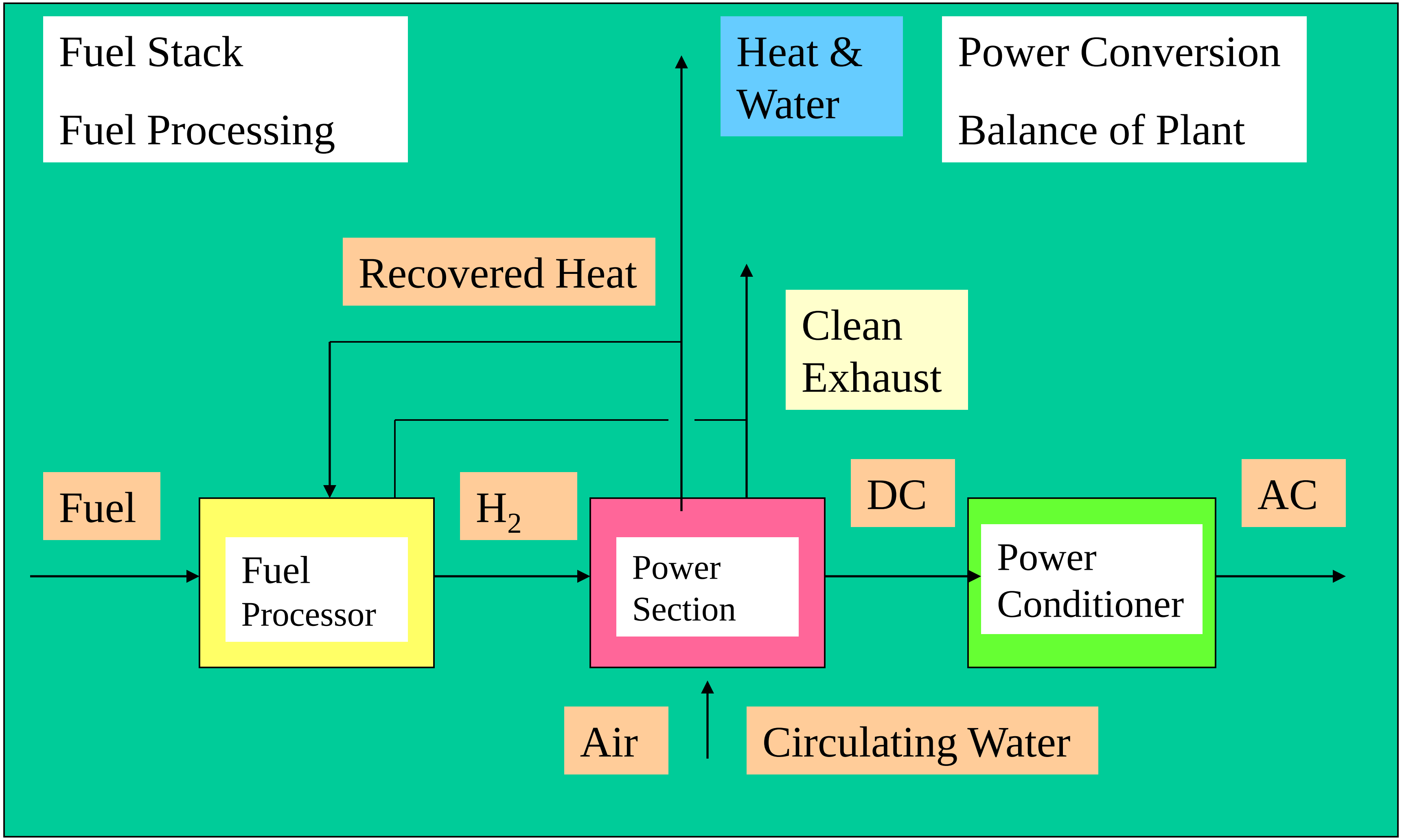
Tubular solid oxide hybrid. This 225-kW hybrid system on test at the University of California is designed around Siemens Westinghouse fuel cells and Ingersoll Rand microturbine which runs off the 850 C exhaust temperature of the fuel cell module.

Hybrid direct fuel cell system. Compressed air is heated by the waste heat recovery unit (HRU), expanded through the gas turbine power section, and then used as the fuel cell oxidant. Cathode exhaust is used for fuel preheat and water vaporization; anode exhaust is used for cathode air preheat.



Coal or biomass is gasified to H_2 and CO and fed to HRU. Compressed air is heated by HRU, expanded thru gas turbine, and then used as fuel cell oxidant. Cathode exhaust is used for fuel preheat and water vaporization. Anode exhaust is used for cathode air preheat.

Fuel Cell Concept for Power, Heat and Potable Water



Fuel Stack

Fuel Processing

Heat & Water

Power Conversion

Balance of Plant

Recovered Heat

Clean Exhaust

Fuel

Fuel Processor

H_2

Power Section

DC

Power Conditioner

AC

Air

Circulating Water

Environmental Impact of CHP

- **Environmental Impact of CHP Plants**
  - The primary environmental impacts are no different than those of the same plant used solely for power generation
  - Use of CHP increases the efficiency of energy conversion process and controls, at least in part, the release of heat from power plants into the atmosphere.

CHP Plant
Sofia, Bulgaria

Risks with CHP

- **Technology Risks –** associated with CHP are principally the risks that attach to the particular electricity generation technology being harnessed. (These are discussed with their associated technologies)
- **Economic Risks –** the addition of CHP to a project should improve its financial viability. Certain industries have recognized this, but more often CHP is avoided. This may be due to ignorance – fear of the unknown – that translates into a heightened level of risk.

Trigeneration
(power + heating + cooling)

- **Cooling by Cogeneration –** According to the Institute for Energy and Environment Research (IEER), an absorption chiller-heater which also produces electricity is the most efficient cooling and heating system.

- **Absorption cooling systems –** Require heat rather than electricity to produce cooling. As a result, these systems can use a variety of energy resources, including natural gas combustion, waste heat from electricity generation or solar thermal power/energy systems. These systems commonly use either ammonia, water or lithium bromide as refrigerant.

- **Basic Principle -** Heat from a building/source will cause refrigerant to boil and instead of being compressed, it is absorbed by another liquid. The mixture is heated in a boiler to separate the two fluids; each is sent to its own condensing chamber. The absorbent cools and condenses and is returned to absorb more refrigerant. The refrigerant cools and condenses and is returned to the evaporator to pick up more heat.