Pratt & Whitney
A United Technologies Company

ORGANIC RANKINE CYCLE TECHNOLOGY

HEAT RECOVERY APPLICATIONS

UNITED TECHNOLOGIES CORPORATION

Pratt & Whitney
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Hamilton Sundstrand

Pratt & Whitney

Sikorsky

Otis

UTC Fire & Security

UTC Power

Carrier

PRATT & WHITNEY OVERVIEW

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Large Engines

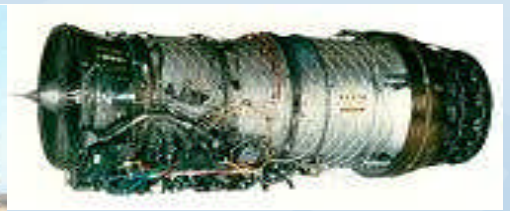
Small Engines

Aftermarket Services

Space Propulsion

Power Systems

Military Engines



PRATT & WHITNEY POWER SYSTEMS

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PRATT & WHITNEY
POWER SYSTEMS

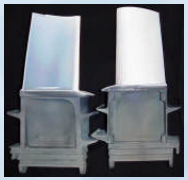
Large Engines

30 – 60 MW

Small Engines

1 – 4 MW

After market



Marine

Mobile Power

25 MW

Heat to Electricity

clean energy ahead
TURBODEN
A PRATT & WHITNEY POWER SYSTEMS COMPANY

PWPS GLOBAL FOOTPRINT*

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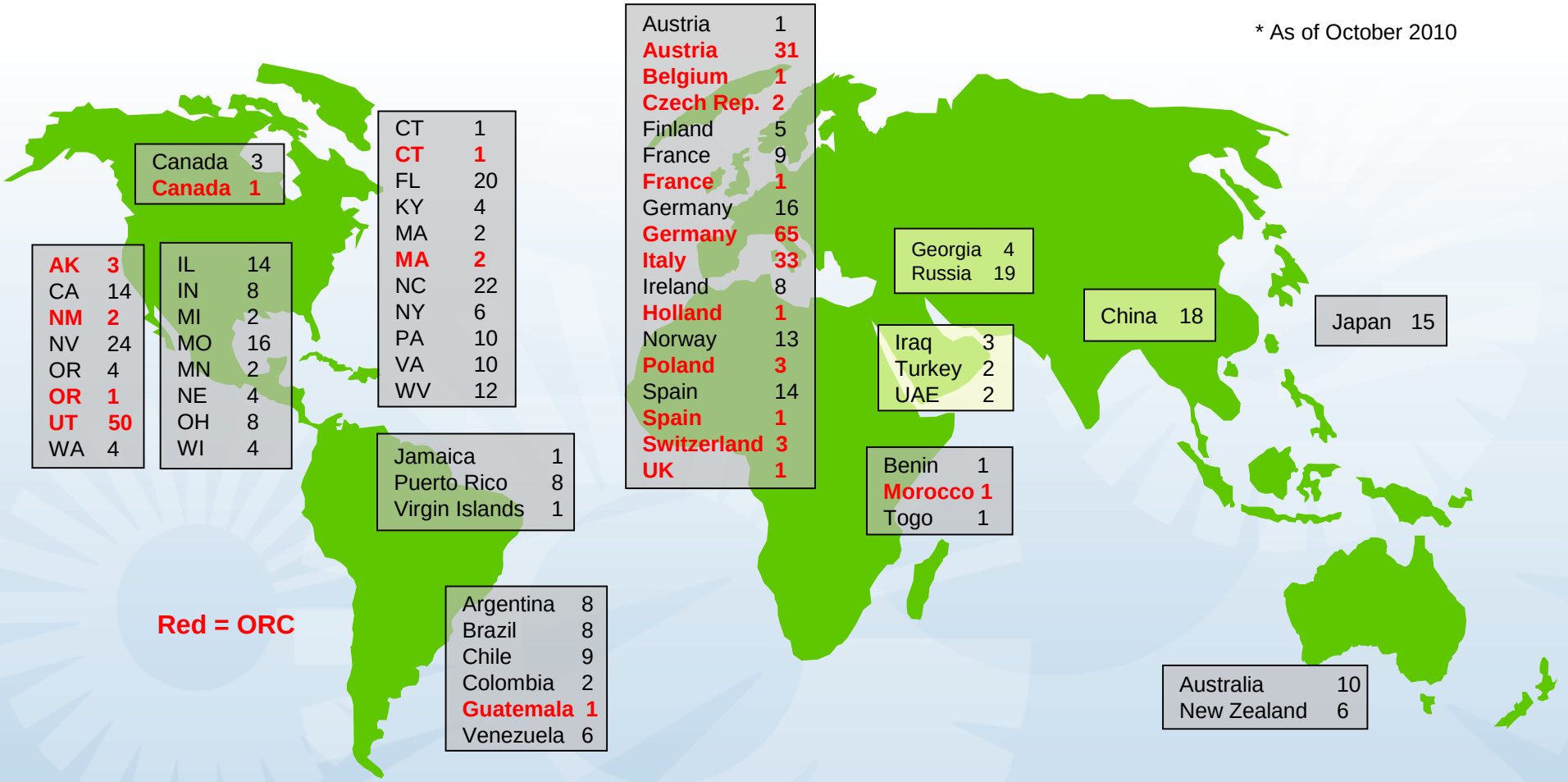
* As of October 2010



Over 200 ORC's and Over 2000 Gas Turbines Installed in 40 Countries

HEAT TO ELECTRICITY GENERATION

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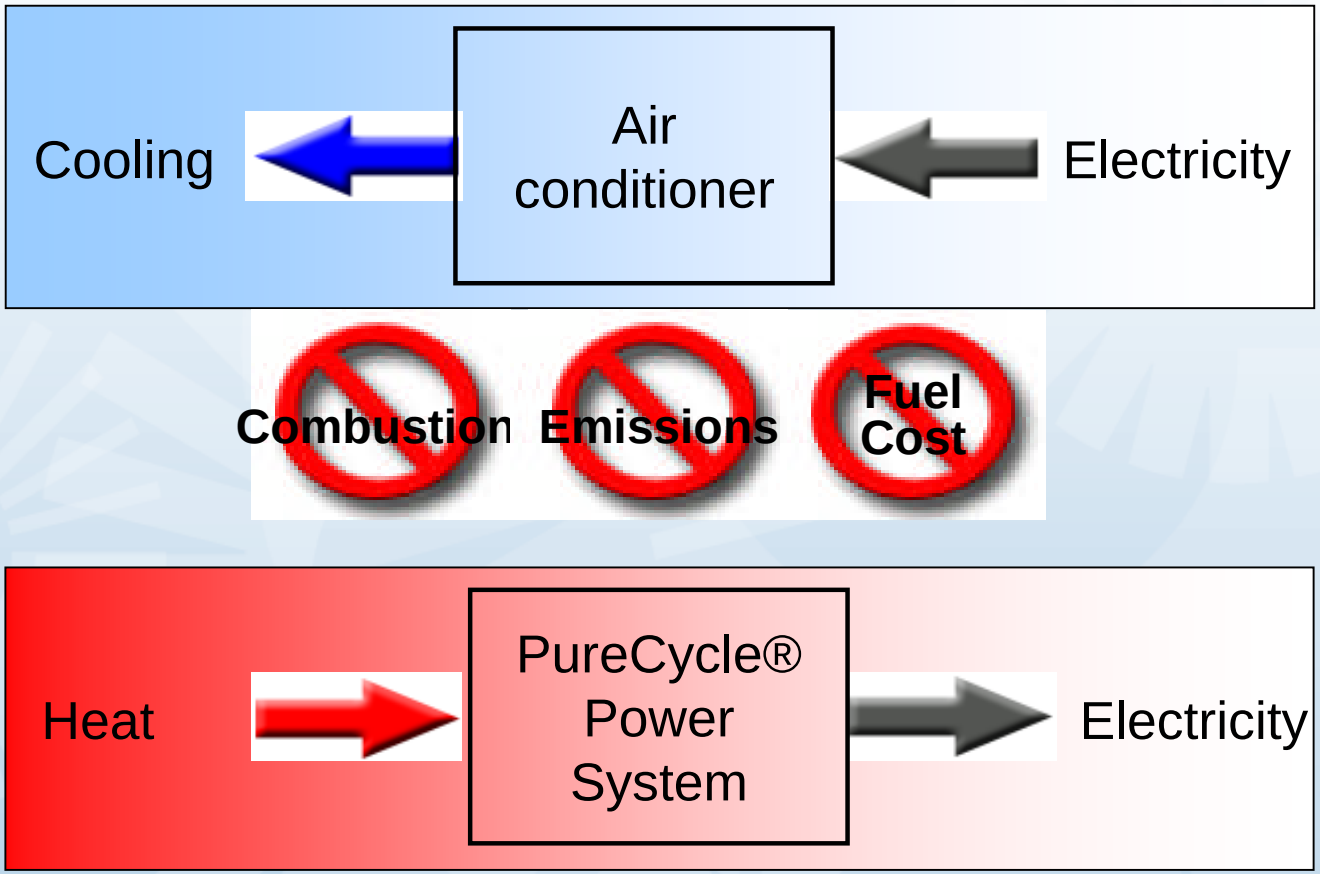
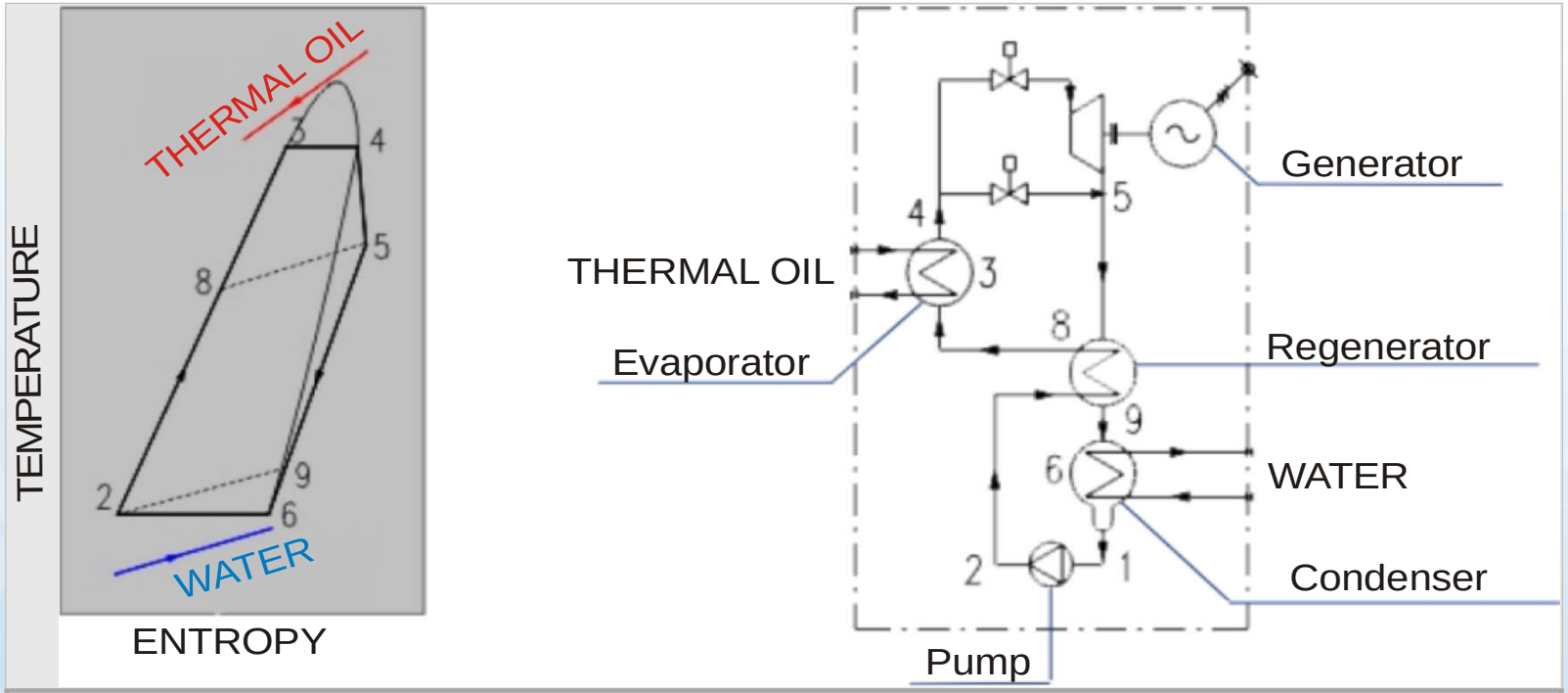
"Reverse" of air conditioning cycle



ORC THERMODYNAMIC PRINCIPLE



The turbogenerator uses the hot temperature thermal oil to pre-heat and vaporize a suitable organic working fluid in the evaporator (8 3 4). The organic fluid vapor powers the turbine (4 5), which is directly coupled to the electric generator through an elastic coupling. The exhaust vapor flows through the regenerator (5 9) where it heats the organic liquid (2 8). The vapor is then condensed in the condenser (cooled by the water flow) (9 6 1). The organic fluid liquid is finally pumped (1 2) to the regenerator and then to the evaporator, thus completing the sequence of operations in the closed-loop circuit.

HIGH MOLECULAR MASS FLUID – ADV.

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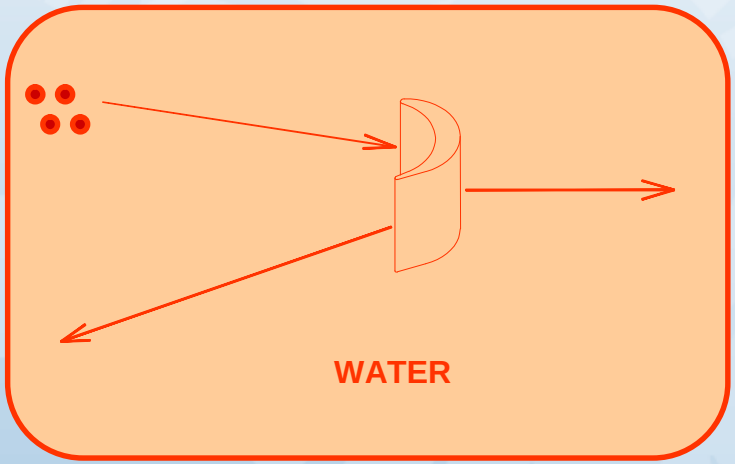
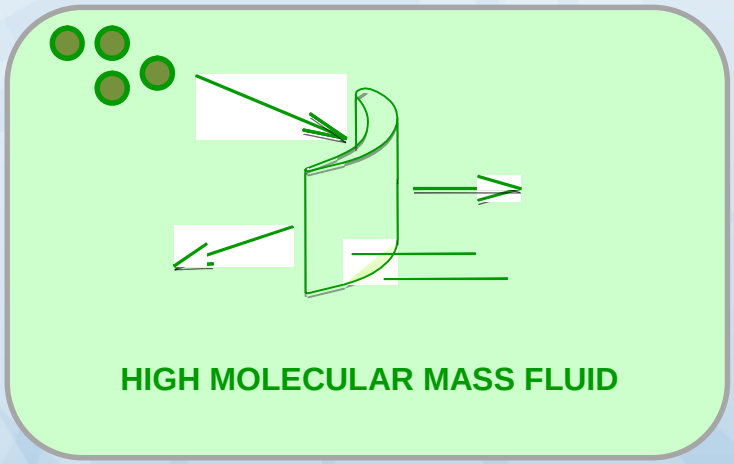
Water

- Small, fast moving molecules
- Metal parts and blade erosion
- Multistage turbine and high mechanical stress

Organic Fluid

- Very large flow rate
- Larger diameter turbine
- No wear of blades and metal parts





KEY ADVANTAGES

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Technical advantages

- High cycle efficiency
- Very high turbine efficiency (up to 90%)
- Low mechanical stress of the turbine due to the low peripheral speed
- Low RPM of the turbine allows a direct drive electric generator without reduction gear
- No erosion of blades due to the absence of moisture in the vapor nozzles

Operational advantages / results

- Simple start-stop procedures
- Automatic / continuous operation
- No on-site operator needed
- Quiet operation
- High Availability (availability > 98%)
- Partial load operation down to 10% of nominal power
- High efficiency even at partial load
- Low O&M requirements: about 3-5 hours / week
- Long life

TURBODEN – GLOBAL ORC LEADER

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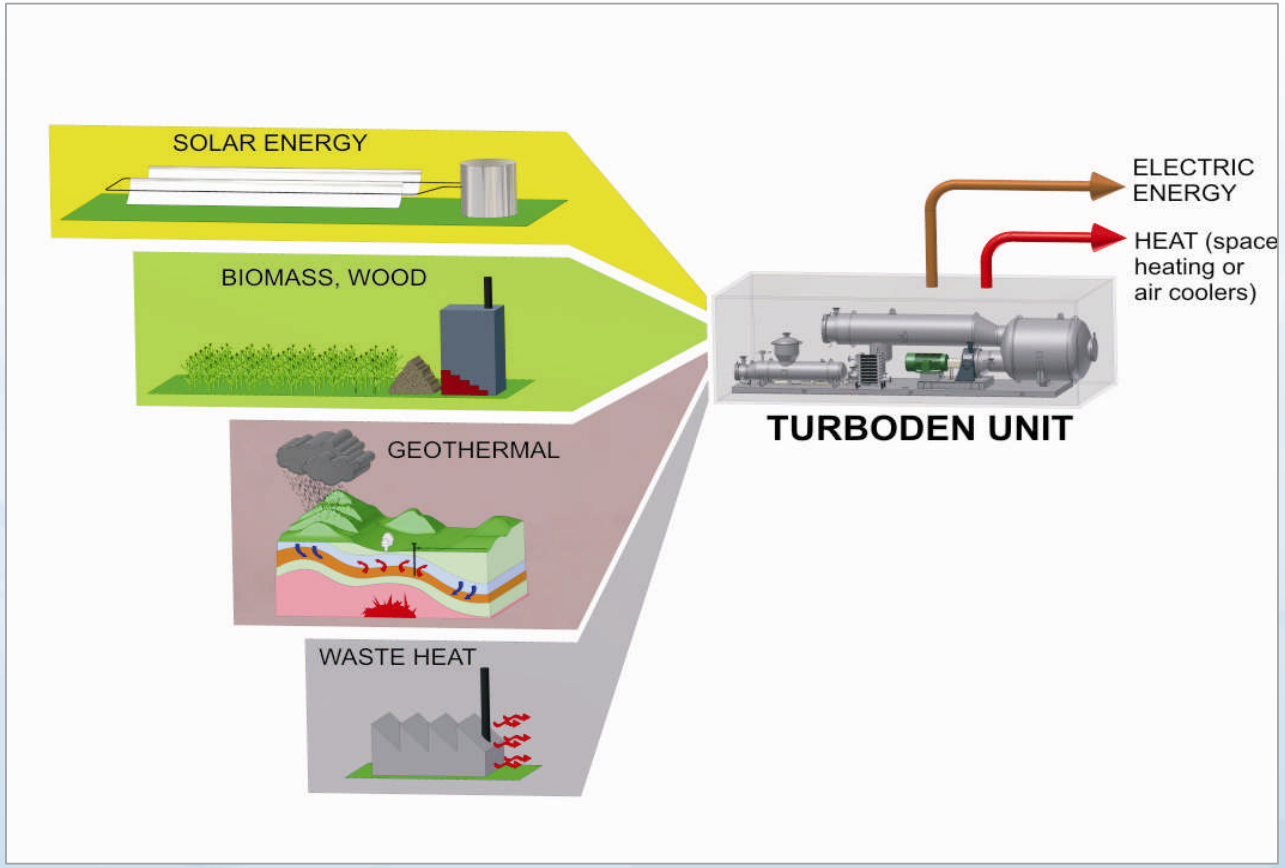
- Turboden designs and manufactures Organic Rankine Cycle (ORC) products
- 30 years of ORC experience
- Standard sizes from 400 kW to 5 MW
- Customized to > 10 MW
- Many renewable sources including recip engines



TURBODEN PRODUCT LINE

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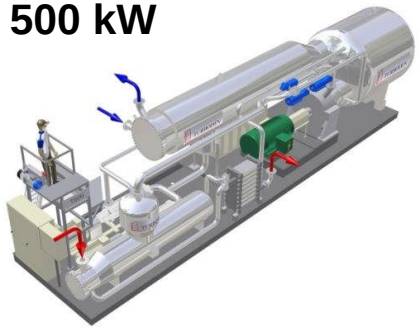
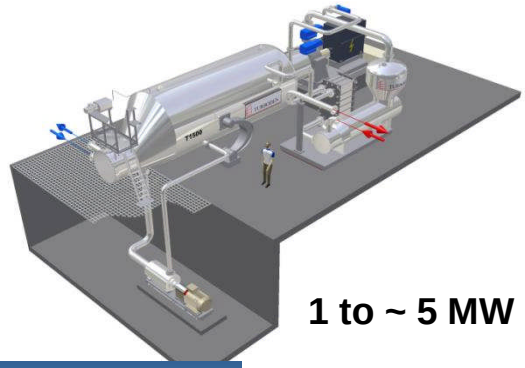
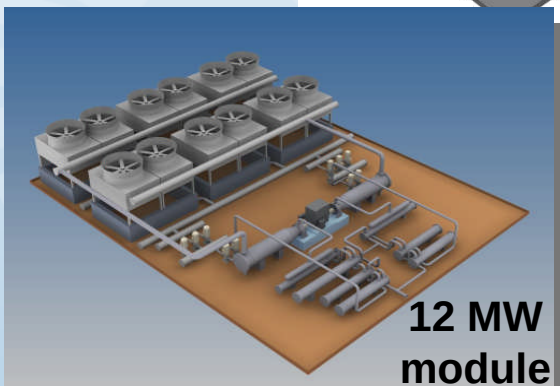
~ 500 kW





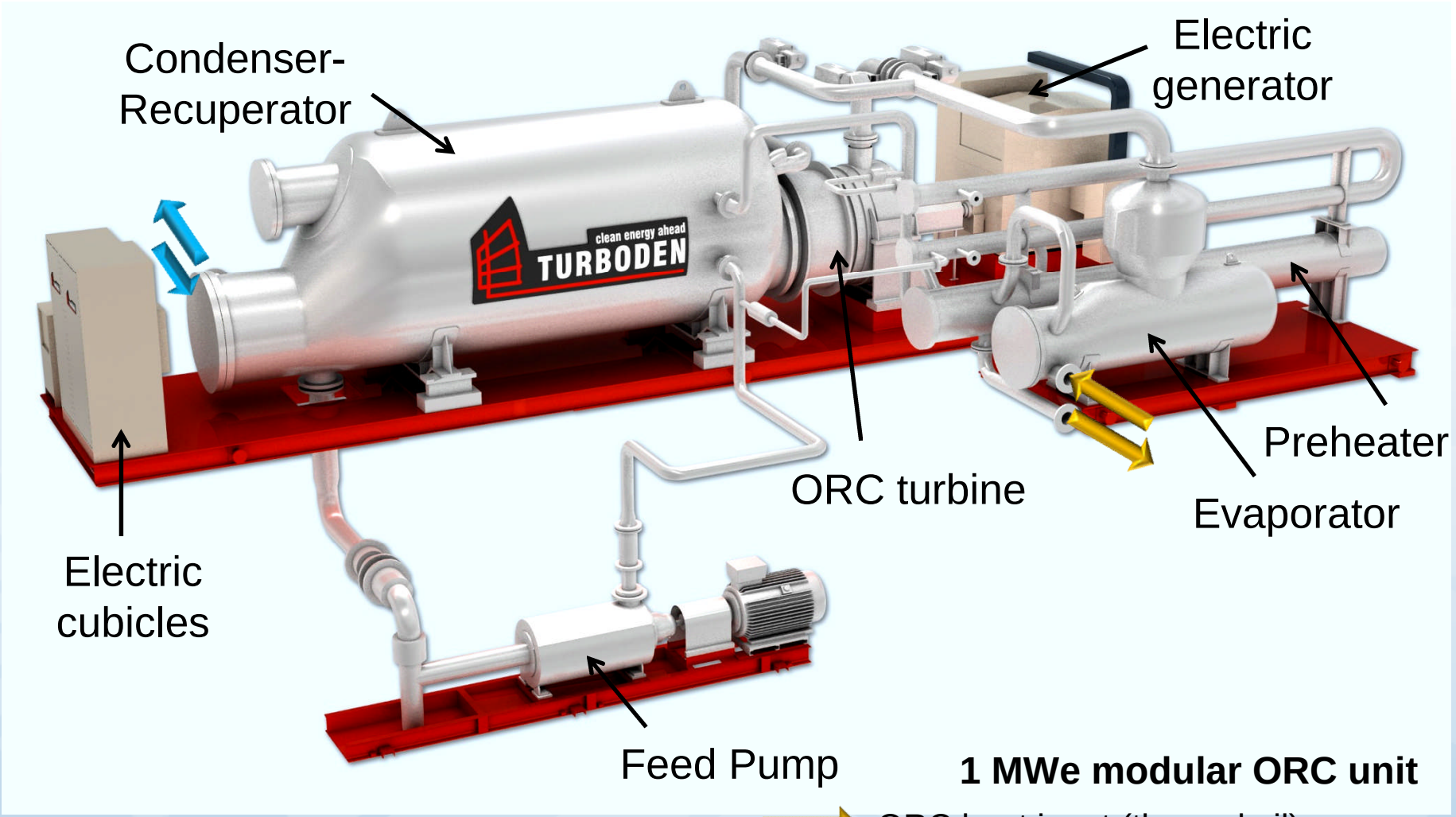
1 to ~ 5 MW



12 MW module

- High cycle efficiency (up to 24%)
- Size flexibility: 400 kW to 12 MW
- High field availability (> 98%)
- Partial load operation (down to 10%)
- Low Operation & Maintenance requirements (~ 150-250 hrs/yr)
- Long life > 20 years
- Simple, unmanned operation
- Direct drive generator
- Remote monitoring and control

TD UNITS – MAIN COMPONENTS



INSTALLATIONS - TURBODEN

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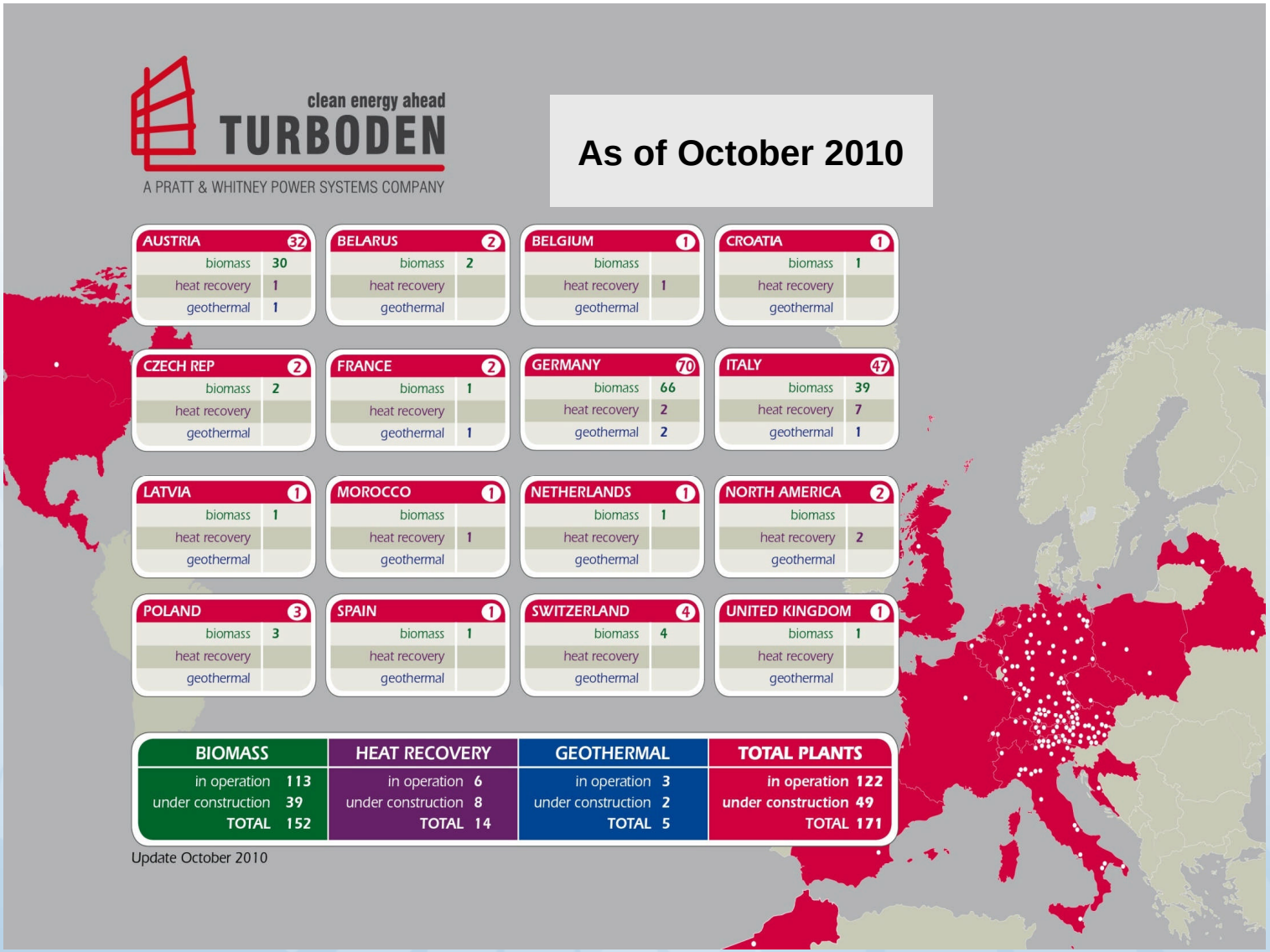

HR UNITS – STANDARD SIZES

Pratt & Whitney
A United Technologies Company

*Typical Performance Characteristics for Turboden Heat Recovery (HR) Units**

		TD4 HR	TD6 HR	TD7 HR	TD10 HR	TD14 HR	TD18 HR	TD22 HR	TD27 HR
Input — Thermal Oil									
Nominal Temperature (In/Out)	°F	527/302	500/302	518/302	518/302	527/302	536/302	536/302	545/311
	°C	275/150	260/150	270/150	270/150	275/150	280/150	280/150	285/155
Thermal Power Input	MMBtu/hr	7.51	9.73	11.77	15.36	22.01	29.69	37.54	46.08
	kW	2,200	2,850	3,450	4,500	6,450	8,700	11,000	13,500
Output — Cooling Water									
Cooling Water Temperature (In/Out)	°F	77/95	77/95	77/95	77/95	77/100	77/104	77/108	77/118
	°C	25/35	25/35	25/35	25/35	25/38	25/40	25/42	25/48
Thermal Power to the Cooling Water	MMBtu/hr	6.01	7.69	9.31	12.16	17.39	23.41	29.63	36.35
	kW	1,760	2,253	2,728	3,563	5,096	6,860	8,682	10,650
Performance									
Gross Electric Power	kW	418	567	687	898	1,302	1,762	2,220	2,740
Gross Electric Efficiency		19.0%	19.9%	19.9%	19.9%	20.2%	20.3%	20.2%	20.3%
Captive Power Consumption	kW	18	22	27	33	52	62	80	110
Net Active Electric Power Output	**kW**	**400**	**545**	**660**	**865**	**1,250**	**1,700**	**2,140**	**2,630**
Net Electric Efficiency**		18.2%	19.1%	19.1%	19.1%	19.2%	19.6%	19.5%	19.5%
Electrical Generator		asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.	asynch., 3 phase, L.V.
Size of Plant	ft	49 x 10 x 10	49 x 10 x 10	49 x 10 x 10	49 x 15 x 11	43 x 20 x 20	49 x 23 x 16	56 x 23 x 16	56 x 23 x 16
	m	15 x 3 x 3	15 x 3 x 3	15 x 3 x 3	15 x 5 x 3	13 x 6 x 6	15 x 7 x 5	17 x 7 x 5	17 x 7 x 5
	Skid	Single skid	Single skid	Single skid	Single skid	Multiple skid	Multiple skid	Multiple skid	Multiple skid

CHP UNITS – STANDARD SIZES

Pratt & Whitney
A United Technologies Company

*Typical Performance Characteristics for Turboden CHP Units**

		TD6 CHP	TD7 CHP	TD10 CHP	TD14 CHP	TD18 CHP	TD22 CHP
Input — Thermal Oil							
Nominal Temperature (In/Out)	°F	572/464	572/464	572/464	572/464	572/464	572/464
	°C	300/240	300/240	300/240	300/240	300/240	300/240
Thermal Power Input	MMBtu/hr	11.06	13.02	17.54	22.92	33.41	41.02
	kW	3,240	3,815	5,140	6,715	9,790	12,020
Output — Cooling Water							
Cooling Water Temperature (In/Out)	°F	140/176	140/176	140/176	140/176	140/194	140/194
	°C	60/80	60/80	60/80	60/80	60/90	60/90
Thermal Power to the Cooling Water	MMBtu/hr	8.77	10.38	13.95	18.15	26.76	32.77
	kW	2,569	3,040	4,087	5,318	7,842	9,601
Performance							
Gross Electric Power	kW	641	738	1,016	1,339	1,863	2,304
Gross Electric Efficiency		19.8%	19.3%	19.8%	19.9%	19.0%	19.2%
Captive Power Consumption	kW	30	35	48	58	79	97
Net Electric Efficiency**		**18.9%**	**18.4%**	**18.8%**	**19.1%**	**18.2%**	**18.4%**

**Data indicated can be optimized taking into account the actual features of the specific project.*

***Ratio between net active power output and thermal power input from thermal oil.*

ELECTRIC ONLY (HIGH EFF) UNITS

Pratt & Whitney
A United Technologies Company

*Typical Performance Characteristics for Turboden High-Efficiency (HRS) Units**

		TD12 HRS	TD24 HRS
Input — Thermal Oil			
Nominal Temperature (In/Out)	°F	581/403	572/412
	°C	305/206	300/211
Thermal Power Input	MMBtu/hr	16.44	32.88
	kW	4,817	9,634
Output — Cooling Water			
Cooling Water Temperature (In/Out)	°F	77/95	81/99
	°C	25/35	27/37
Thermal Power to the Cooling Water	MMBtu/hr	12.14	24.38
	kW	3,556	7,143
Performance			
Gross Electric Power	kW	1,188	2,342
Gross Electric Efficiency		24.7%	24.3%
Captive Power Consumption	kW	49	94
Net Active Electric Power Output	kW	1,139	2,248
Net Electric Efficiency**		**23.6%**	**23.3%**

KEY MARKET SECTORS

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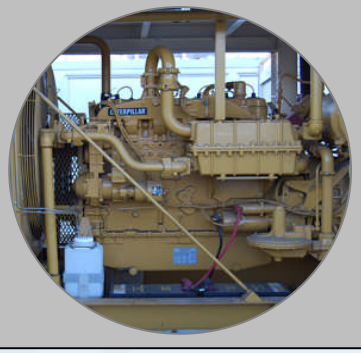
Biomass

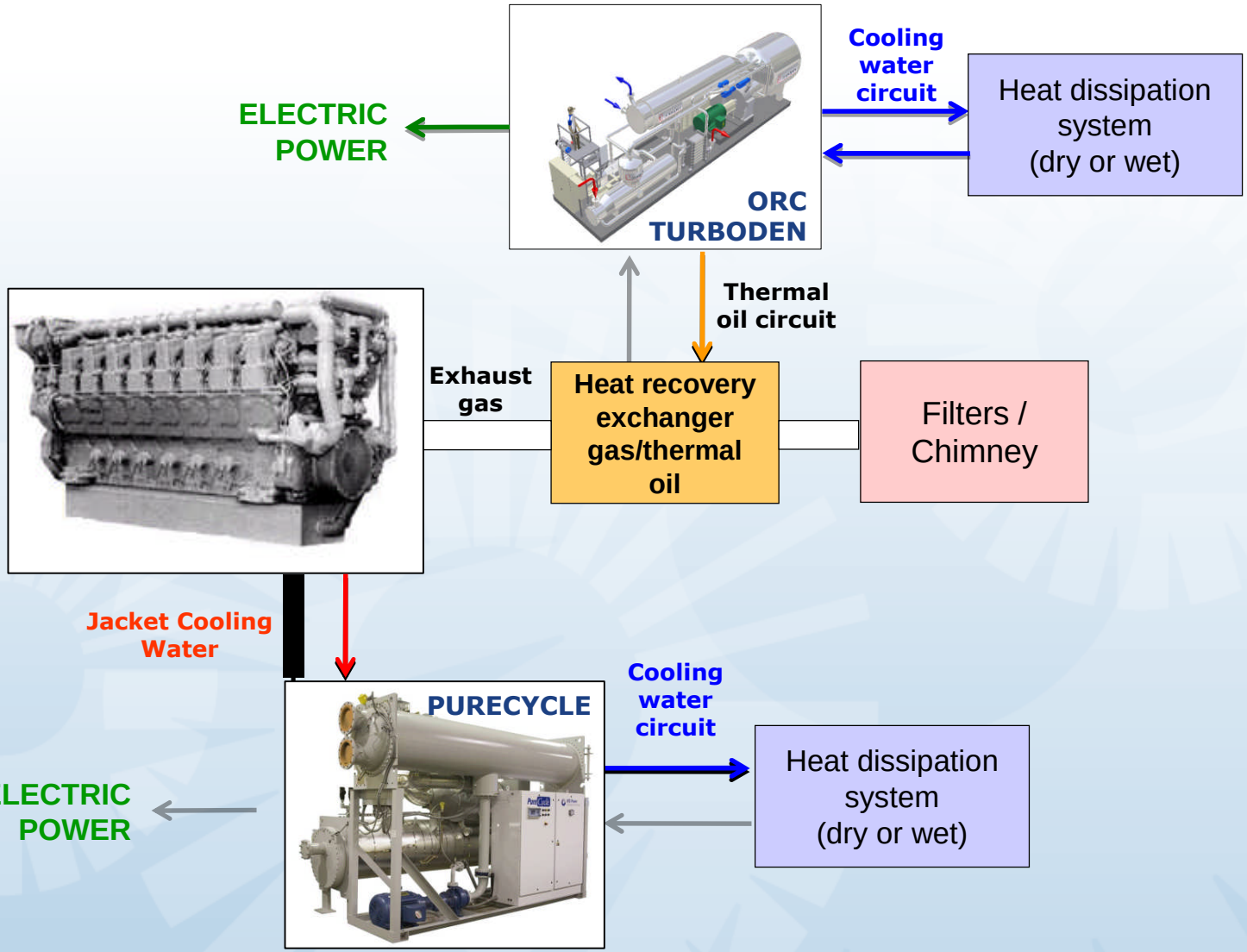
Engine and Industrial Waste Heat



Oil & Gas

Solar

IC ENGINES: UP TO 10 % ADD'L POWER



IC ENGINES: TD REFERENCE PLANTS

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Project	ORC Module	Site	Engines
Pisticci I	**TURBODEN 18 HR SPLIT (1,8 MWe)**	**Pisticci**	3 x 8 MWe Wartsila Diesel engines
Oxon	**TURBODEN 6 HR SPLIT (0,6 MWe)**	**Pavia**	1 x 8 MWe MAN Diesel engine
FinPower	**TURBODEN 6 HR DIR. EXCH. (0,6 MWe)**	**Visano**	1 x 7 MWe Wartsila Diesel engine
Pisticci II	**TURBODEN 40HR SPLIT (4,5 MWe)**	**Pisticci**	3 x 17 MWe Wartsila Diesel engines
Cereal Docks	**TURBODEN 6 HR DIR. EXCH. (0,6 MWe)**	**Portogruaro**	1 x 7 MWe Wartsila Diesel engine
Eukrasia	**TURBODEN 6 HR SPLIT (0,6 MWe)**	**Catania**	2 x 1 MWe JGS/GE gas engine + 3 x 0,8 MWe JGS/GE gas engine + 1 x 0,6 MWe JGS/GE gas engine
Blue Tower	**TURBODEN 6 HR (0,6 MWe)** **Under construction**	**Herten (D)**	2 x 2,1 MWe MWM gas engine (+ additional heat from process)
Ulm	**TURBODEN 10 HR cogenerative (0,8 MWe)** **Under construction**	**Senden (D)**	2 x 2 MWe JGS/GE gas engine (+ additional heat from process)
Land & Marine Blue NG	**2 x TURBODEN 10 HR (0,8 MWe)** **Under construction**	**Southall (UK)** **Beckton (UK)**	1 x 14 MWe MAN Diesel engine

GAS TURBINES: UP TO 30% ADD'L POWER

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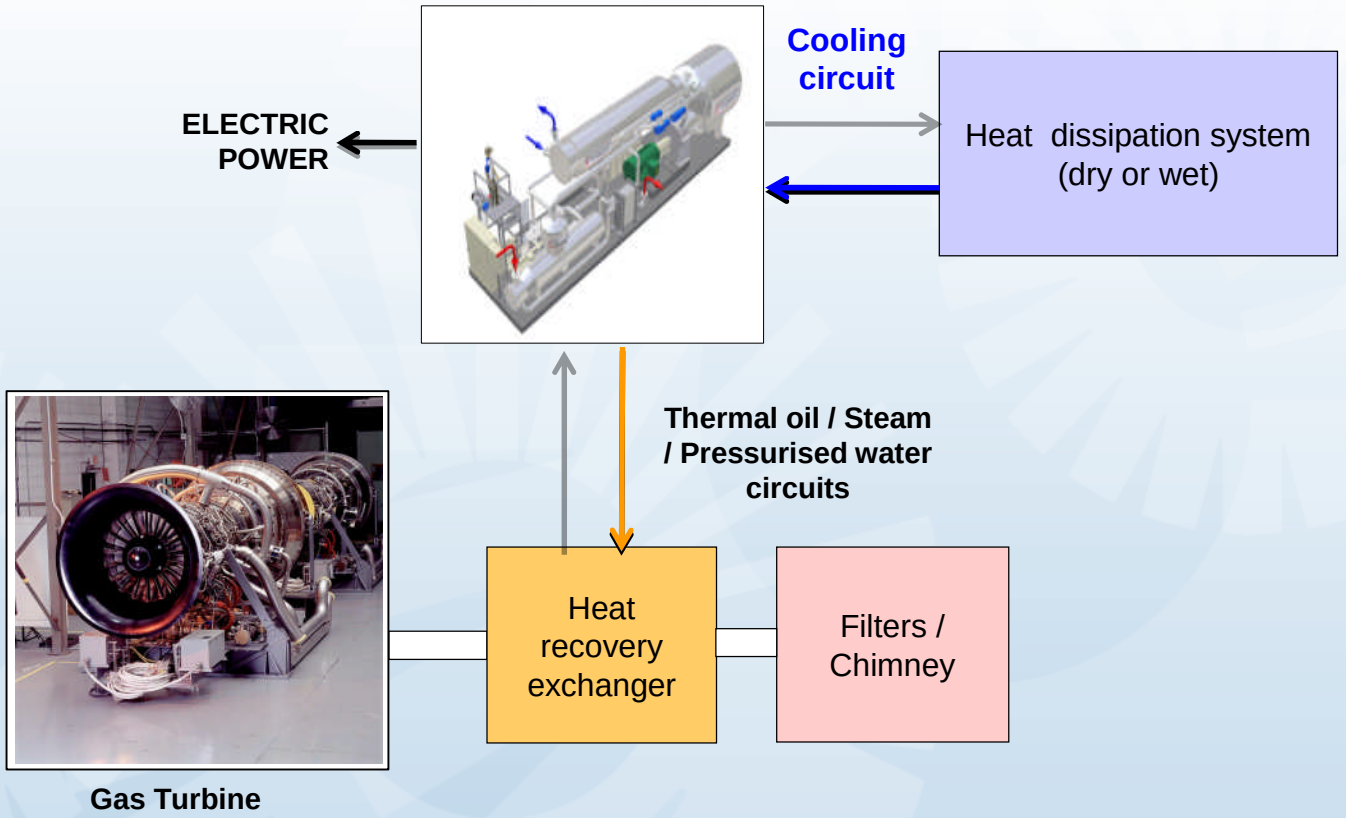
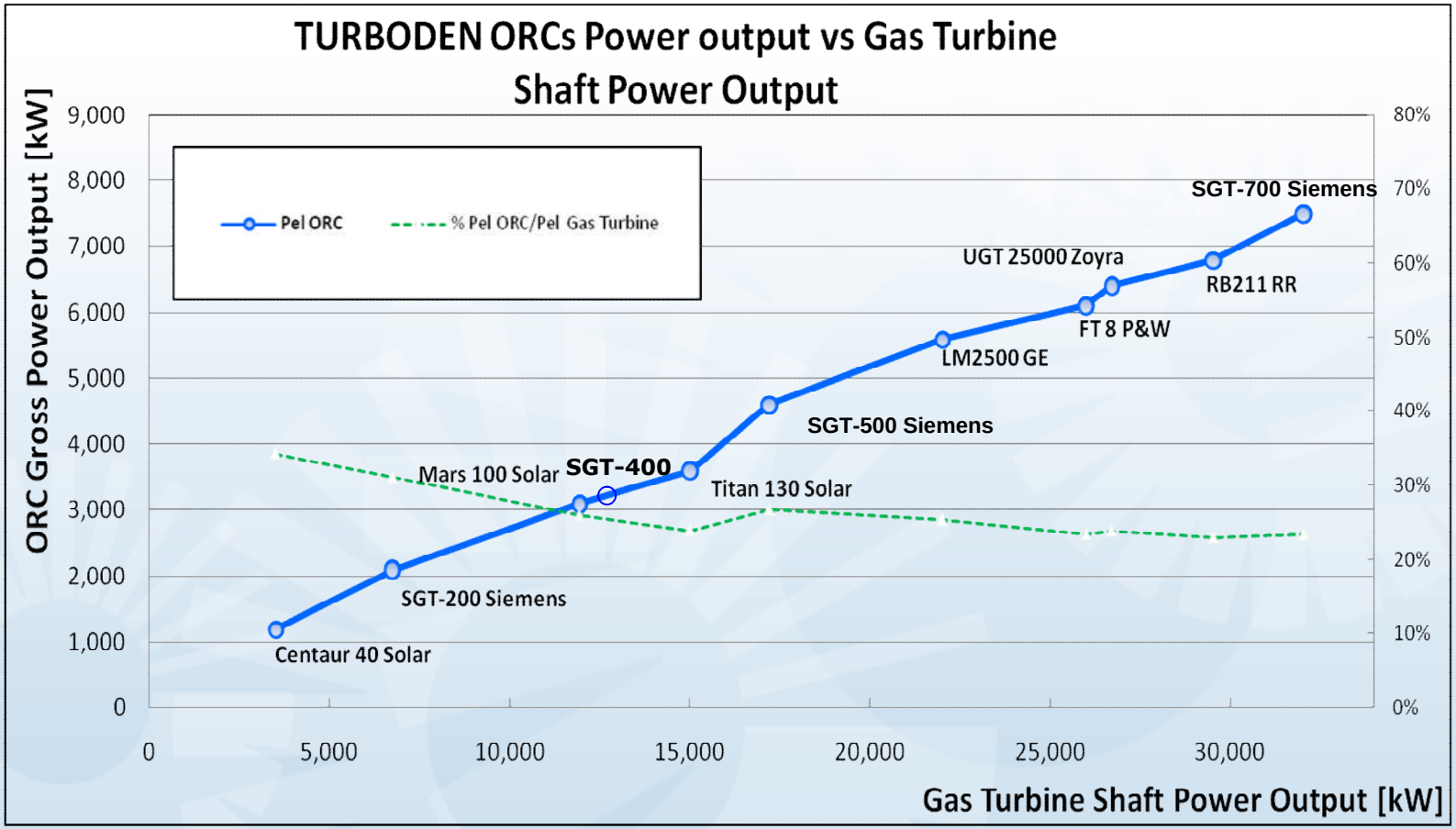


GAS TURBINES – TYPICAL OUTPUTS



ORC suitable for heat recovery in:

- Remote/unmanned locations with variable operating loads (ex., gas compressor stations)
- Continuous applications
- "Peak load" power stations (easy and fast start-up procedures)

NOTE: Indicative values assuming ambient air temperature of 15°C, Gas Turbines operating at nominal load; calculations based on Gas Turbine exhaust gas properties as reported in specific suppliers web sites.

GAS TURBINES: REFERENCE PLANTS

Pratt & Whitney
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TransGas™

Heat Source: Solar Centaur 40

- 3505 kW Shaft Output
- 19.0 kg/sec mass flow
- 446°C Exhaust Temp
- Gas compression station

ORC Model: TD 10 HR

- 865kW Net Electric Output
- 19.1% Electric Efficiency
- 49 X 11 X 15 ft size (60 Tons)

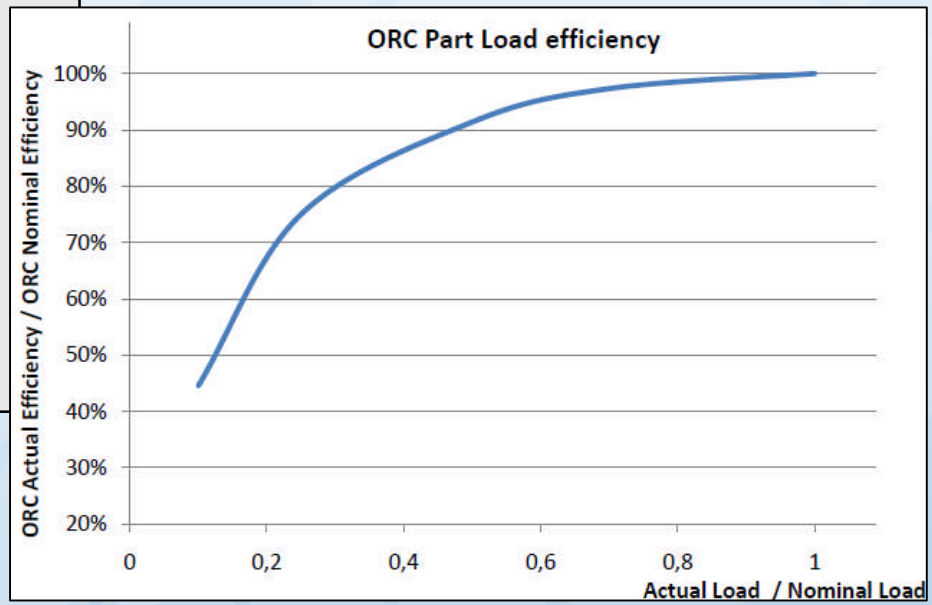
Benefits

- 25% increase in power output
- 25% reduction in CO2 footprint

SYSTEM ADVANTAGES

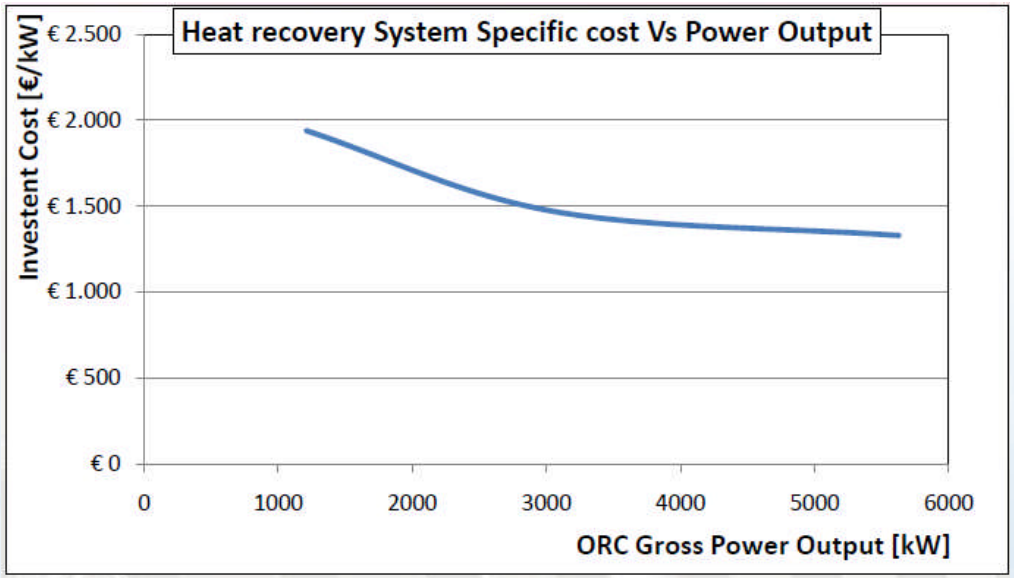
Pratt & Whitney
A United Technologies Company

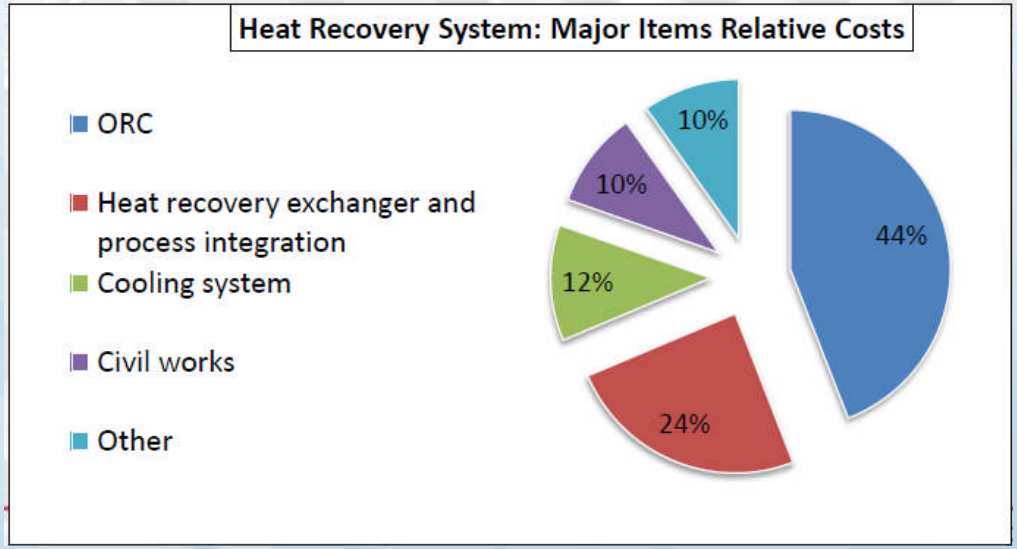
- Completely automated – no operator
- Very low O&M Costs
- No effect on main power plant operation
- Simple Start/Stop procedures
- Maintains good efficiency at partial load
- Low turbine RPM, low mechanical stress
- Can reach efficiencies up to 25%
- Do not consume water
- Remotely monitored and controlled
- Turn-down to 10% of nominal power
- Quiet Operation



INVESTMENT COSTS

- ORC accounts for ~45% of total
- Cost Influenced by:
  - Size (See Curve)
  - Average air temperature
  - Heat recovery option selected





HEAT RECOVERY APPLICATIONS

Pratt & Whitney
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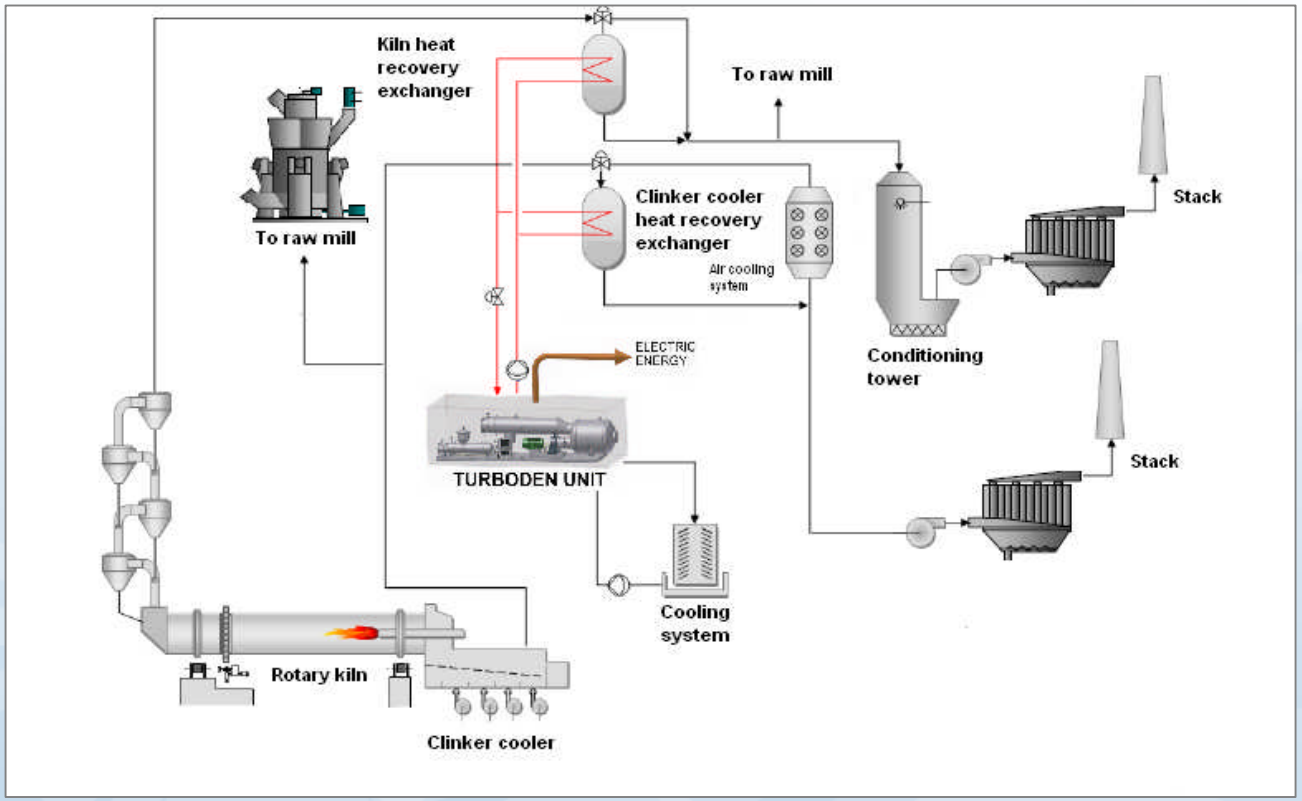
Typical limits	GAS >480°F (250°C)	LIQUID >195°F (90°C)	STEAM / VAPOR
Cement	✓	☐	☐
Glass	✓	✓	☐
Oil & Gas	✓	✓	✓
Chemicals	✓	✓	✓
Steel / Non Ferrous	✓	☐	✓
Pulp & Paper	☐	✓	✓
Food	☐	✓	✓
Waste treatment	✓	☐	✓
Thermal Oxidizers	✓	✓	☐
Power generation	✓	☐	✓

CEMENT PRODUCTION PROCESS



Exhaust Gas:

- High dust content
- Different operating conditions depending on mill operation, season, plant upsets, etc.

Exhaust gas streams:

- Kiln pre-heater gas
- Clinker cooler gas

CEMENT PRODUCTION REFERENCE

Pratt & Whitney
A United Technologies Company

إسمنت المغرب
Ciments du Maroc
Italcementi Group

Reference Case study: PRS gas waste heat recovery

- Clinker production capacity: ≈ 5.000 ton/day
- Heat source: exhaust gas @ 330°C
- Gas cooled down to 220°C (extra heat used for raw material pre heating)

- ORC electric power: About 2 MWe
- Client: CIMAR – ITALCEMENTI GROUP (Morocco)
- Under construction, start up Q4, 2010

REFRACTORY PRODUCTION EXAMPLE

Pratt & Whitney
A United Technologies Company

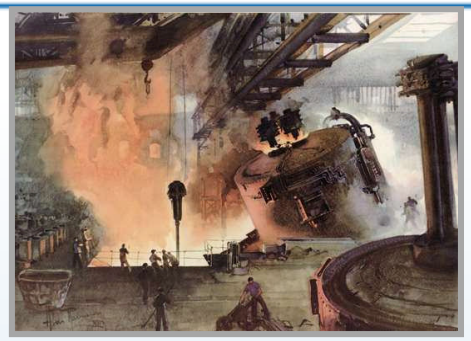
RHI

Refractory ovens exhaust gas

- Refractory production capacity: ~250 ton/day
- Heat source: exhaust gas @ 500 °C
- Gas cooled down to ~ 150 °C

- ORC electric power: About 1 MWe
- Client: RHI GROUP (Radenthein - Austria)
- In operation since: Q1, 2009

STEEL INDUSTRY



- Rolling, forging
- Heat treatment
- Strip processing

- Relatively clean exhaust gas at moderate temperature
- Cost effective for ORC ≥ ~ 1 MW

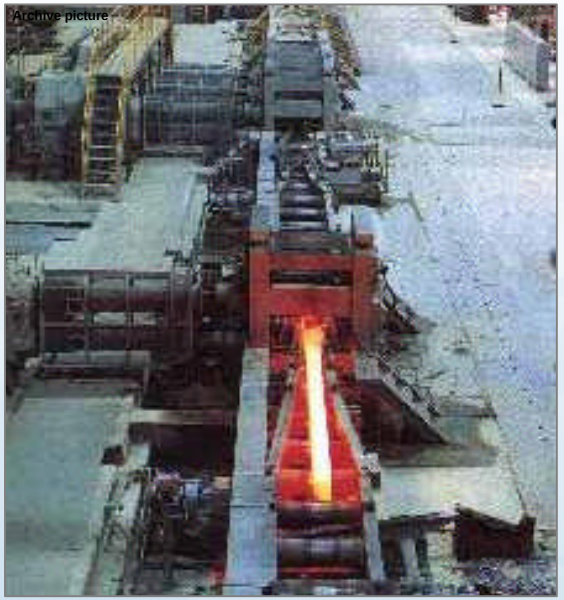
- Sinter
- Blast furnace
- BOF
- EAF

- Interface between process and energy recovery unit is critical
- Exhaust gas:
  - high flow
  - high temperature
  - high dust content
  - large variations in operating cycle
  - environmental constraints

ELEC. ARC FURNACE EXAMPLE 1

Pratt & Whitney
A United Technologies Company

- **Billet re-heating furnace**
  - **Production capacity: ~ 100 MT/h**
  - **Heat source: exhaust gas @ 500°C (930°F)**
  - **Gas cooled down to 150°C (355°F)**
- **No heat carrier: direct heat exchange**
- **Exhaust Gas Characteristics:**
  - **Absence of dust (natural gas fired)**
  - **Variable conditions depending on mill operation, etc.**
  - **ORC electric power: ~ 1 MW**



Study for merchant and re-bar mini-mill – Italy
Sponsored by EU **Life+** program

H·REII
Heat Recovery in
Energy Intensive Industries

ELEC. ARC FURNACE EXAMPLE 2

Pratt & Whitney
A United Technologies Company

EAF off-gas with steam production

- **EAF: 40 MT**
- **Heat source: exhaust gas**
- **20 MT/hr of steam @ 13-20.5 bar**
- **Steam used in ejectors for vacuum cleaning**
- **Residual steam (~ 15 MT/hr @ 15 bar) for the ORC**

ORC electric power: ~ 1 MW

Georgsmarienhütte
GmbH · seit 1856 · Edelstahl

Proposal for ***Georgsmarienh tte Gmbh***

ELEC. ARC FURNACE EXAMPLE 3

Pratt & Whitney
A United Technologies Company

EAF + Bloom / Billet

- **EAF Exhaust + WBF Skids / exhaust**

Heat resources

- **EAF: 20 MT/hr of steam @ 14-28 bar (220-440 psi)**
- **WBF: saturated steam @ 16 bar (250 psi)**
- **WBF skids: hot water 150 m3/hr @ 110 C (230 F) – return at 90 C (150 F), partly used for district heating**

- **ORC electric power: ~ 3.7 MW**

Proposal for long high-grade steel mini-mill - Germany

GLASS INDUSTRY

Pratt & Whitney
A United Technologies Company

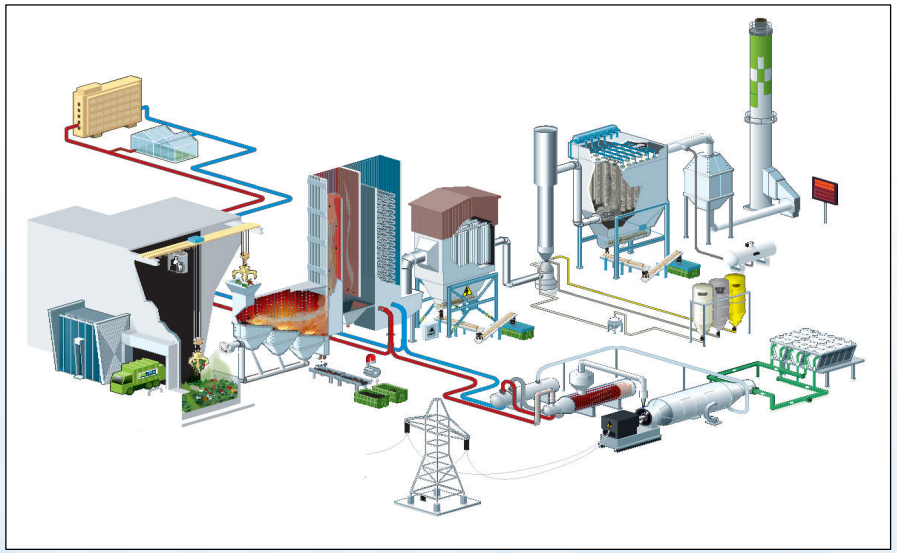
Heat source properties:

- High exhaust gas temperature
- Constant operating conditions
- Exhaust gas with moderate dust content
- Exhaust gas must be cooled not below 200°C

- High efficiency ORC used (~ 25% efficiency)

REFERENCE CASE - INCINERATOR

Pratt & Whitney
A United Technologies Company



Heat recovery from pressurized water boiler in waste incinerator

- **Q2, 2008 start-up (MIROM, Belgium)**
- **Hot water at 180°C (back 140 °C)**
- **Cooling source: Water/Air**
- **Total electric power: 3 MW**
- **Net electric efficiency: 16,5%**
- **Availability: > 98%**

ADVANTAGES – TURBODEN + PWPS

Pratt & Whitney
A United Technologies Company

• Products	EPC/Turnkey or Equipment Only
• Size flexibility	280 kW - 12 MW Building Blocks
• Wide temperature range	91°C to > 300°C
• ORC Experience	30 years
• Proven reliability	Standard designs/P&W Quality Standards
• Modularity	Factory assembled systems
• Aftermarket capability	Global Service Infrastructure /
• Financial strength	Backed by Pratt & Whitney
• Lead time	~ 12-14 Months for custom made units

THANK YOU !

www.turboden.com

www.pw.utc.com

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