Master of Science in *Energy Engineering Renewables for Environmental Sustainability*

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School of Industrial and Information Engineering
Academic Year 2017-18

Lecture notes for:
Bioenergy and Waste-to-Energy Technologies

Production of electricity and heat: Power cycles

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Lecture outline

- *Basics of thermodynamic cycles*
- *Steam cycles in large BtE and WtE plants*
- *The pursuit of high efficiency in WtE plants*
- *CHP production as a way to increase efficiency*
- *Medium-large scale BtE plants*
- *Small scale BtE plants, the ORC technology*
- *Very small steam turbine-based cycles*

Production of electricity (power)

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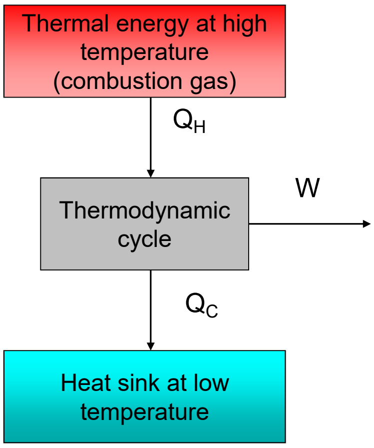

Once thermal energy is available at high temperature, as it is in the hot flue gas produced by burning biomass and/or waste, it can be used to feed a thermodynamic cycle for the production of only electricity (i.e. “power”) or the Combined production of Heat and Power (CHP).

The Rankine steam cycle

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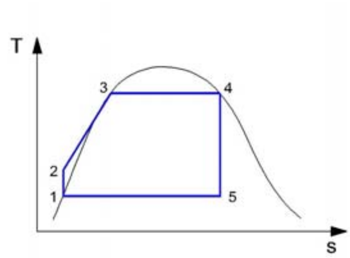
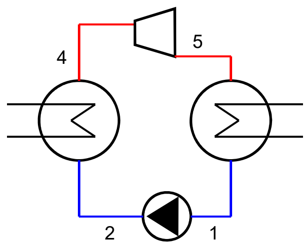


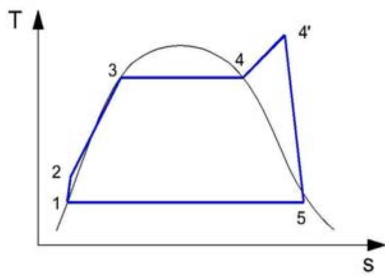


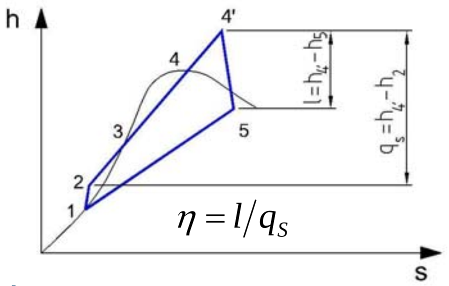
Simple cycle, ideal machines

1-2 compression
2-3 preheating
3-4 evaporation
4-5 expansion
5-1 condensation

- It is known as the most effective way to covert thermal energy in mechanical energy.
- It uses water as working fluid, which is abundant, cheap, non-toxic, non-flammable, non-explosive.
- Moreover, water present a very high specific storing capacity of energy, thanks both to its high specific heat and its very relevant latent heat of evaporation.

The Rankine steam cycle





Superheated cycle, real machines

1-2 compression
2-3 preheating
3-4 evaporation
4-4' superheating
4'-5 expansion
5-1 condensation

- Reliable and well-proven technology.
- Widespread all over the world.
- Typically large scale applications → very strong economies of scale.
- Difficult to be implemented in small scale application with limited costs.

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Steam cycles in large BtE and WtE plants

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- They present sizes much smaller than those of conventional fossil fuel-fired thermoelectric power plants (max size of some tens of electric megawatts, vs. some hundreds). This implies that:
  - The machines, primary the steam turbine, suffer a very strong scale effect on performances. Thus, the machines used in BtE and WtE plant typically present modest performances.
  - Due to the scale effect on costs, the small size of these cycles make non-economic the adoption of several sophistications typically adopted in large size power cycles (reheating, high feedwater preheating temperature and number of stages, Lujngstrom air preheater, etc.).
- The critical characteristics of the waste fuel make very expensive the adoption of advanced steam conditions in WtE plant, as well as common cycle configurations (re-heat).
- Typically, the design of WtE plants tends to favor reliability rather than performances, since anyway waste **must be disposed of**.

Isentropic expansion efficiency of steam turbines

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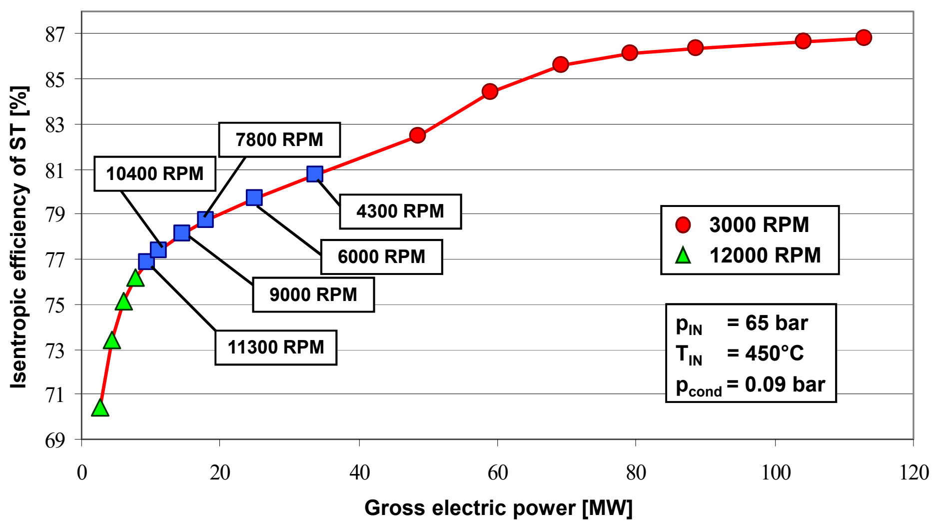
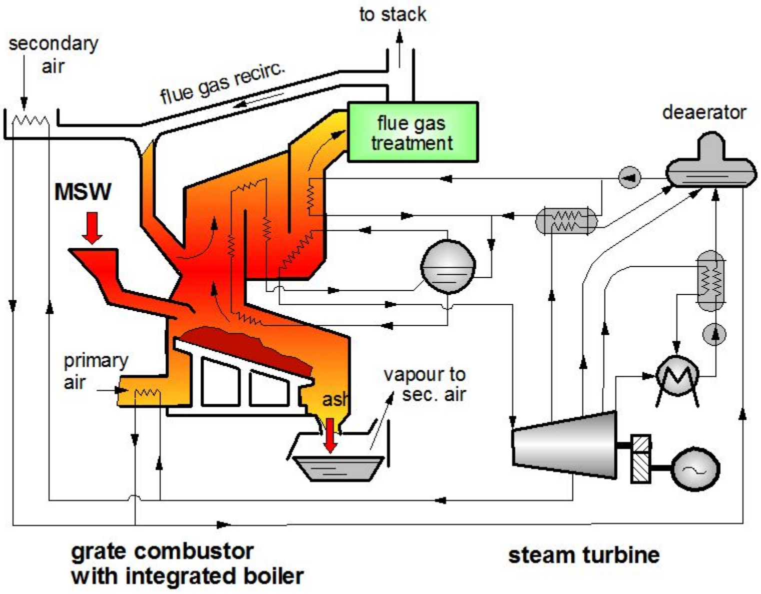
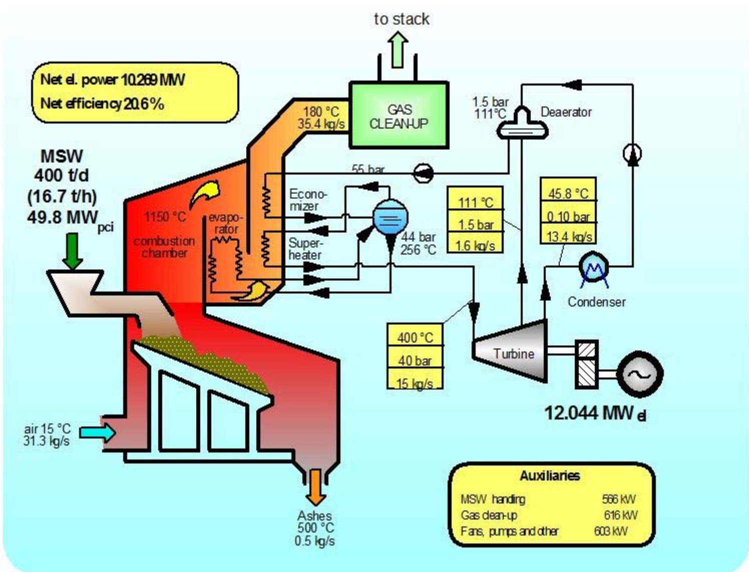


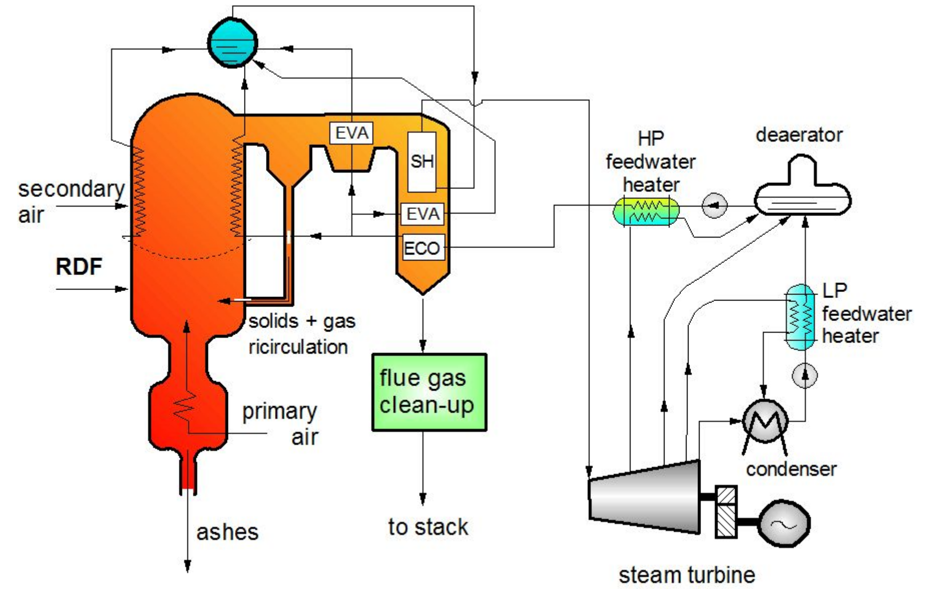
Steam cycle of a grate-based WtE plant



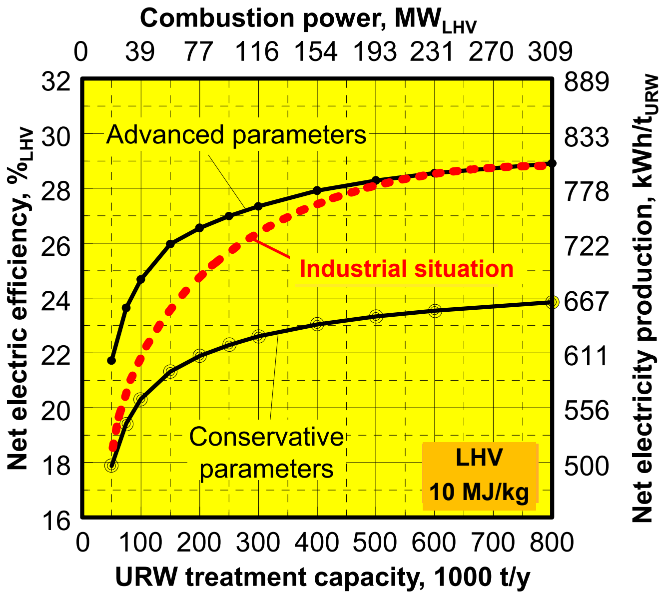
Steam cycle of a grate-based WtE plant
Mass and energy balances



Steam cycle of a fuidized bed-based WtE plant



Scale effect on performances of WtE plants (net electric efficiency)



Corrosion limits the evaporating pressure (waste-fired boilers)

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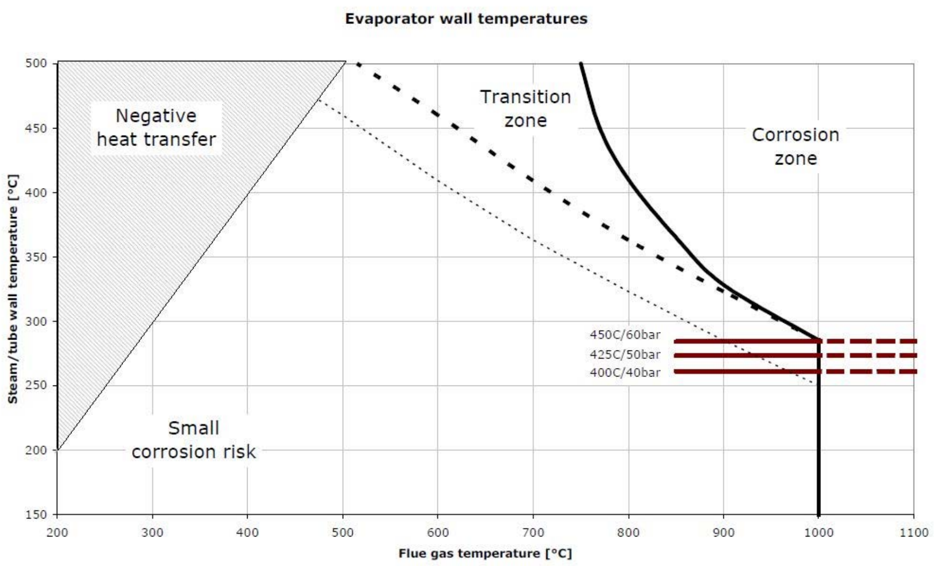

B. Kamuk, "Consequences by operating at extreme steam parameters". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

Corrosion limits the superheating temperature (waste-fired boilers)

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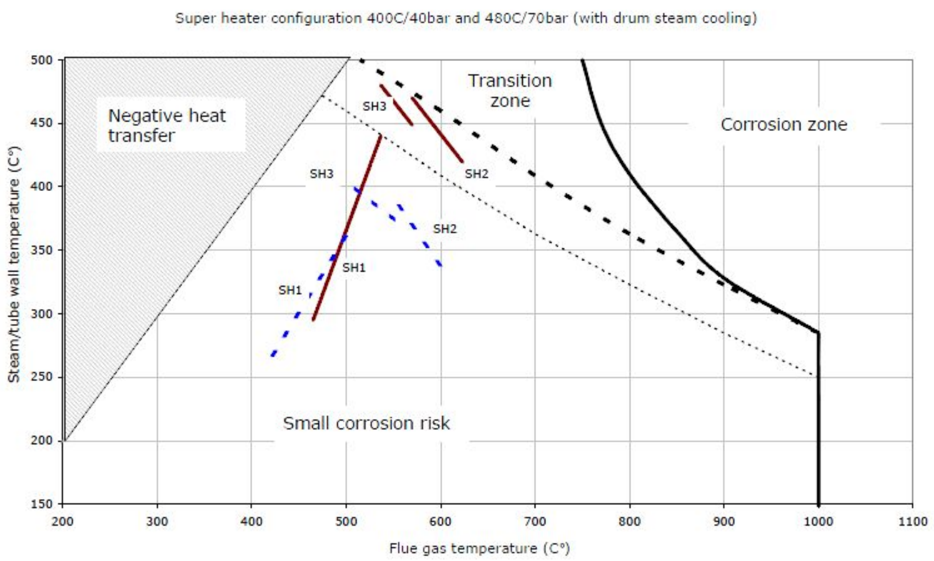

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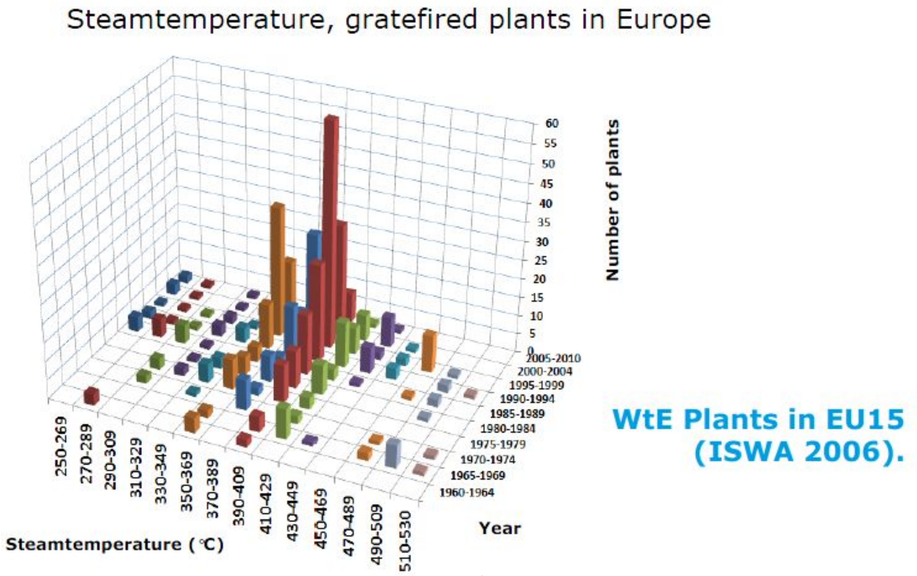
European WtE plants



B. Kamuk, "Consequences by operating at extreme steam parameters". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

Steam cycle in WtE plants: final remarks

- Maximum SH temperature below 420-450°C to avoid corrosion problems in the SHs.
- No RH to avoid doubling the critical parts of the boiler.
- As a consequence, maximum evaporation pressure below 65-70 bars, to avoid excessive liquid formation in the last part of the turbine expansion, as well as to limit the temperature of the evaporating tube walls of the boiler (and so avoid corrosion problems).
- Air pre-heating, when present, is done with steam: no Ljungstrom preheater can be used.
- Few (or none) regenerative feedwater pre-heaters to limit costs and keeping a low temperature at the inlet of the boiler.
- Low efficiency of the steam turbine due to the small size.

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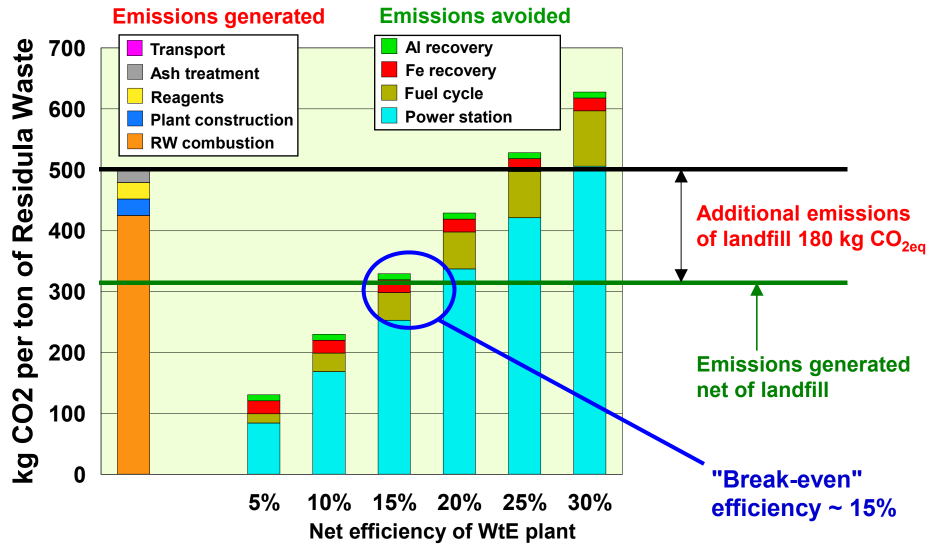
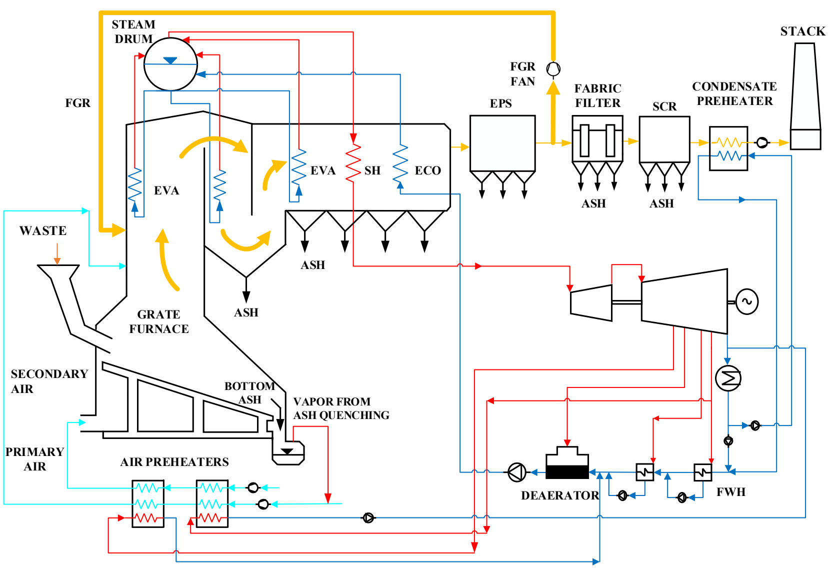
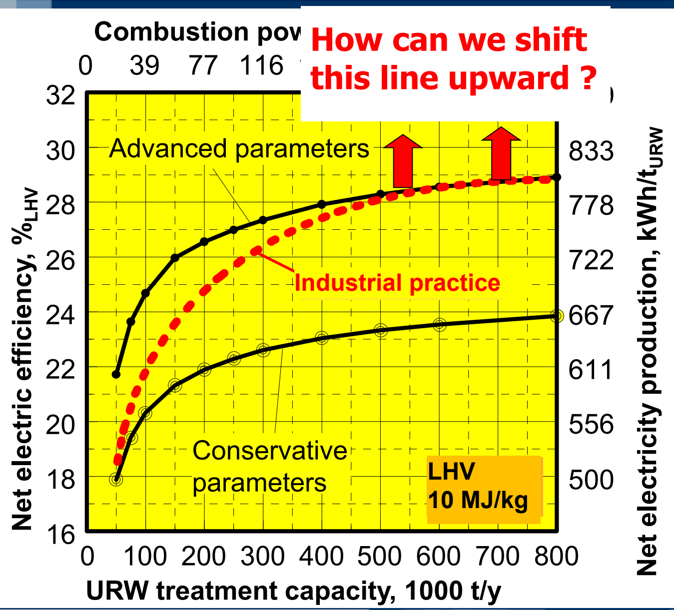
Why efficiency is so important ?



Modern, advanced combustion plant



Industrial practice vs scale



Possible routes to increase efficiency

1) Increase scale --> larger plants
2) Improve steam cycle:
   - better cycle parameters --> higher P_{ev}, T_{SH}, lower P_{cond}
   - more sophisticated configuration --> more regenerators, reheat
3) Use auxiliary, high-quality fuels in complex, integrated configuration

- P_{cond} is determined by ambient conditions and water availability
- Higher P_{ev} necessarily requires either higher T_{SH} or reheat to limit liquid fraction at steam turbine outlet

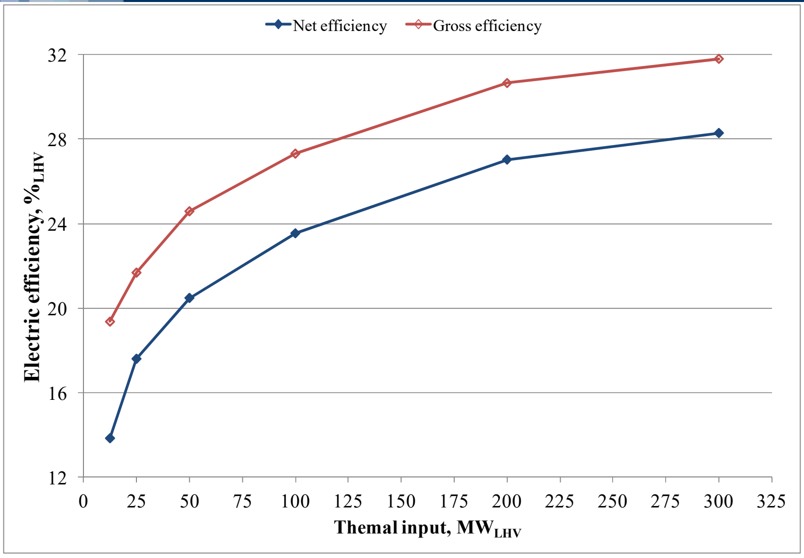
⇨ must go to either higher T_{SH} and/or reheat ⇦

Sophistication level of WtE plants as function of the size – typical assumptions

Nominal thermal input, MW_{LHV}	12.5	25	50	100	200	300
Waste flowrate, kg/s	1.209	2.418	4.836	9.671	19.342	29.014
Treatment capacity (@ 7,800 h/y), t/y	33,913	67,826	135,652	271,304	542,609	813,913
O_2 in flue gases at boiler exit, $\%_{vd}$	7.5	7.0	6.5	6.0	5.5	5.5
Steam pressure at turbine inlet, bar	30	35	40	45	65	70
Steam temperature at turbine inlet, °C	350	380	400	420	440	450
No. of steam bleedings for air preheating	1	1	2	2	2	2
Final heat recovery from flue gas	No	No	Yes	Yes	Yes	Yes
LP regenerative condensate preheater	No	No	Yes	Yes	Yes	Yes
Feedwater temperature at boiler inlet, °C	120	120	140	140	140	140
O_2 in flue gas at stack, $\%_{vd}$	8.5	8.0	7.5	7.0	6.5	6.5
Flue gas temperature at stack, °C	~180	~180	135	135	135	135

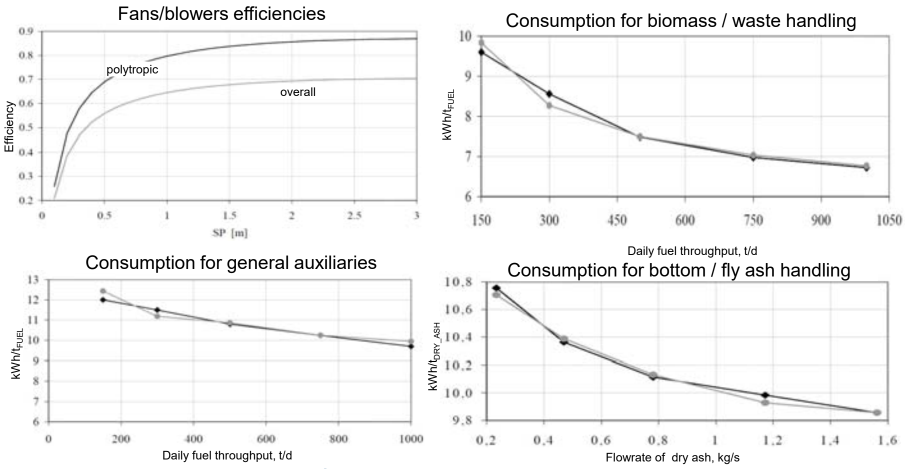
Economies of scale makes available for large sizes more resources that can be used in part to lower the specific cost of the technology, in part to increase the sophistication of the plant layout (with the consequence of higher performances and a further decrease of specific costs).

Sophistication level of WtE plants as function of the size – results



Auxiliary consumption weights more on small plants that on large ones.

Auxiliary consumptions of large BtE and WtE plants



- Electric consumption for heat rejection to ambient, mainly due to the cooling of the condenser, is typically assumed as proportional to the amount of heat rejected. For water cooled-condenser about 1%, for evaporative towers about 1.5%, for air-cooled condenser about 2%,

Efficiency gains associated with the adoption of enhanced steam conditions

IS THE STEAM PARAMETER THE KEY TO A HIGHER ELECTRICAL EFFICIENCY?

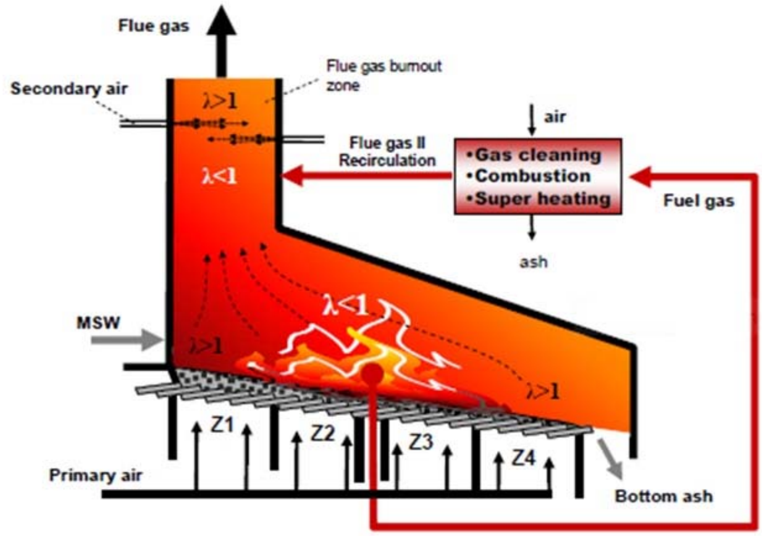
Approximate increase of eletrical efficiency for a 20 t/h plant

- 400/40 : 22,0% (basis) 13,4 MW
- 425/50 : 23,1% (+1,1%point) +0,6 MW
- 425/70 : 23,7% (+1,7%point) +1,0 MW
- 480/70 : 24,8% (+2,8%point) +1,7 MW
- 500/130: 26,2% (+4,2%point) +2,6 MW

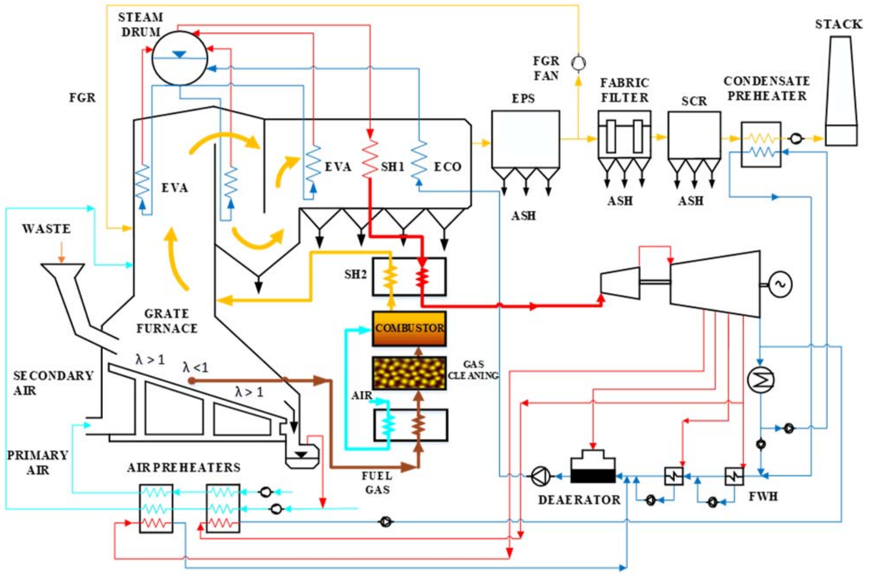
B. Kamuk, "Consequences by operating at extreme steam parameters". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

The challenge of higher T_{SH}

"Bypass" concept (Hans, 2010)

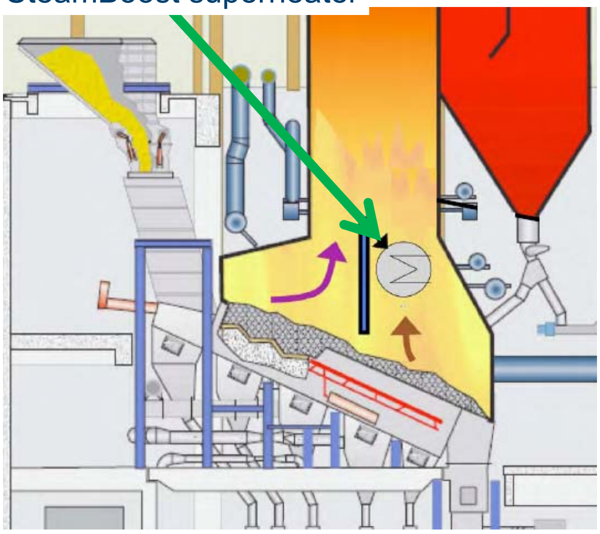


Plant scheme with by-pass concept

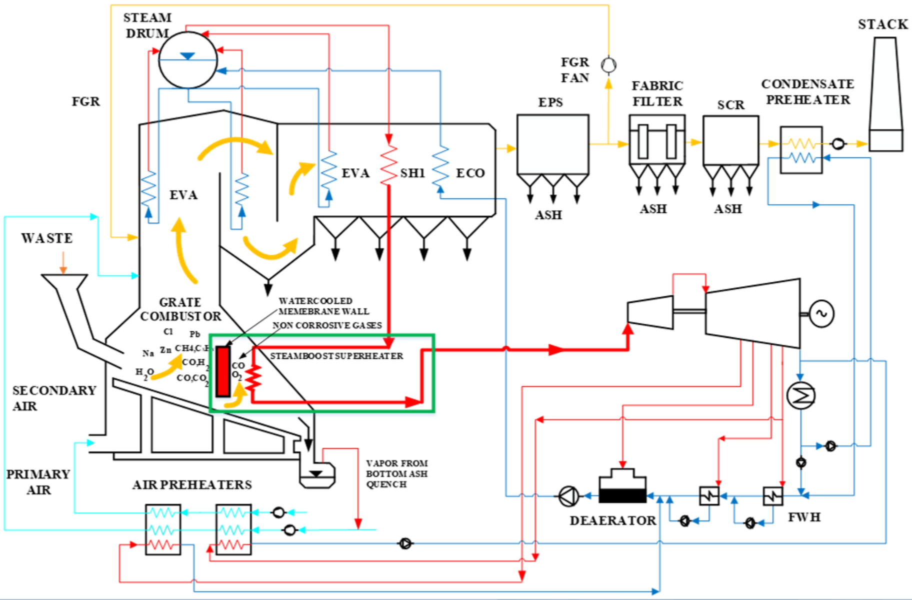


"Steam Boost" concept (Madsen, 2007)

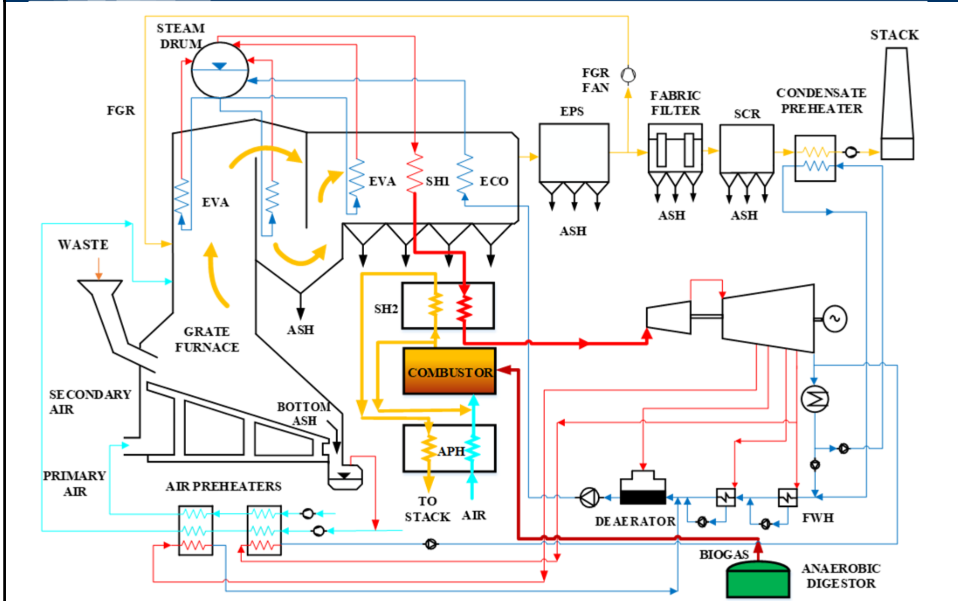
SteamBoost superheater



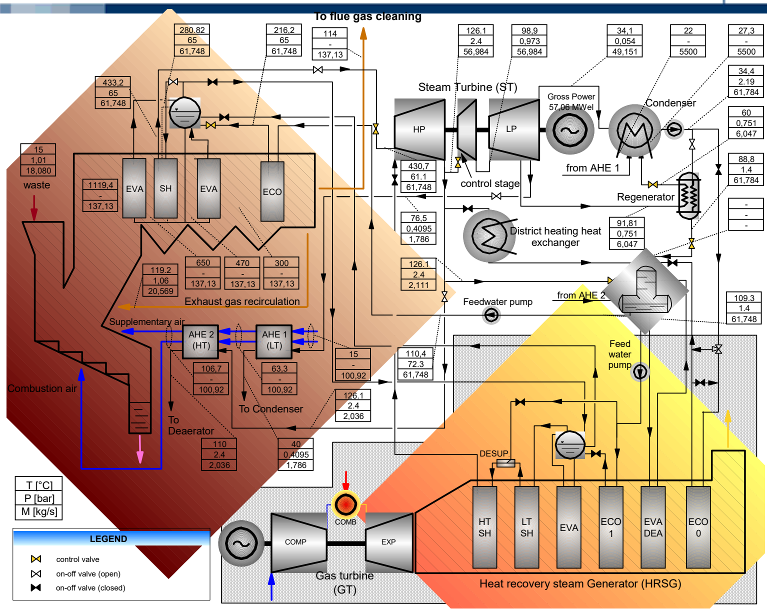
Plant scheme with steamboost



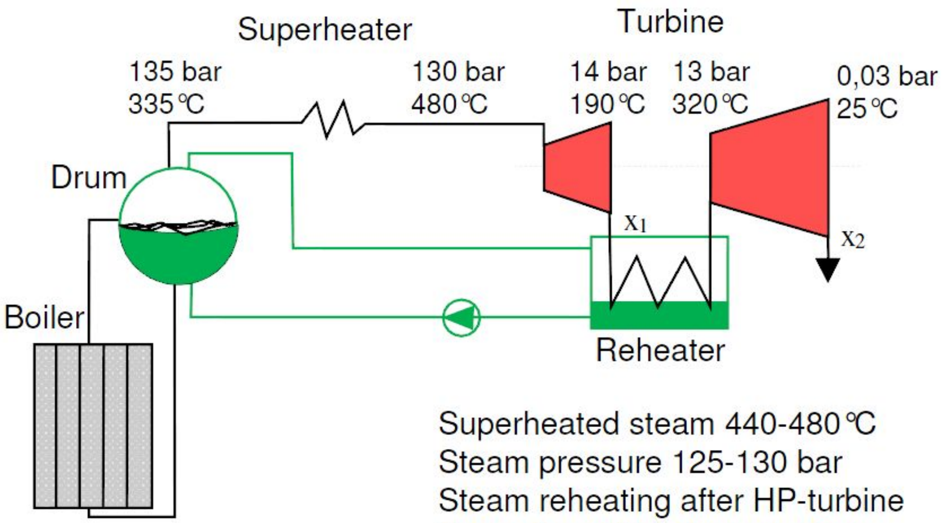
External superheating with Biogas



Integration with Combined Cycles



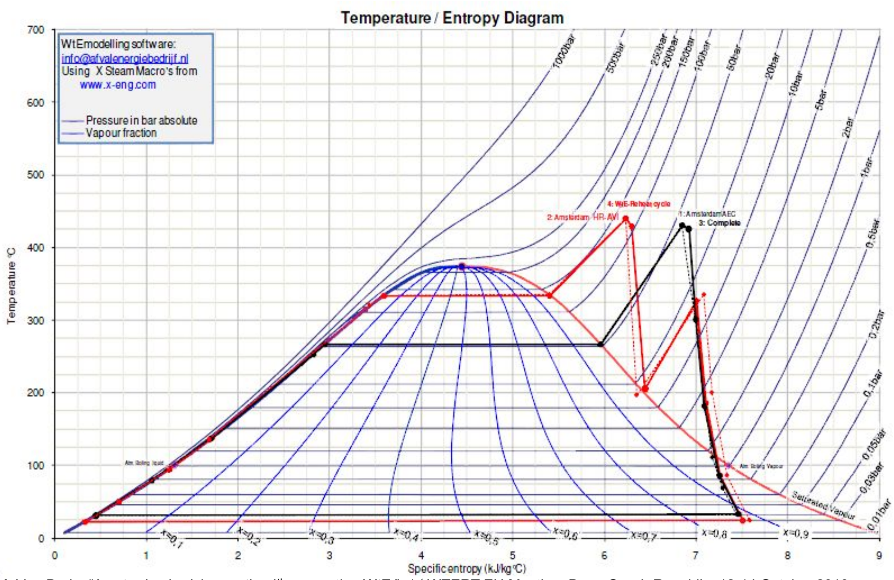
Extreme / innovative solutions to improve energy efficiency



Superheated steam 440-480 °C
Steam pressure 125-130 bar
Steam reheating after HP-turbine
Second and Third economiser

M. Van Berlo, "Amsterdam's vision on the 4th generation WtE ". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

Extreme / innovative solutions to improve energy efficiency



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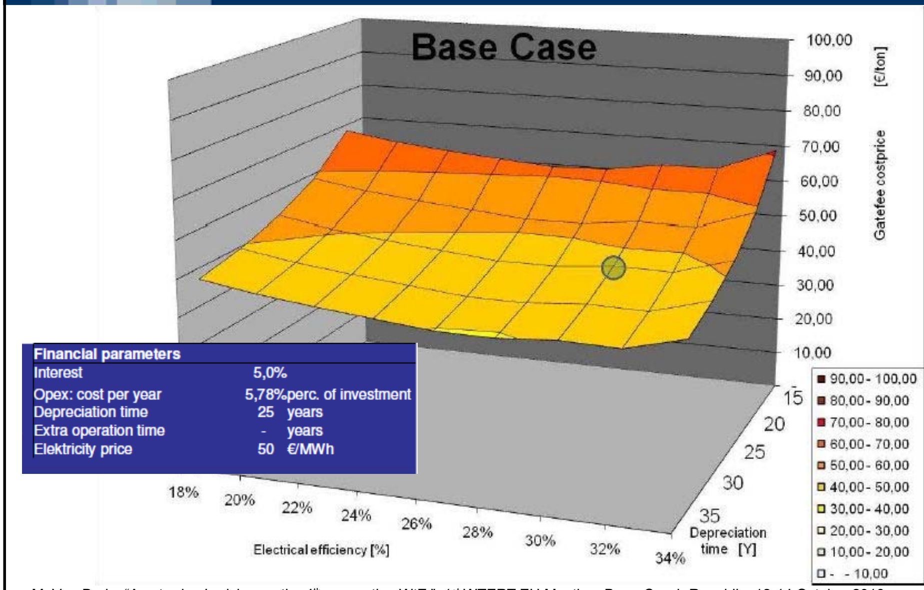
Economic incentive to the improvement of the energy performances of WtE plants



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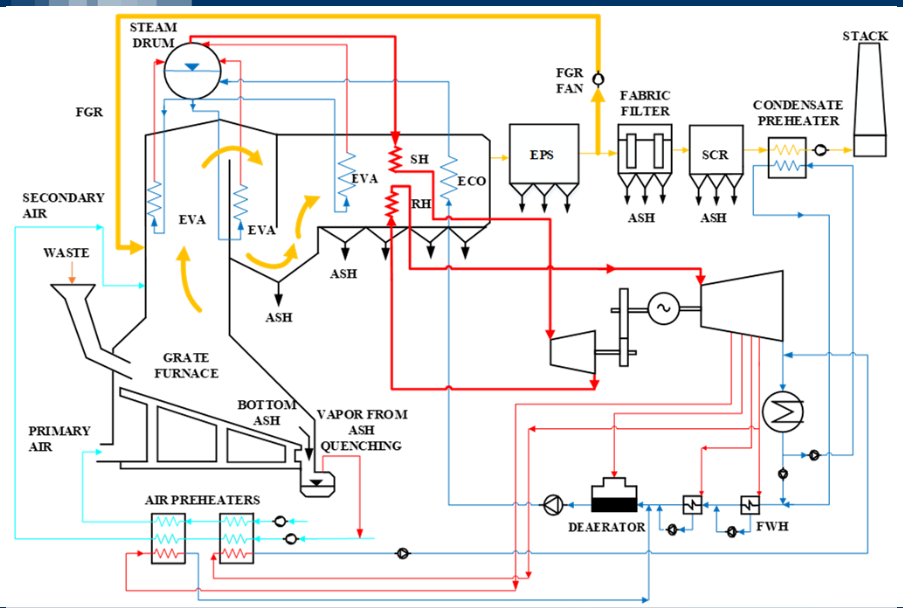
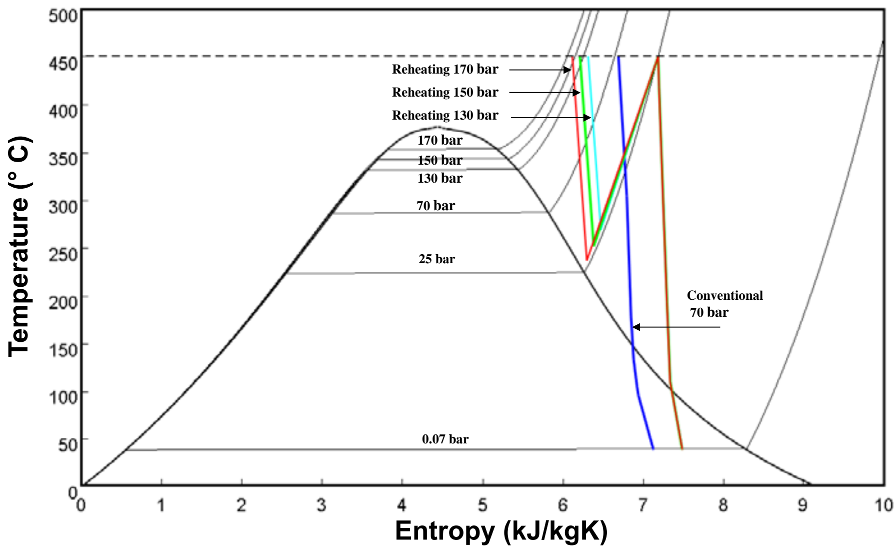
"Full" steam reheat

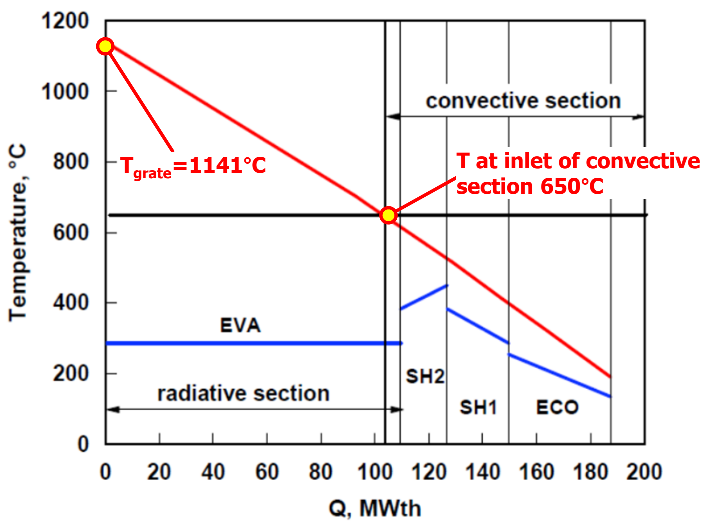


Thermodynamic cycle



Implications for boiler design

Conventional plant, Pev=70 bar, T_{SH}=450°C, FGR=15%



Implications for boiler design

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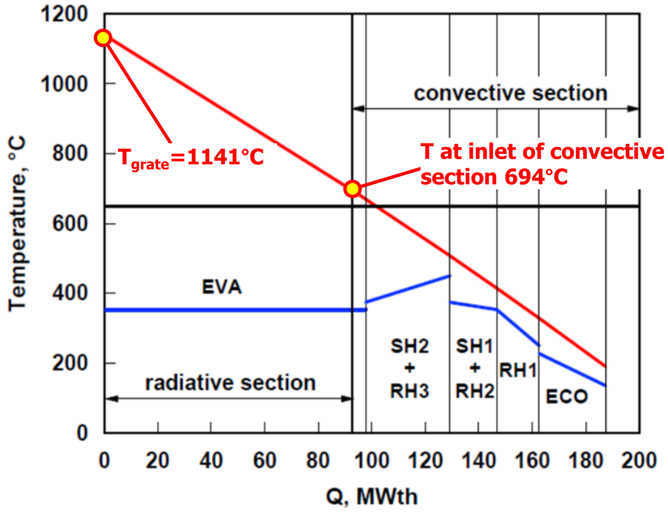
Plant with RH, Pev=170 bar, $T_{SH}=T_{RH}=450°C$, FGR=15%



Higher FGR as means to mitigate T_{gas}

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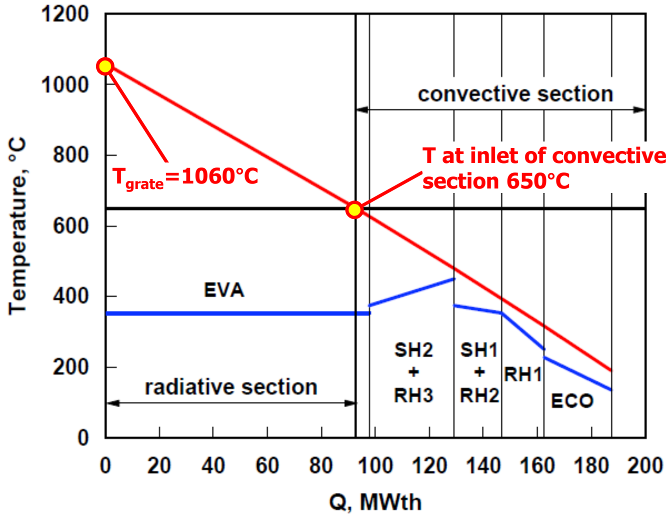
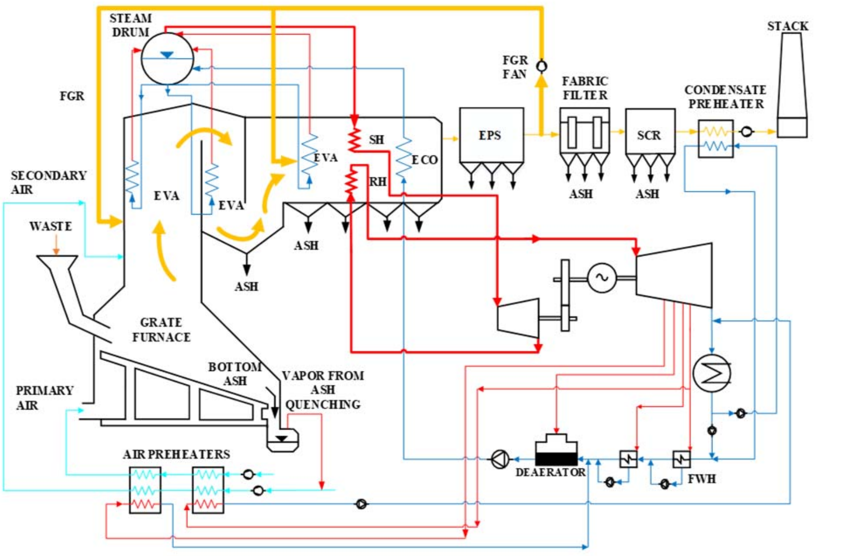
Plant with RH, Pev=170 bar, $T_{SH}=T_{RH}=450°C$, FGR=22.9%

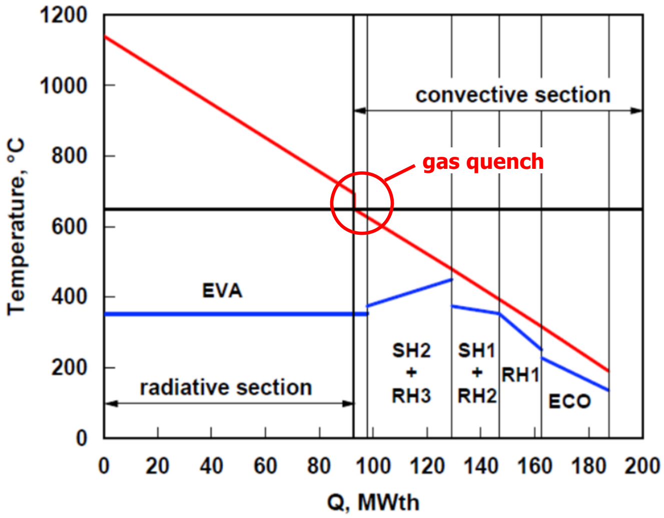


"Flue Gas Quench" (FGQ)



"Flue Gas Quench" (FGQ)

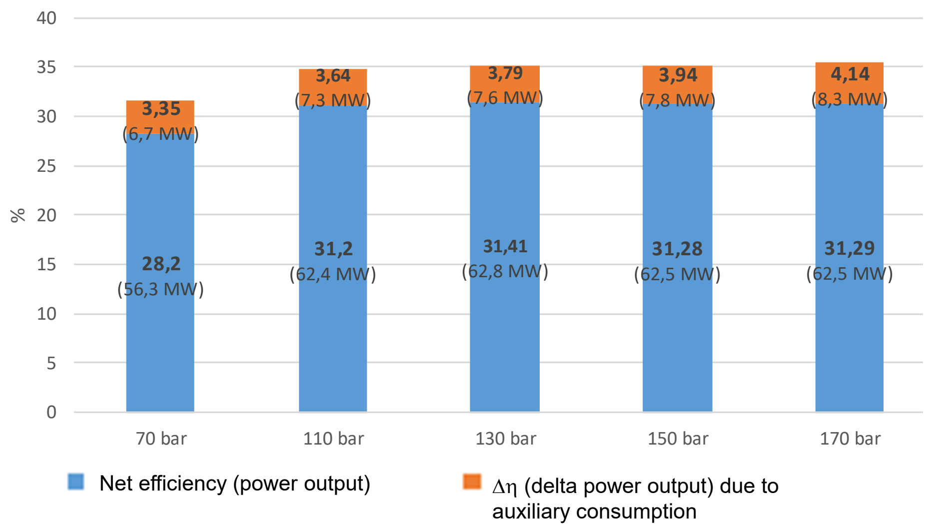
Plant with RH, Pev=170 bar, T_{SH}=T_{RH}=450°C



FGR = 15%(*) in comb. chamber
+
FGR = 7.9%(*) at outlet of radiative section

(*) referred to flow at outlet of economizer

Efficiency vs Pev



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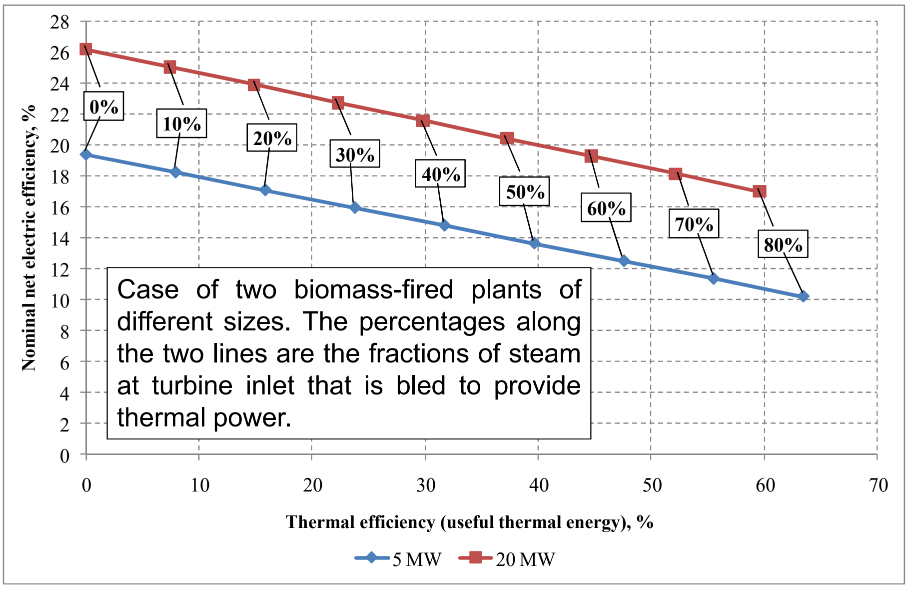
The Combined Heat and Power (CHP) generation as a way to increase efficiency



Energy recovery from waste according to the UE 2008-98 Directive

A waste incinerator is classified as an energy recovery facility in the case that the R1 coefficient results greater than 0.60 for plants build before 1/01/2009, and greater than 0.65 for plants build after 31/12/2008.

$$R1 = \frac{E_P - (E_F + E_I)}{0{,}97 \times (E_W - E_F)} \times CCF$$

E_P annual energy production both in the forms of electricity and heat;

E_F annual energy supplied by fuels different from waste, but that contribute to the production of energy;

E_W annual energy supplied by the waste on the basis of its LHV;

E_I annual energy import, except E_W and E_F;

0,97 correction coefficient that takes into account the heat losses due to the discharge of hot bottom ash and boiler radiation;

CCF Climate Correction Factor (now 1.00 – 1.25; 1.00 – 1.12 in the future).

All the energies are converted into primary energy by means of conversion coefficients: 1 for the energy content of waste and other fuels (LHV basis), 2.6 for electricity and 1.1 for heat (thermal energy).

R1 as a function of η_{el} and η_{th}

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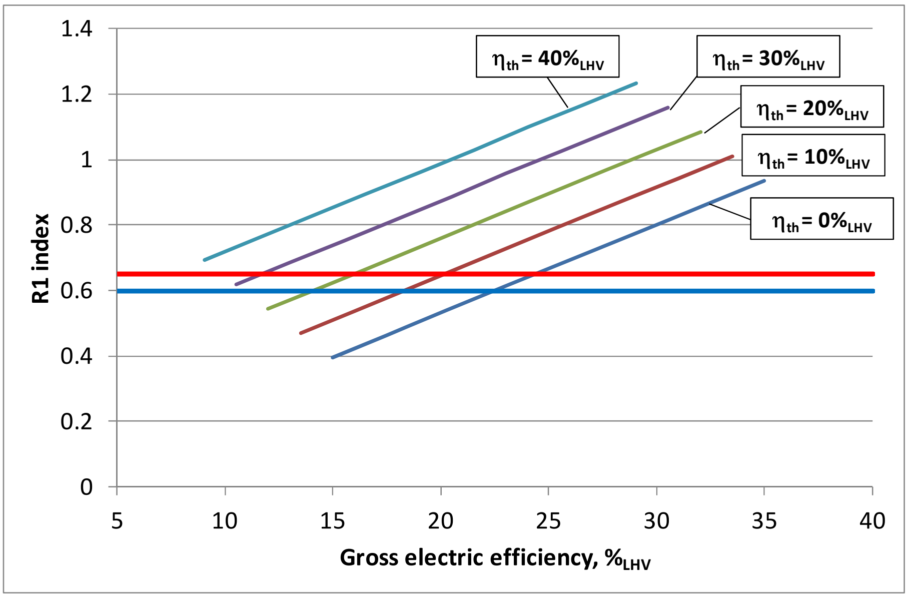

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Typical parameters of convention BtE plants

Plant size:	5 MW_E	20 MW_E
Evaporating pressure, bar	64.9	97.8
Superheating temperature, ° C	450	520
No. of turbine bleedings	2	2
Bleeding pressures, bar	3.73 / 0.56	3.73 / 0.49
Turbine rotational speed, rpm	9,000	6,000
Condensing pressure, bar	0.12	0.12
No. of parallel lines	2	2
O_2 concentration at boiler exit, $\%_{vw}$	4.5	4.0
Flue gas temperature at boiler exit, ° C	185	185
Flue gas recirculation, %	10.0	10.0
O_2 concentration at stack, $\%_{vw}$	5.5	5.0
Flue gas temperature at stack, ° C	135	135

Typical performances of convention BtE plants

	Only electricity 5 MW plant	CHP 5 MW plant	Only electricity 20 MW plant
Thermal input, MW_{LHV}	25.80	25.80	76.40
Biomass (straw), t/y	48,364	48,364	143,216
Nominal net electric efficiency, %	19.38	15.94	26.18
Net electric efficiency (yearly average), %	19.0	15.62	25.66
Actual electric power, MW_E	4.90	4.03	19.6
Thermal power, MW_T	-	6.14	-
Annual electricity production, MWh_E	38,220	31,433	152,880
Annual thermal production, MWh_T	-	47,892	-
Production of bottom ash, t/y	3,700	3,700	10,940
Production of fly ash, t/y	375	375	1,100
Production of flue gas treatment residues, t/y	475	475	1,400

Effect on performances of the cooling media (condensing pressure)

Keeping constant the electric size of the plant at 20 MW_E.

Cooling means:	Air	Evaporating towers	Water
Condensing pressure, bar	0.12	0.08	0.05
Nominal net electric efficiency, %	26.18	27.42	28.66
Thermal input, MW_{LHV}	76.40	72.94	69.77
Biomass consumption (straw), t/y	143,216	136,722	130,791
Condenser power, MW_T	46.00	43.05	40.46

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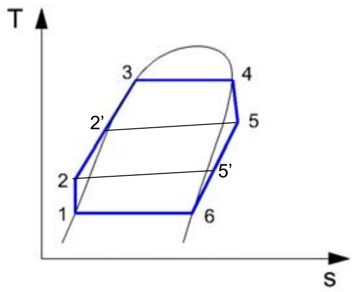
Why steam cycles are not adapt for small scale applications?

- For good performances, high pressures and temperatures (tens of bars, more than 200°C) are required also at small scale, making most of the cycle components expensive (the boiler, piping, steam turbine, etc.).
- Steam superheat is required to avoid too much liquid in the turbine exhaust → maximum temperatures still higher than those already high needed for evaporation.
- Since the great enthalpy drop across the turbine, multistage schemes, with significant numbers of stages, are required also for small turbines.
- Since the great specific energy content of water, only very small mass flowrates are needed in small scale applications. At high pressure, this correspond to very limited volumetric flowrates → very small turbine cross-section → very high rotational speed to reach the high peripheral velocity required → need for large gear boxes, which can introduce relevant losses and increase the plant cost.
- Because of the very high critical pressure of water, the expansion ratio across the turbine is huge, causing a great variation in the volumetric flowrate → too small at high pressure, too large at low pressure.
- In small applications, the turbine for a steam cycle remains a very complex and expensive machine, but with scarce performances.

Which other solutions for power generation from biomass at small scale?

- In recent years a quite novel technology has gain more and more shares in the market of small scale power generation (from few hundreds kilowatts up to few megawatts of electric power) and small scale Combined Heat and Power (CHP) generation.
- This technology overpasses several limits of the conventional steam cycle in small scale applications.
- It is still based on a Rankine cycle, but it uses working fluids different from water, which are characterized by higher molar masses and a much lower critical pressures than water.
- These fluids are typically organic fluids: hydrocarbons, flurocarbons, siliconic oils (siloxanes), etc. For this reason, the cycle that uses them is commonly called Organic Rankine Cycle (ORC).
- For still smaller applications (tens of kilowatts of electric power) other less widespread and proven technologies exist. An example is the technology of the Stirling’s engine.

The Organic Rankine Cycle (ORC)



1-2 compression
2-2' regeneration
2-3 preheating
3-4 evaporation
4-5 expansion
5-5' regeneration
5-6 de-superheating
6-1 condensation

The characteristics of the working fluid make possible to implement a low temperature (and low pressure), small scale, efficient and quite cheap cycle, in fact:

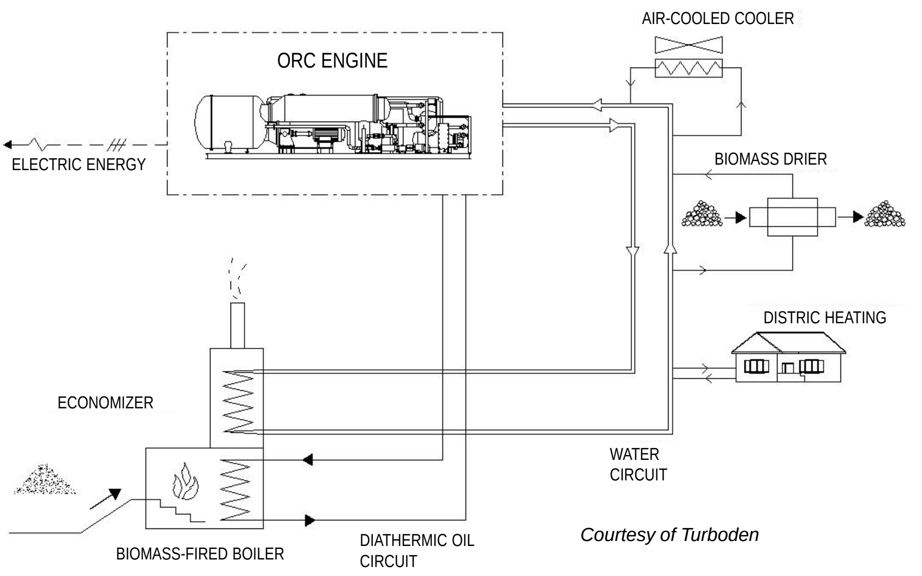
- Low specific energy content of these fluids allow producing significant mass and volumetric flowrates also in small applications. Thus the size of the turbine can be large enough to adopt low rotational speeds and a direct connection to the electric generator without gear box.
- Turbines can be designed with few stages and result quite cheap.

Comparison between a small CHP steam cycle and a CHP-ORC

Common assumptions: Evaporation/Condensing temperature: 260 °C / 100°C (CHP for district heating)
Electric turbine power: 1000 kW
Turbine efficiency: 1.0 (i.e. ideal)
Compression work neglected

	Steam cycle	**ORC**
Evaporation pressure, bar	30 (233°C)	< 10
Condensing pressure, bar	~ 1	~ 0.2
Superheating:	yes, up to 260°C	Not required
T at turbine inlet, °C	260	260
T at turbine discharge, °C	~ 100	~ 220
Regeneration:	No	Required
Isentropic enthalpy drop, kJ/kg	~ 590	~ 60
Vapor quality at turbine discharge	0.83	superheated
Isentropic fluid flowrate, kg/s	~ 1,7	~ 15
Volumetric flowrate at turbine inlet, m^3/s	~ 0.12	~ 0.2
Volumetric flowrate at turbine discharge, m^3/s	~ 2.4	~ 14.0

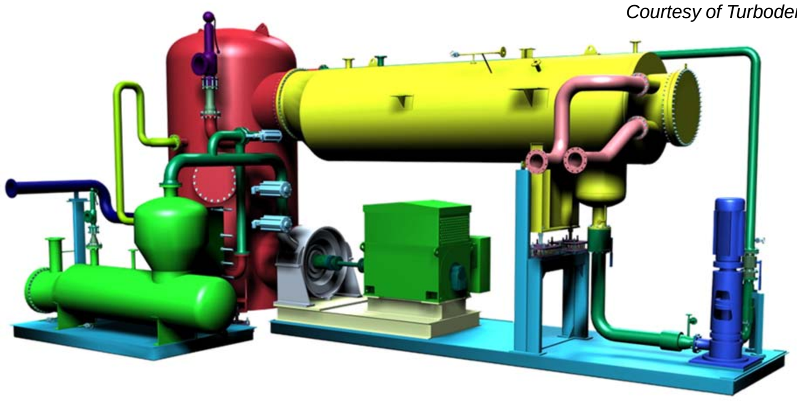
Layout of a CHP ORC-based, biomass-fired system



Courtesy of Turboden

Layout of 1100 kW electric ORC engine

Courtesy of Turboden



- To minimize the amount of working fluid and limit the risk of leakages, turbine, pump, steam generator and condenser are all assembled on a skid.
- The steam generator is connected to the boiler by means of a diathermic oil circuit, thus the boiler is at low (atmospheric) pressure.

Layout of 660 kW electric ORC engine

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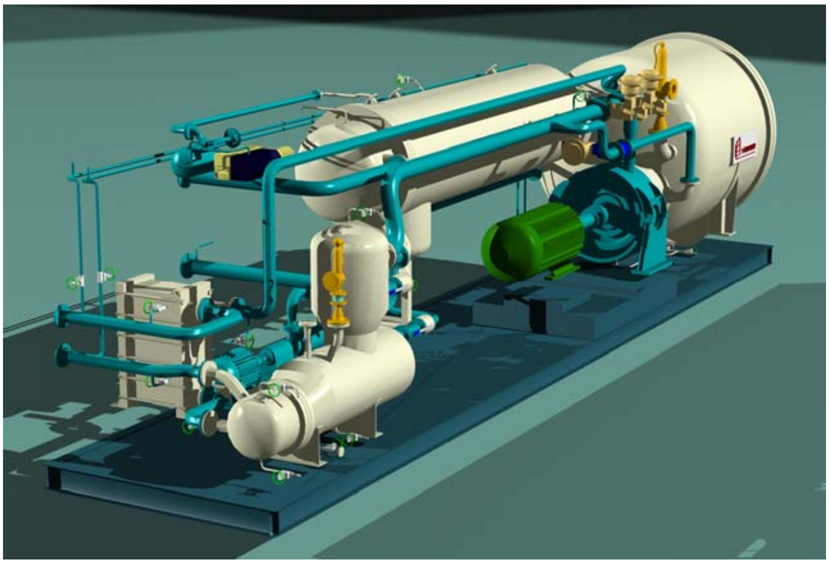

Delivery of a ORC unit

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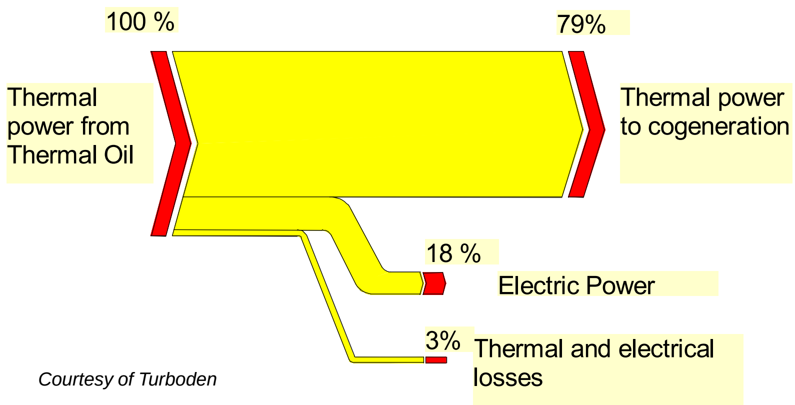
Courtesy of Turboden

Typical energy balance of an ORC unit



Thermal power from Thermal oil is typically 90% (boiler efficiency) of the combustion power.

ORC vs. conventional steam cycles

- Typically, conventional steam cycles presents too high specific costs at sizes smaller than about 5 MW_E.
- At so small scale, CHP is a requirement to make economic the application of any power cycle.
- ORC in CHP layout, under certain conditions (availability of low cost biomass) can be valid solutions in the size range of 0.5-5 MW nominal electric power.

ORC vs. conventional steam cycles

	Conventional steam cycle	ORC
Annual equivalent working hours, h/y	7,500	7,500
Only electricity production layout		
Net overall power, kW	5,000	645
Net electric efficiency, %	20	15
Maximum thermal energy production layout		
Net overall power, kW	3,000	559
Net electric efficiency, %	12	13
Maximum thermal power, MW	10	2.36
Thermal efficiency, %	40	55
Overall efficiency (I TDN law), %	52	68
Annual production		
Electricity, MWh/y	33,500	4,662
Thermal energy, MWh/y	20,000	4,727

Lecture outline

- *Basics of thermodynamic cycles*
- *Steam cycles in large BtE and WtE plants*
- *The pursuit of high efficiency in WtE plants*
- *CHP production as a way to increase efficiency*
- *Medium-large scale BtE plants*
- *Small scale BtE plants, the ORC technology*
- *Very small steam turbine-based cycles*

Very small steam cycles

- They are based on small and very simple steam turbine, featuring not more than 1-3 stages.
- The turbine is quite cheap and low efficient.
- The investment in this technology can be profitable when a fundamental condition holds:
  - there already exists a need for pressurized steam (e.g. for industrial processes), hence the steam turbine can be introduced with minor modification in a steam plant that in any case should be built;
  - this is a situation often encountered in in biomass processing factories (e.g. production of intermediate biomass goods).

Very small steam cycles

Siemens SST-040 series	
Power output	75 - 300 kW(e)
Inlet pressure	2 up to 40 bar (a)
Inlet temperature	dry saturated steam up to 400 °C
Exhaust pressure	max. 7 bar (a) up to 0,1 bar (a) condensation

Very small steam cycles

Dresser-Rand

Model	Max HP (kW)	Max Inlet Pressure psig (bar)	Max Inlet Temperature °F (°C)	Max Exhaust Pressure psig (bar)
RLA	1000 (746)	700 (46)	825 (440)	165 (11)
RLVA	1000 (746)	700 (48)	825 (440)	165 (11)
RLHA	up to 2500 (1865)	up to 900 (62)	up to 950 510)	up to 300 (20)
SST	3500 (2600)	700 (48)	825 (440)	up to 150 (11)
C	up to 3353 (2500)	up to 1581 (109)	up to 950 (510)	304 (21)
Z	900 (670)	785 (54)	825 (440)	175 (12)
GSA	3350 (2500)	900 (62)	860 (460)	250 (17)
GTW	up to 4030 (3000)	up to 1500 (103)	1050 (565)	up to 450 (31)
AVT	up to 4025 (3000)	up to 950 (65)	up to 1050 (565)	up to 500 (34)
2TA	4695 (3500)	1815 (125)	1000 (540)	450 (31)