



POLITECNICO DI MILANO



WastEEng 2014

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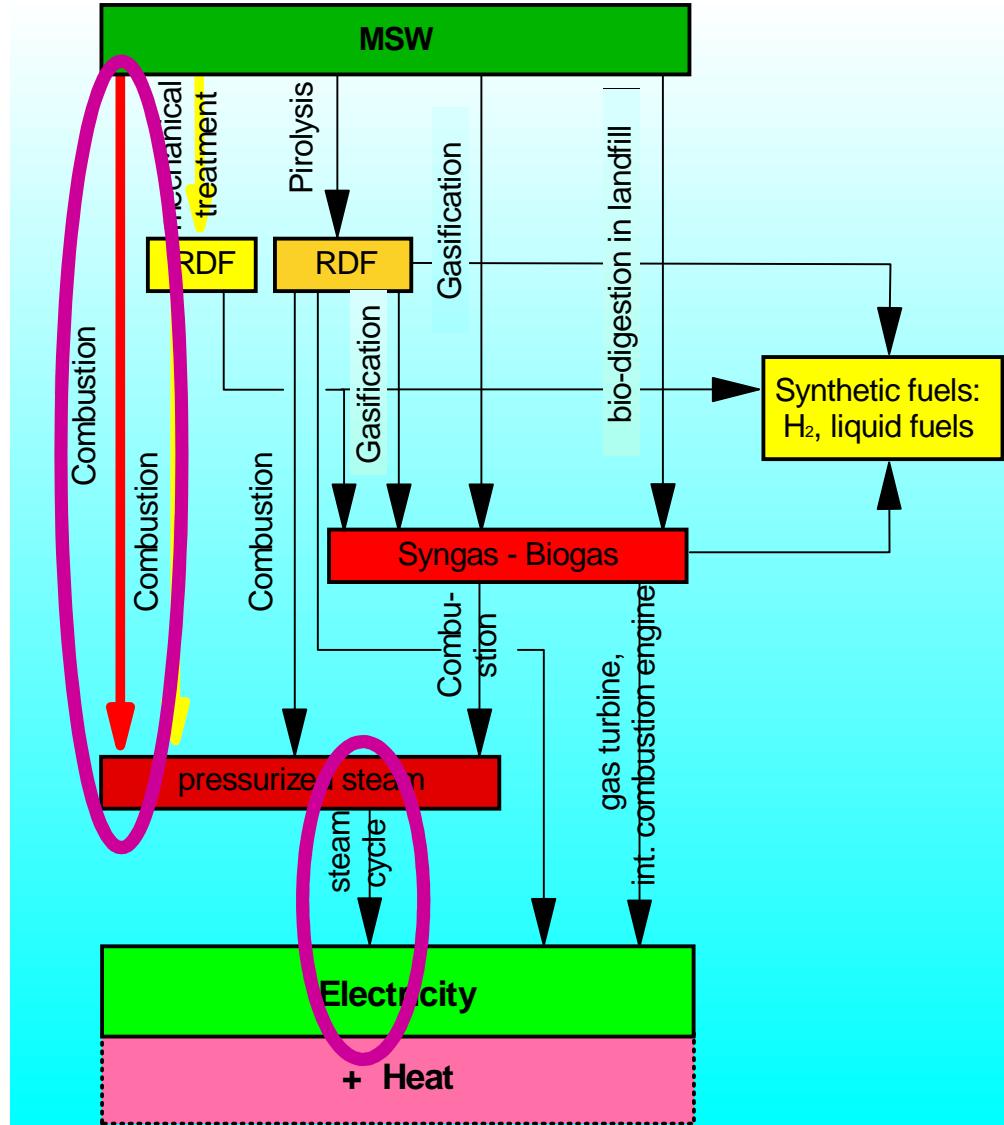
Ultimate energy performances of grate combustor WtE plants

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The paths of energy recovery from waste²

Focus of this presentation:
grate combustors
with
production of electricity only



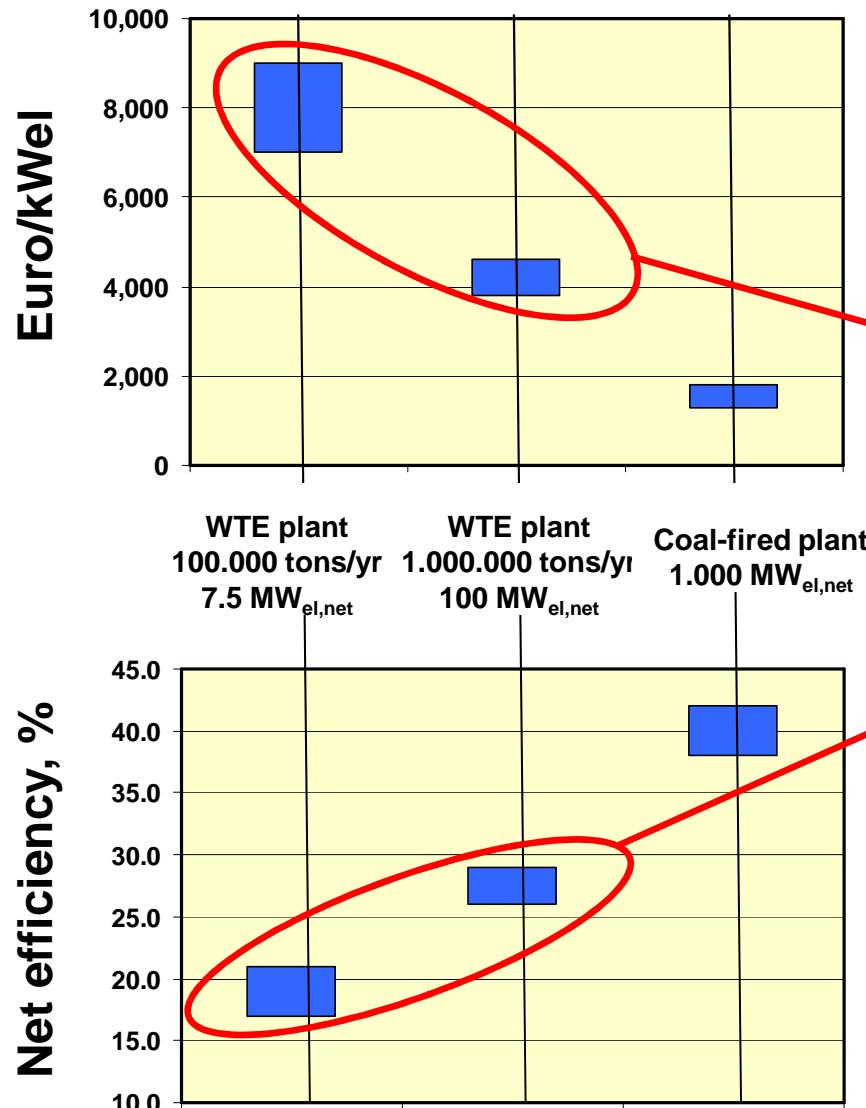


Basic issues of Energy from Waste: a reminder

- Unfavourable physical properties (solid chunks) --> **grate, long residence times, large combustion chamber**
- Unfavourable composition:
 - high moisture content --> **low boiler efficiency**
 - high ash content --> **high aux power consumption, erosion, large boiler**
 - corrosive species --> **limit steam conditions**
 - pollutants --> **heavy flue gas treatment**
- Heating value much lower than for fossil fuels --> **for given power, large flow rates --> high aux power consumption, high costs**
- Small scale --> **low efficiency, high costs**



The price to pay for low quality waste fuel



Capital cost

As a consequence of extremely high capital costs and low efficiency, energy production from waste is economically acceptable only for negative fuel prices (gate fee)

Net electric efficiency



Although the competition with fossil fuel-fired power plants is extremely challenging (and somewhat unfair), viewing WTE plants as power stations rather than a disposal technology is the only way WTE can be accepted by legislators and the public opinion



Waste = Resource



Directions for improvement

1) Decrease costs

- simpler configuration
- use less material
- ease/decrease maintenance
- etc.

2) Increase efficiency

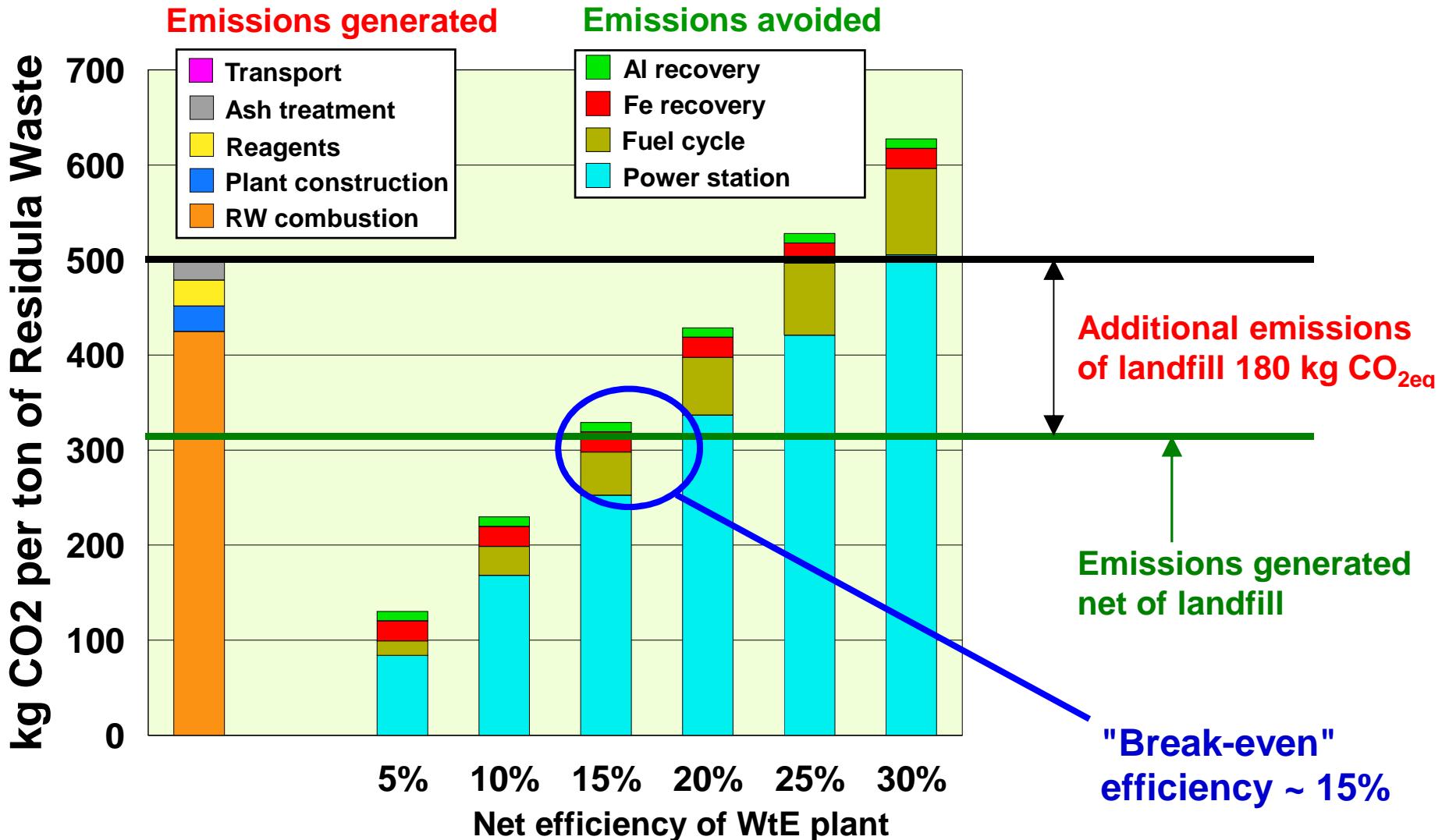
- improve thermodynamic cycle
- adopt different combustion technology (fluidized bed ?)
- adopt technologies other than combustion (gasification ?)

3) Generate additional outputs

- cogeneration of heat & power
- recover materials from bottom ashes
- etc.



Why efficiency is so important ?

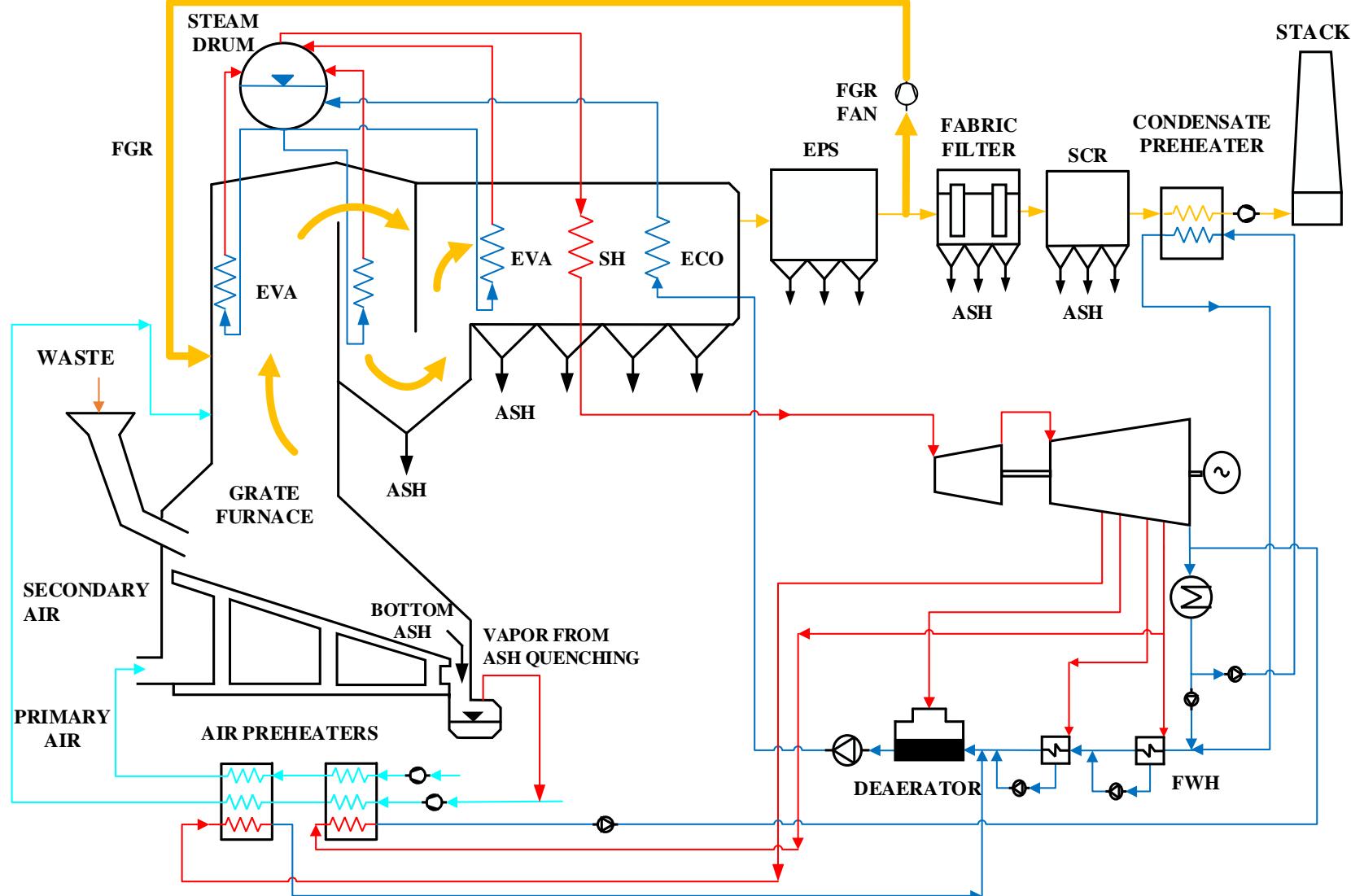


Performances achievable by state-of-the-art grate combustors



Modern, advanced combustion plant

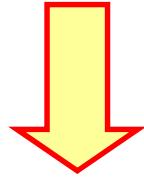
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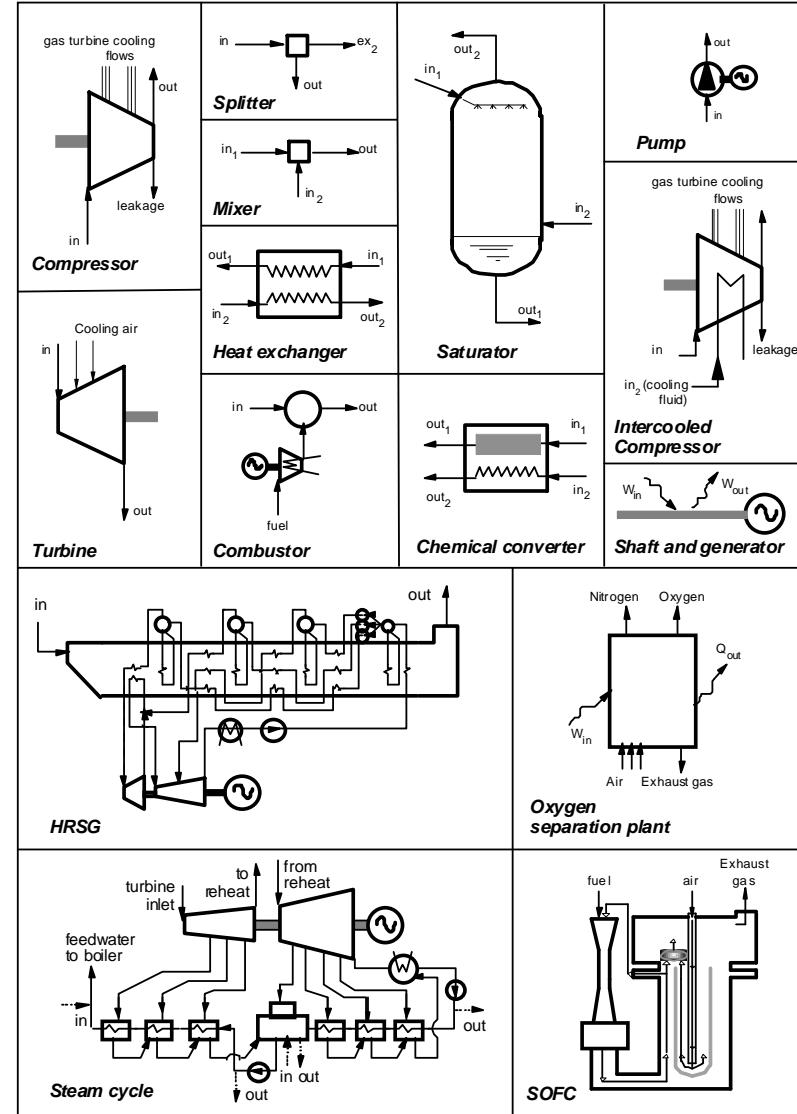


Methodology of performance predictions¹⁰

- GS modular code developed at PoliMI / Princeton
- Thermoflex / SteamPro
- Aspen Plus



- estimation of operating parameters (P, T, mass flows) and performances of each component
- evaluation of mass / energy balances
- overall performances
- costs





Typical operating parameters

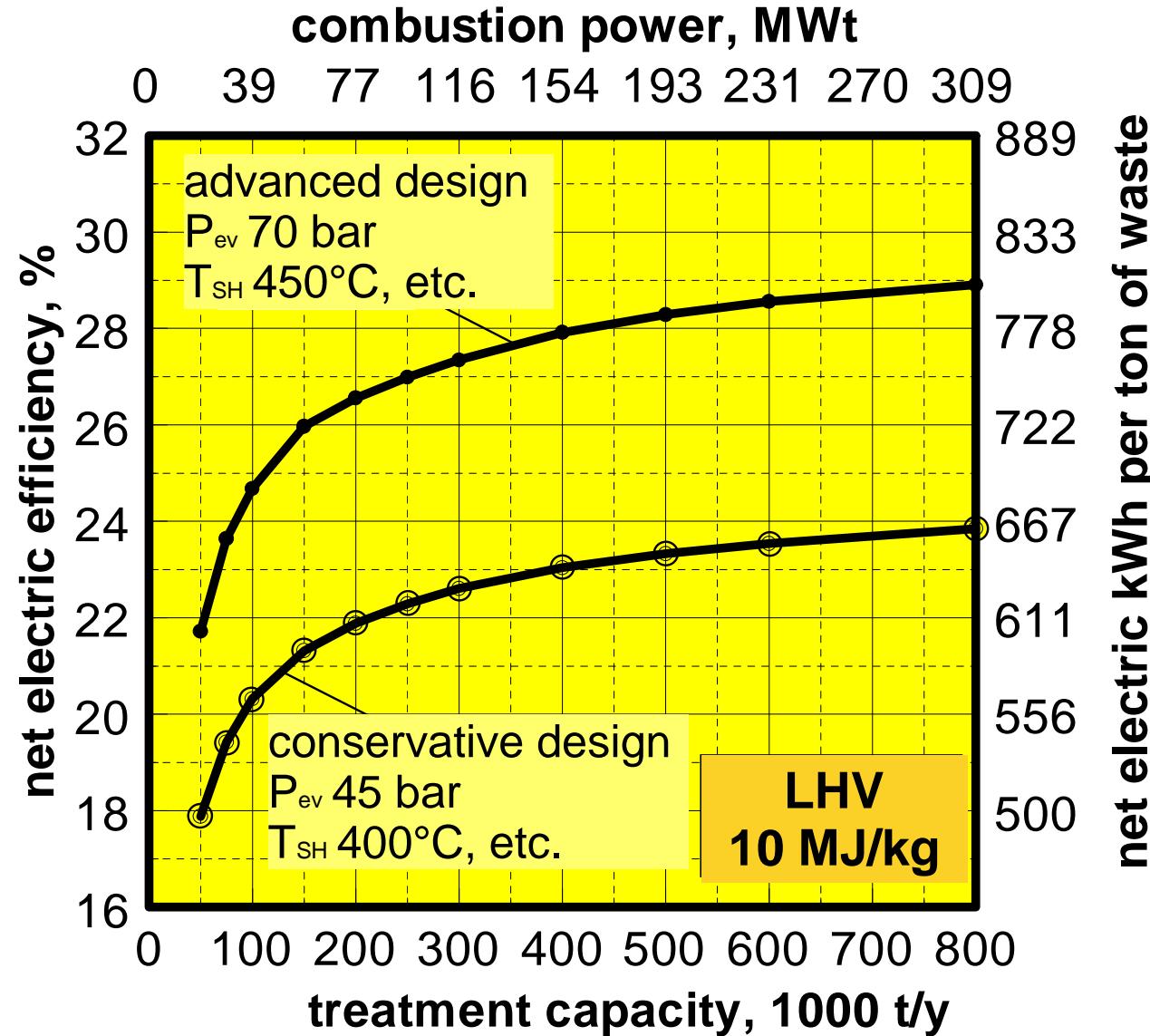
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design parameter	unit	plant size	
		small (conservative design)	large (advanced design)
evaporation pressure	bar	45	70
extraction for air pre-heating		3.0	1.0/6.5
deaerator pressure		2-3	
condensation pressure		0.10	0.06
gas temperature at SH inlet	°C	max 650	
steam temperature at SH outlet		400	450
gas temperature at end of heat recovery		160	135
temperature of primary air		120	150
temperature of secondary air		120	150
steam bleeds for air heaters	% mass	1	2
LP feedwater heaters ahead of deaerator		1	2
MP feedwater heaters		none	
flue gas recirculated	% vol	15.0	
oxygen at boiler outlet		6.0	5.0
loss due to unburnt carbon		0.8	



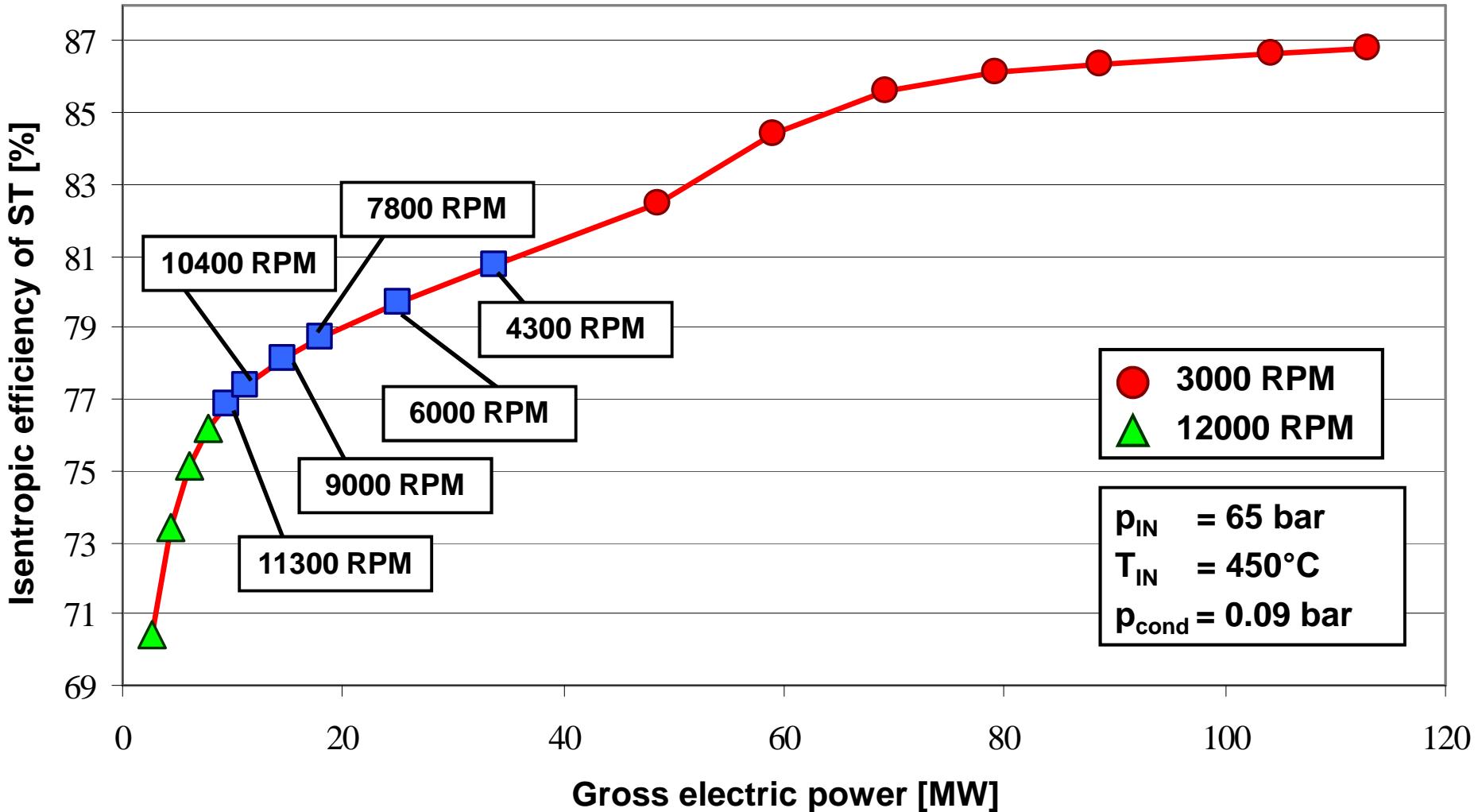
Effect of steam parameters and scale

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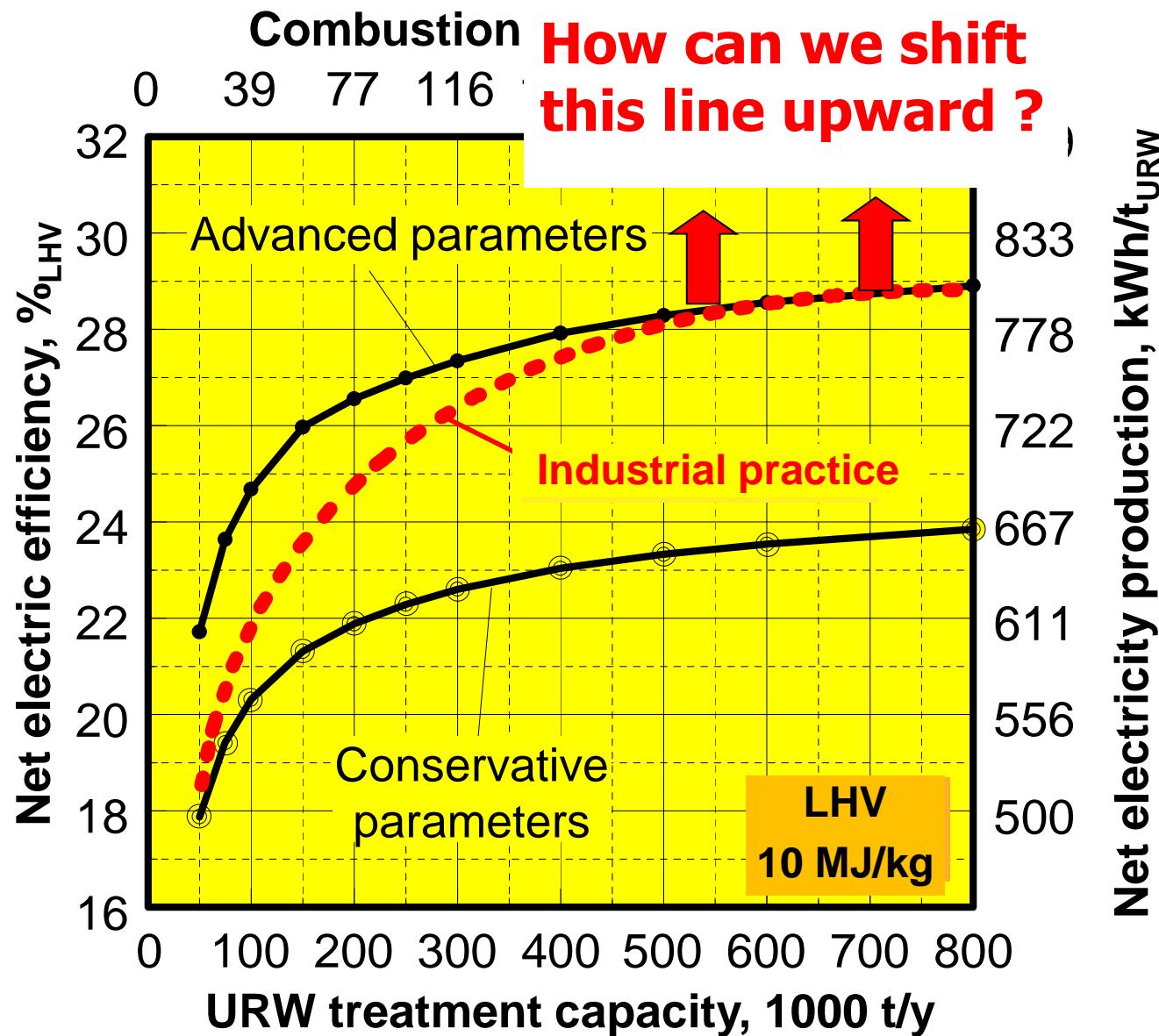
Isentropic efficiency of steam turbines





Industrial practice vs scale

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Possible routes to increase efficiency

- 1) Increase scale --> larger plants
- 2) Use auxiliary, high-quality fuels in complex, integrated configurations --> see presentation by dr. S. Guerreiro + related refs
- 3) Improve steam cycle:
 - better cycle parameters --> higher P_{ev} , T_{SH} , lower P_{cond}
 - more sophisticated configuration --> reheat

and given that:

- 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



Increase T_{SH} ?





The challenge of higher T_{SH}

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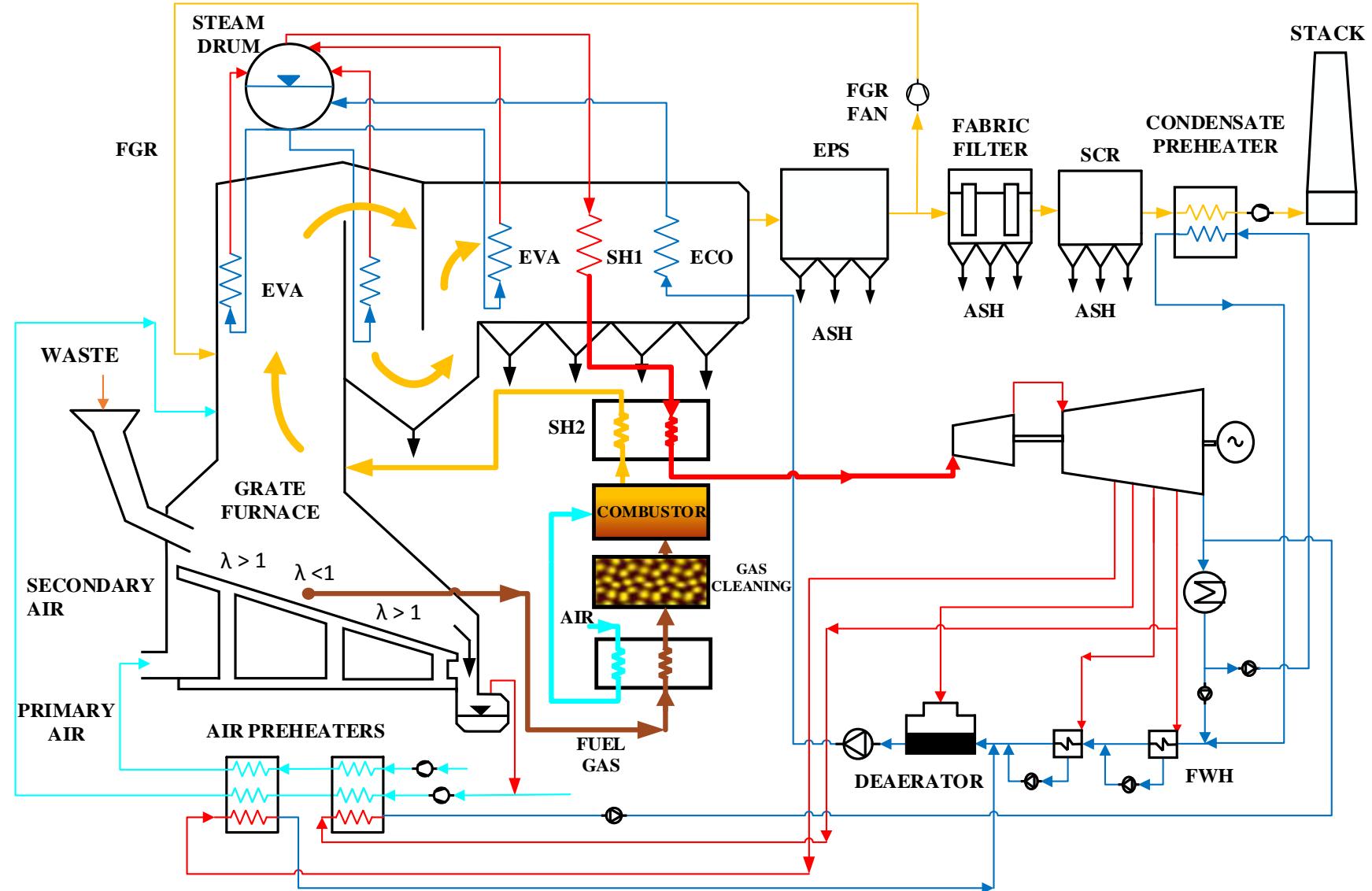


**Superheater tubes of
plant in Acerra (Italy)
 $T_{SH} = 500^{\circ}\text{C}$**



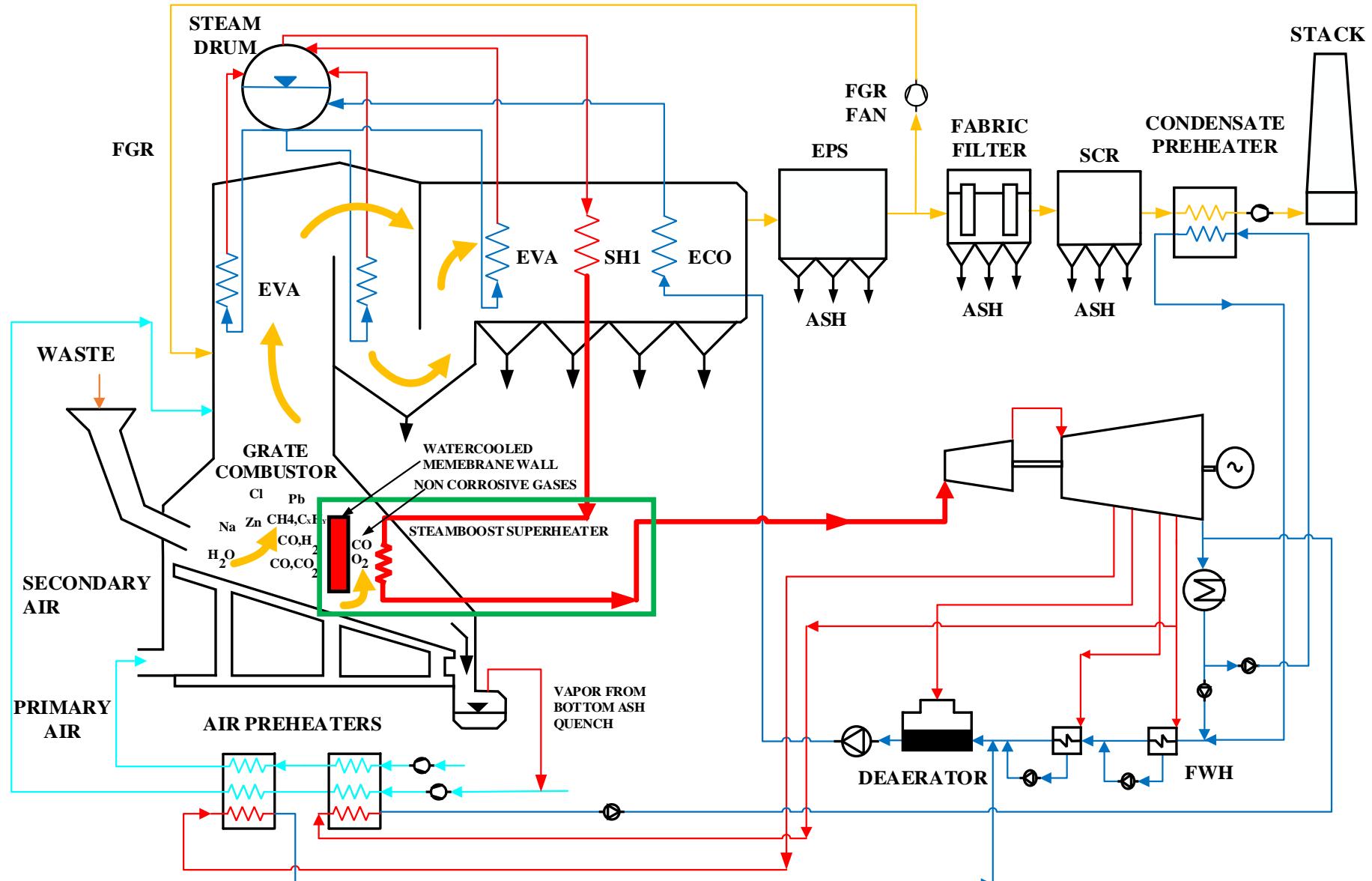
"Bypass" concept (Hans, 2010)

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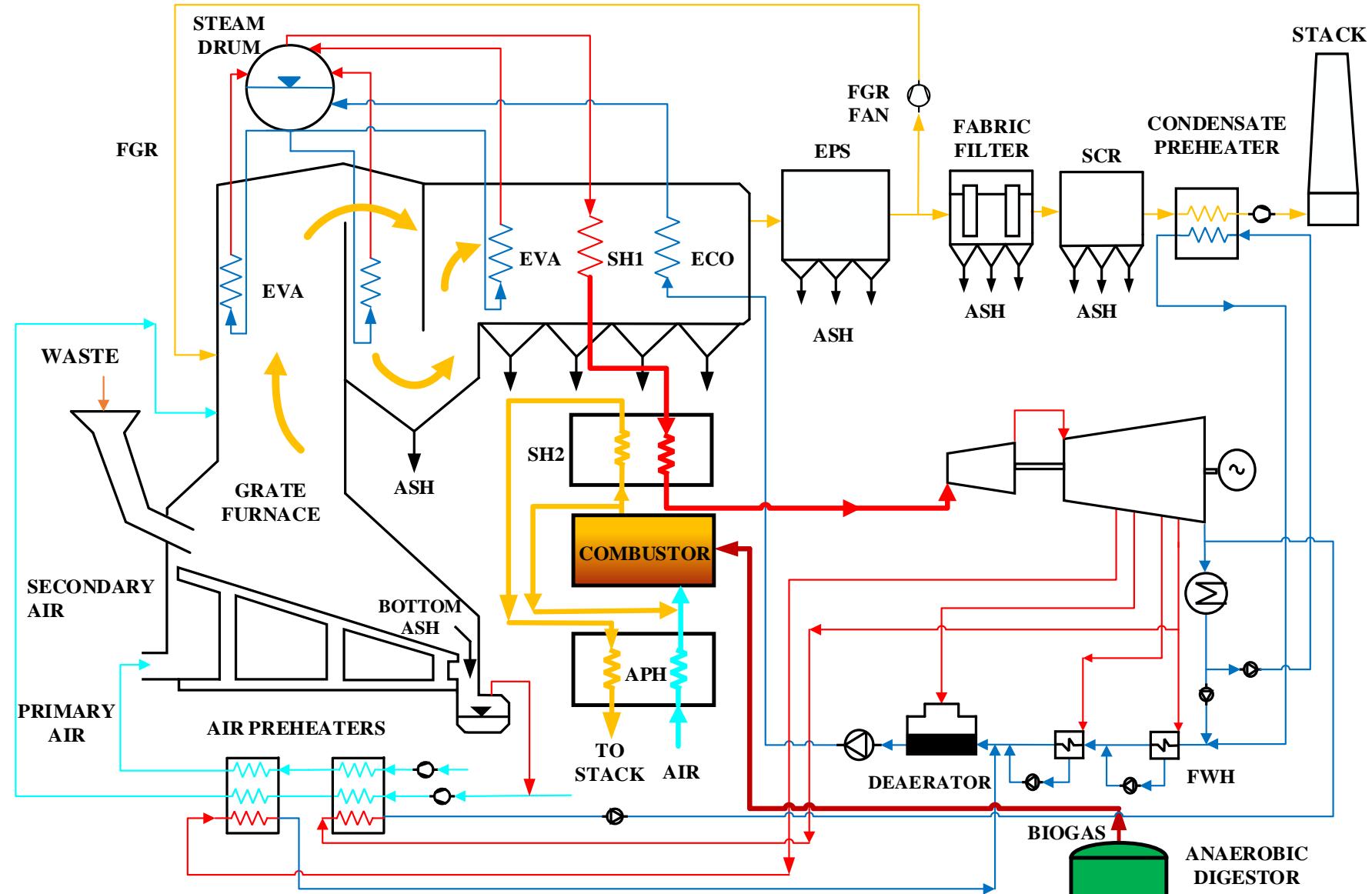
"Steam Boost" concept (Madsen, 2007)¹⁹





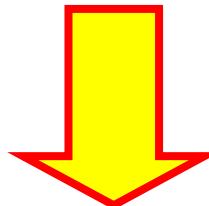
External superheating with Biogas

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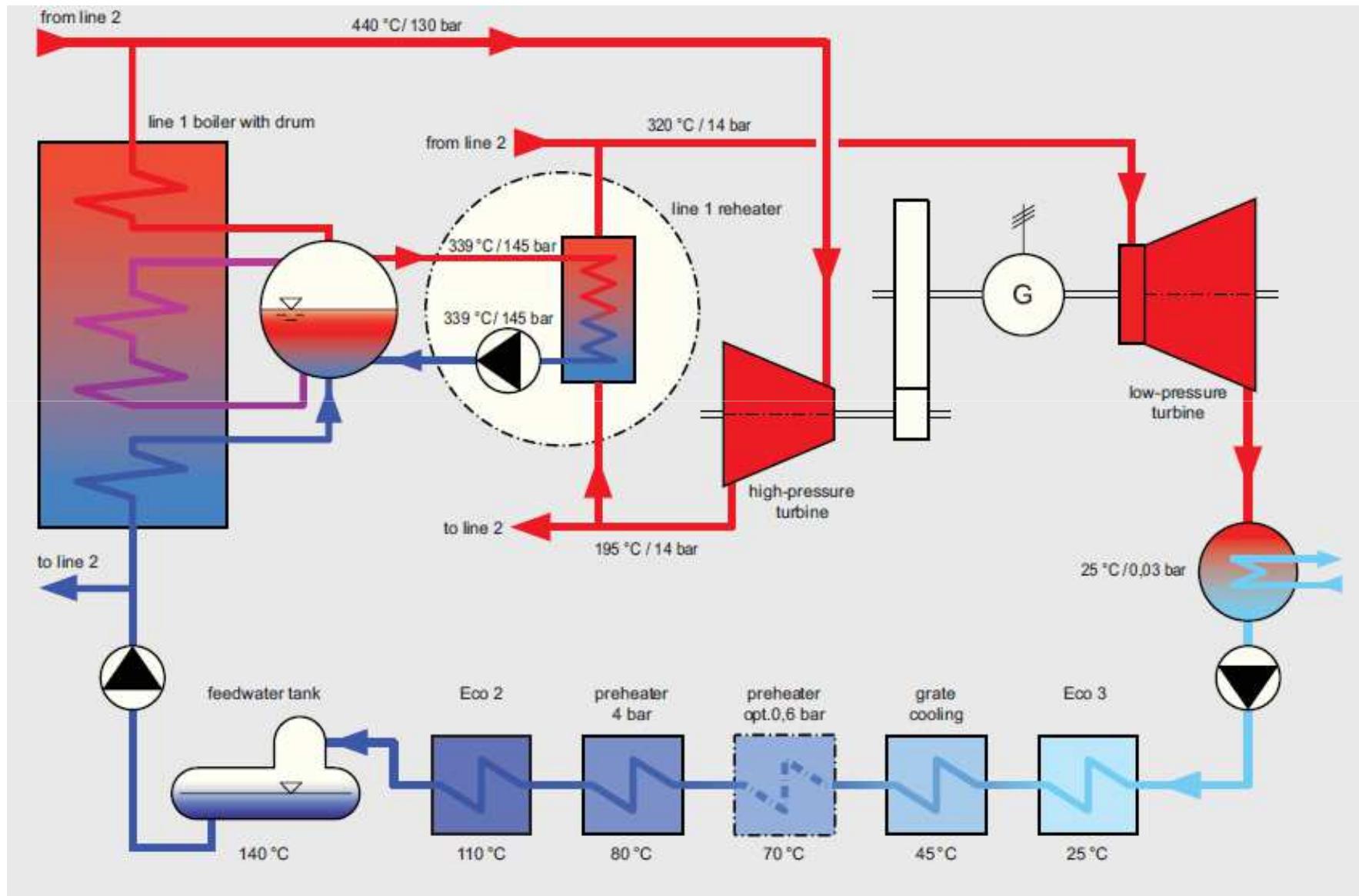
Given the challenge of high T_{SH} , improving efficiency by adopting more sophisticated configurations - rather than by increasing T_{SH} - seems attractive



steam Reheat (RH)

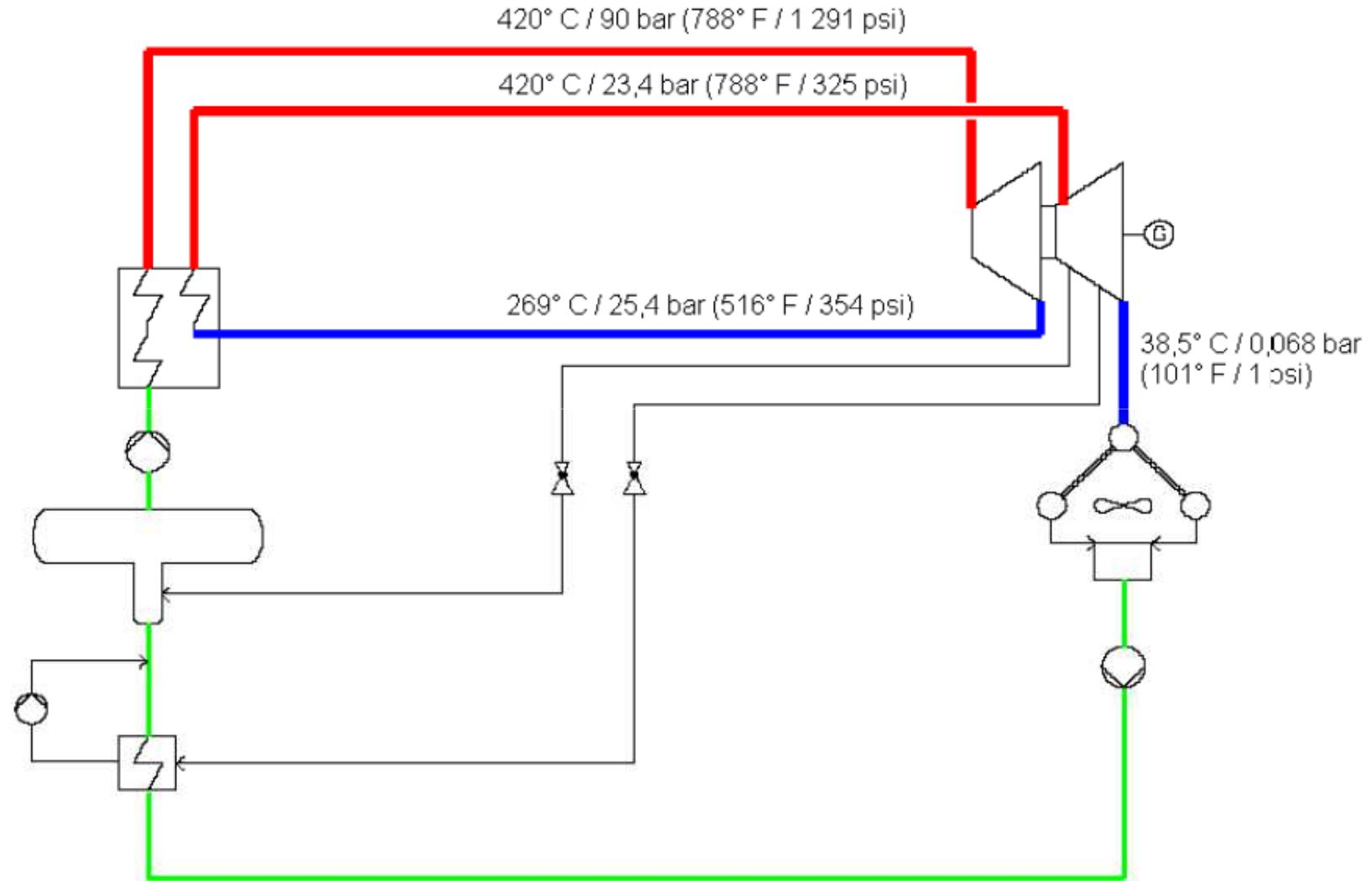


Reheat via high-pressure liquid (Amsterdam)²⁰

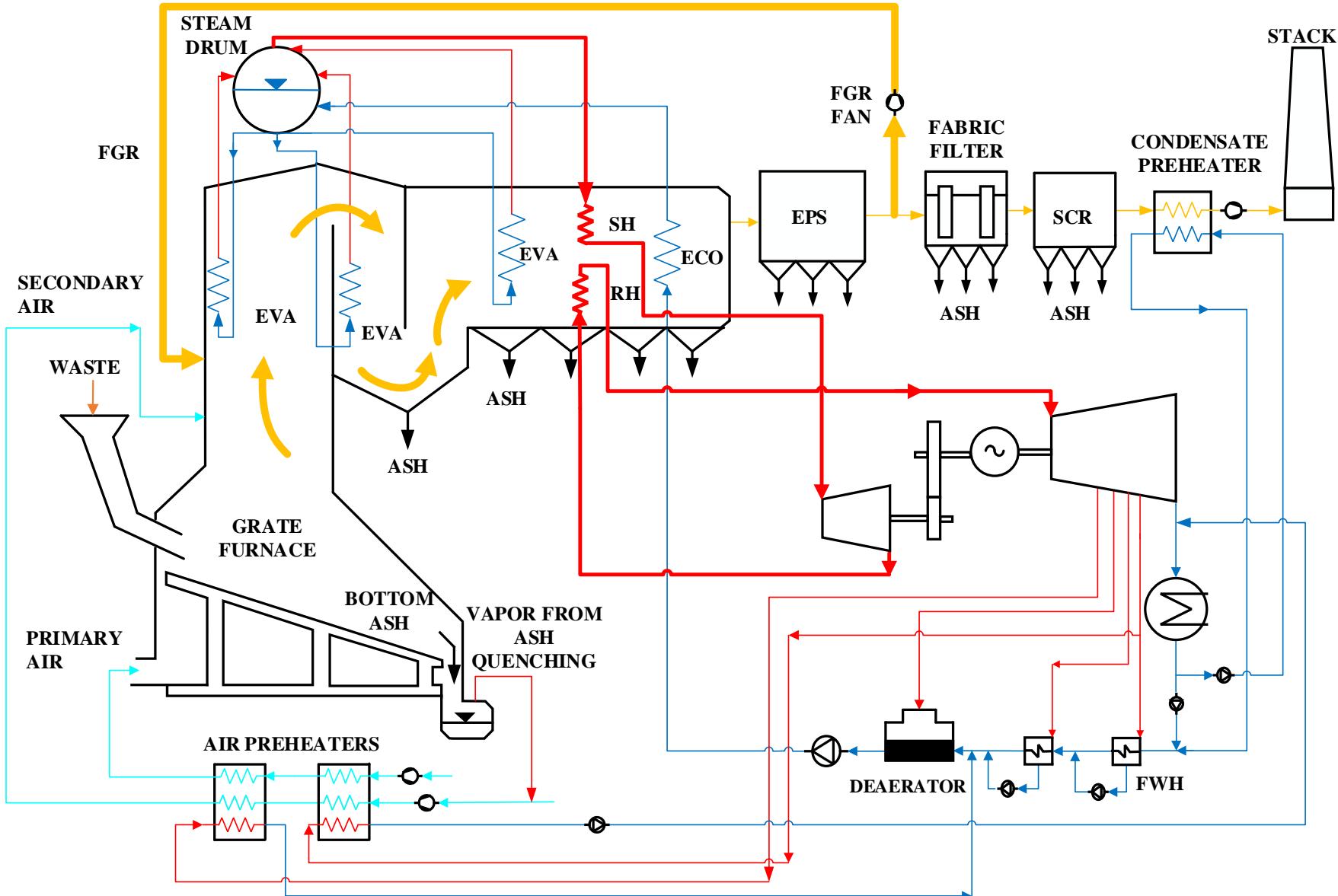




Fisia-Babcock plant in Ruedersdorf (Berlin)²³



"Full" steam reheat





Assumptions

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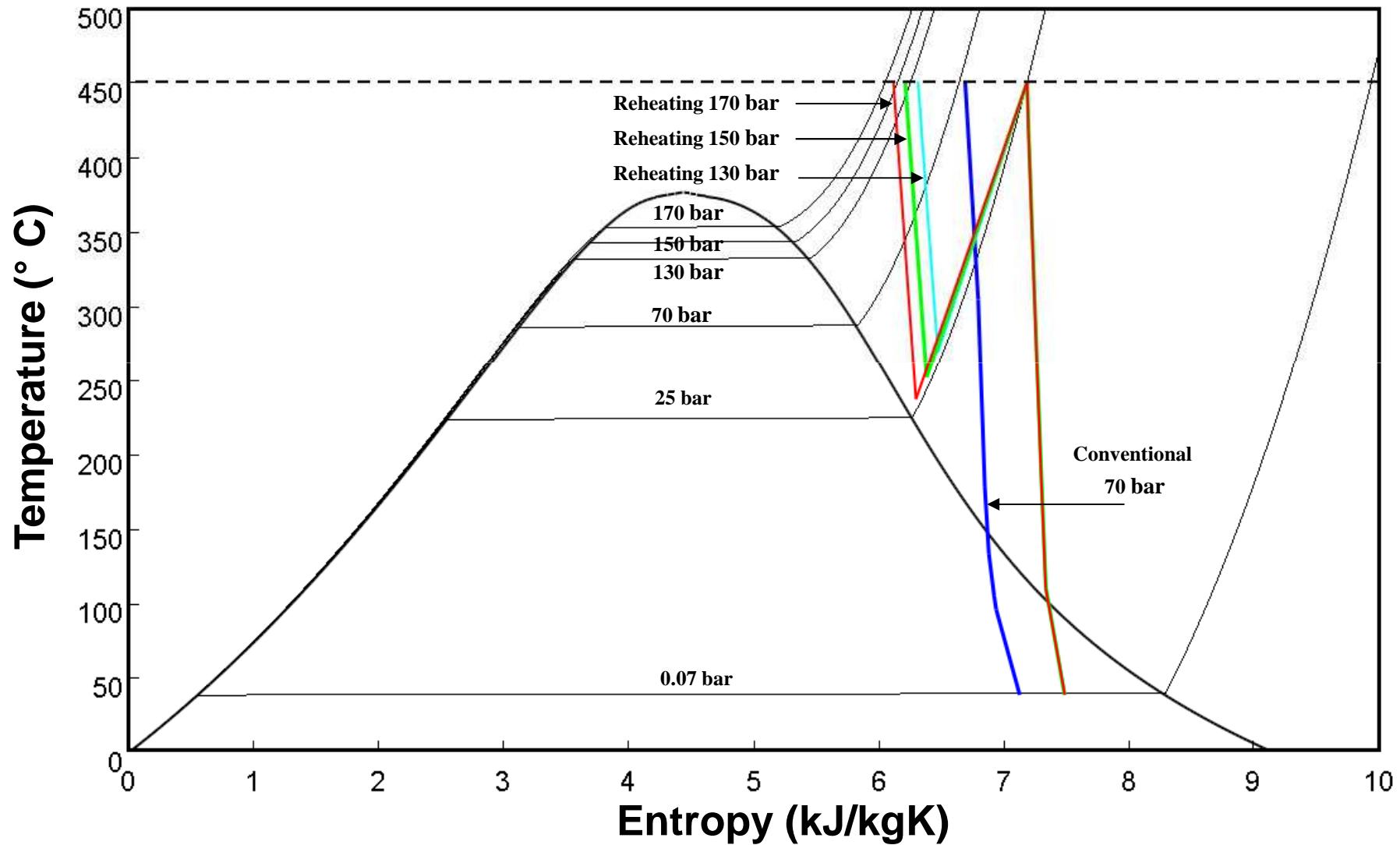
design parameter	unit	plant configuration			
		CONV	RH130	RH150	RH170
LHV of waste fuel	MJ/kg		10,34		
combustion power	MW		200		
evaporation pressure		70	130	150	170
reheat pressure		-	25	25	25
extraction for air pre-heating	bar			0.88/6.30	
deaerator pressure				3.0	
condensation pressure				0.07	
gas temperature at SH inlet				max 650	
steam temperature at SH outlet				450	
steam temperature at RH outlet	°C	-	450	450	450
gas temperature at eco outlet				190	
gas temperature at end of heat recovery				135	
temperature of prim/sec air				150	
steam bleeds for air heaters				2	
LP feedwater heaters ahead of deaerator				2	
blowdown				1.0	
water ΔP/P in economizer	%			15.0	
steam ΔP/P in SH / RH				8.0	
flue gas recirculated (*)	% mass	15.0	26.9	31.2	35.8
oxygen at boiler outlet	% vol			6.0	
oxygen at stack	% vol			7.0	
unburnt carbon in bottom ash	% mass			2.0	
thermal losses in boiler / heat exchangers	%			1.0	

(*) as fraction of flue gas flow at economizer outlet



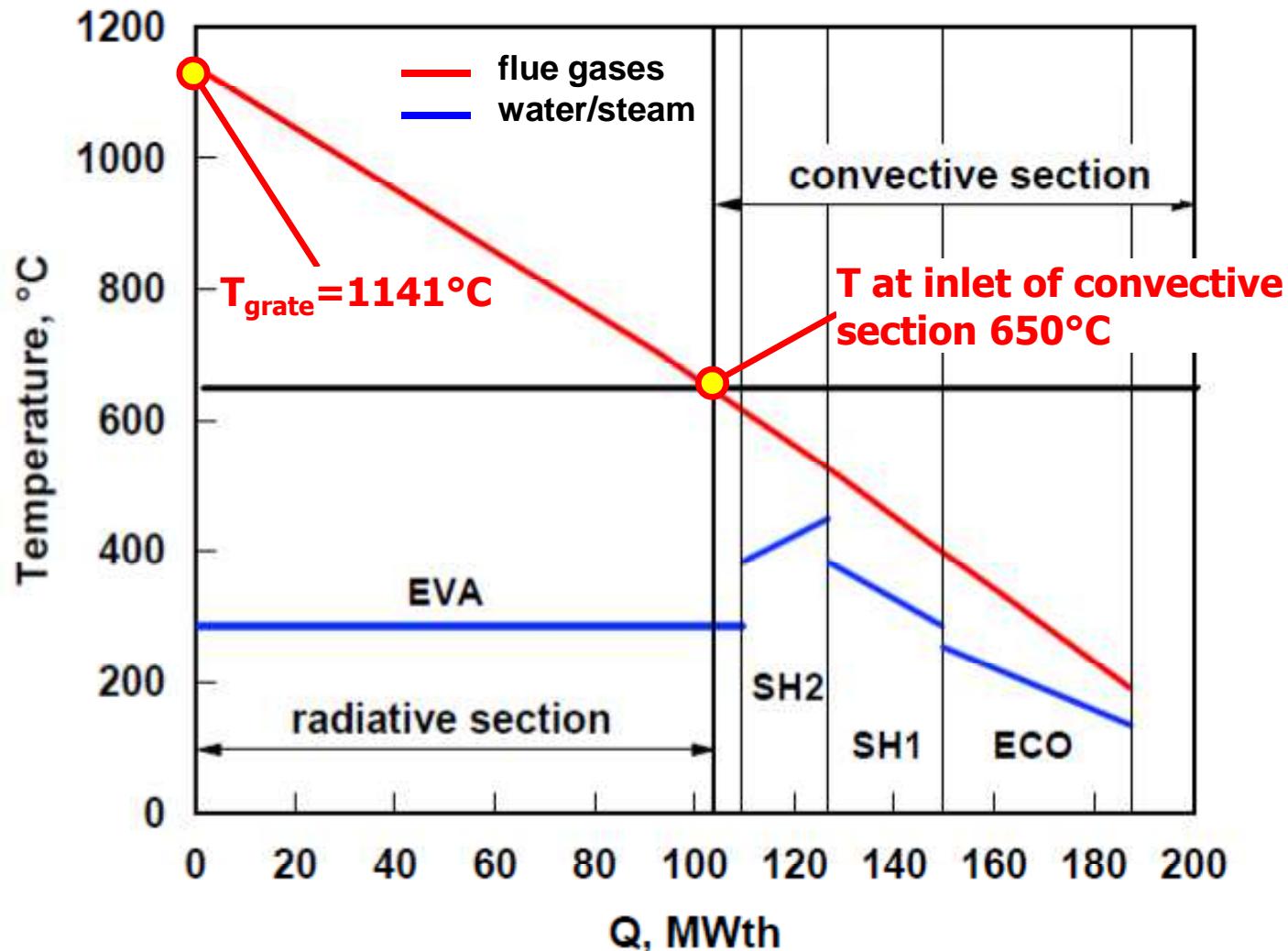
Thermodynamic cycle

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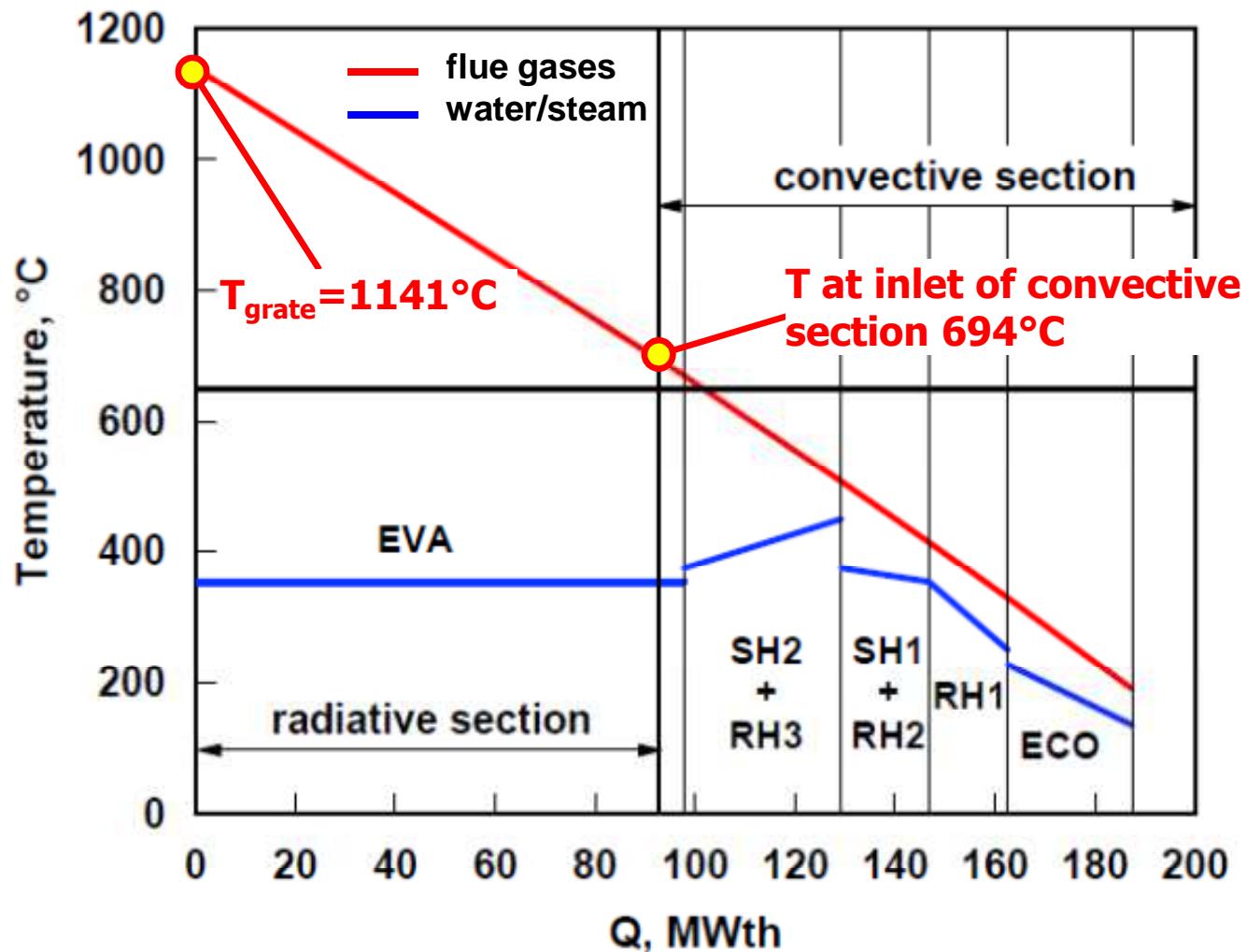
Conventional plant, $P_{ev}=70$ bar, $T_{SH}=450^\circ\text{C}$, FGR=15%





Implications for boiler design

Plant with RH, $P_{ev}=170$ bar, $T_{SH}=T_{RH}=450^{\circ}\text{C}$, FGR=15%

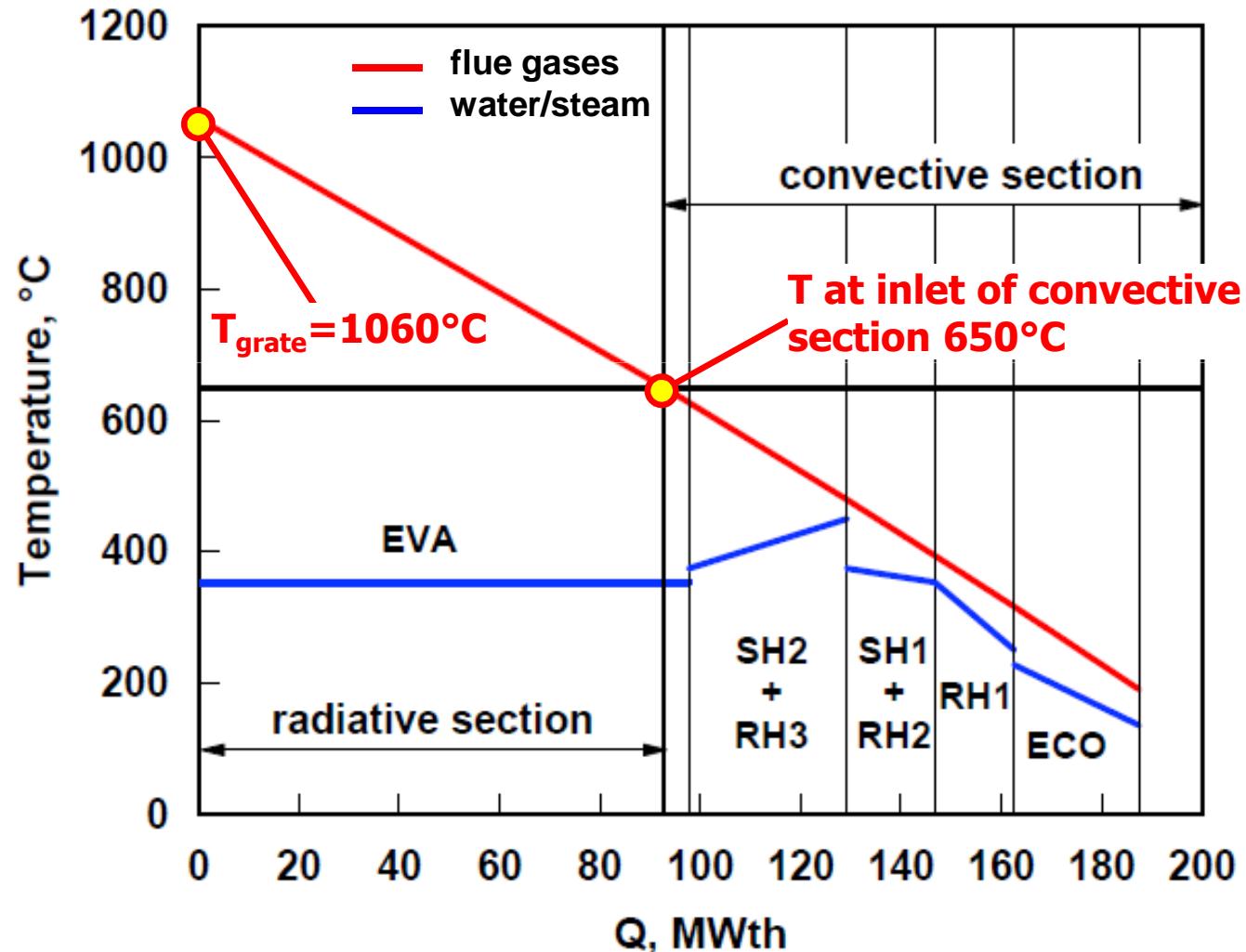




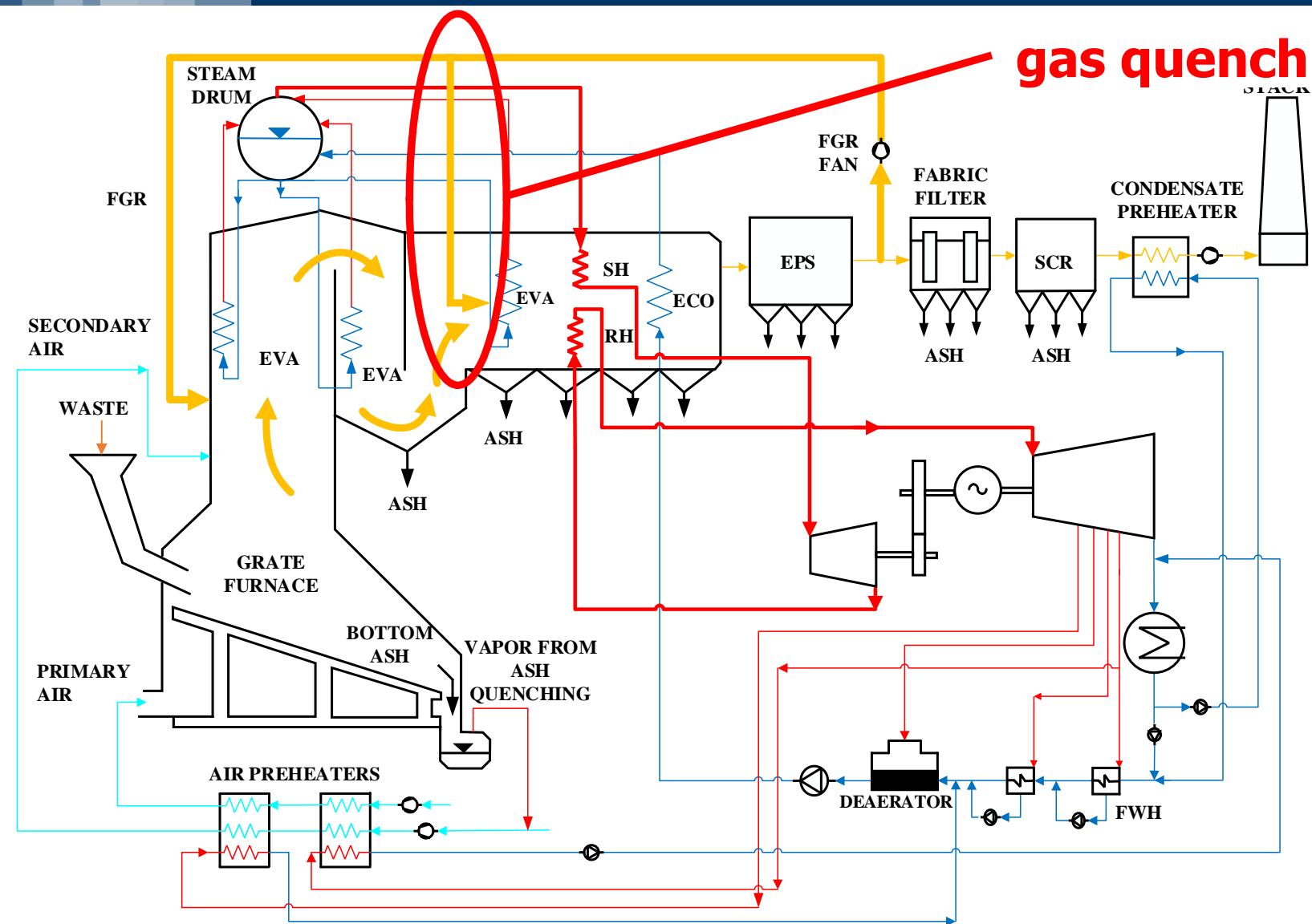
Higher FGR as means to mitigate T_{gas}

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Plant with RH, $P_{\text{ev}}=170 \text{ bar}$, $T_{\text{SH}}=T_{\text{RH}}=450^\circ\text{C}$, $\text{FGR}=22.9\%$



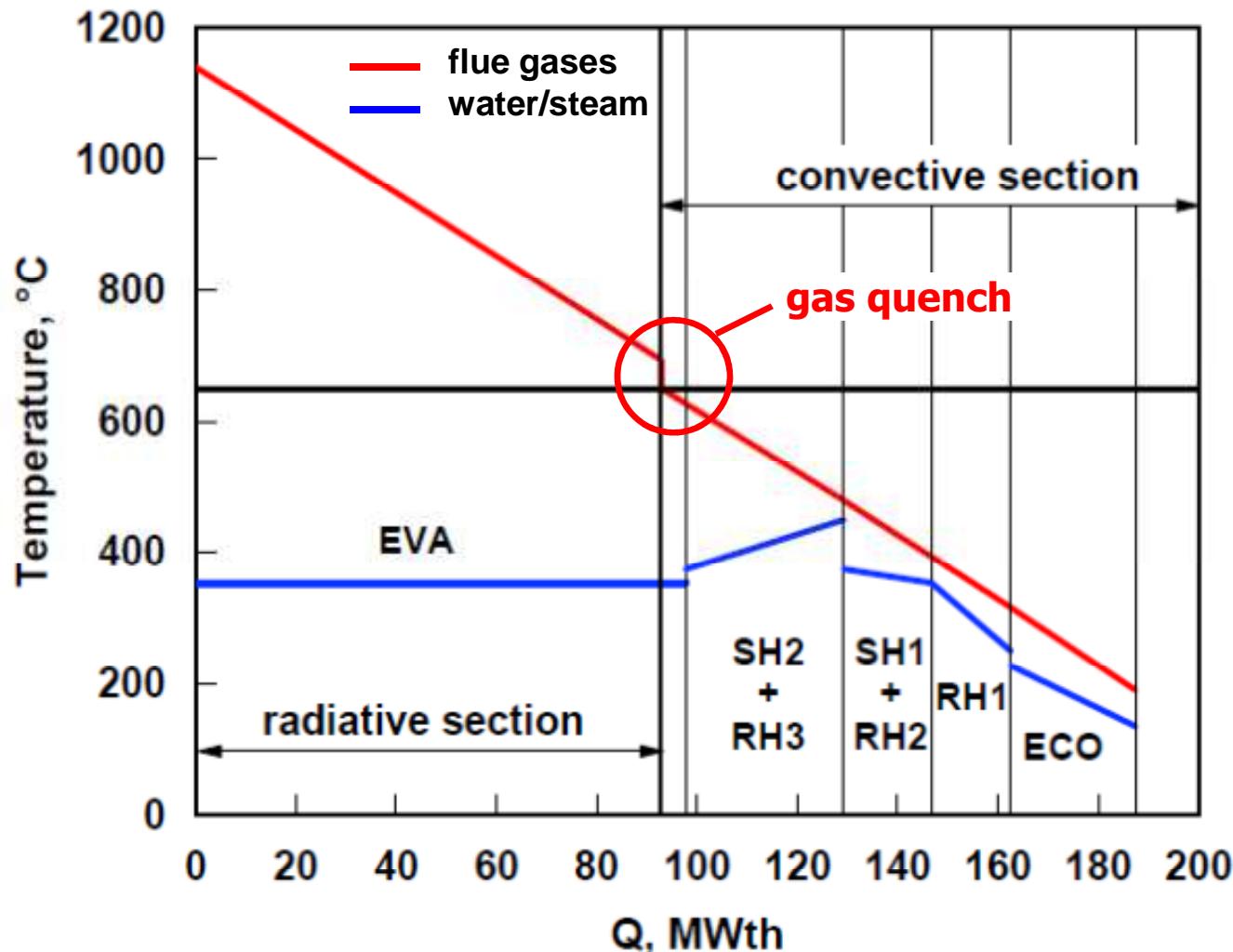
"Flue Gas Quench" (FGQ)





"Flue Gas Quench" (FGQ)

Plant with RH, $P_{ev}=170$ bar, $T_{SH}=T_{RH}=450^\circ\text{C}$



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

**(*) referred to flow
at outlet of
economizer**

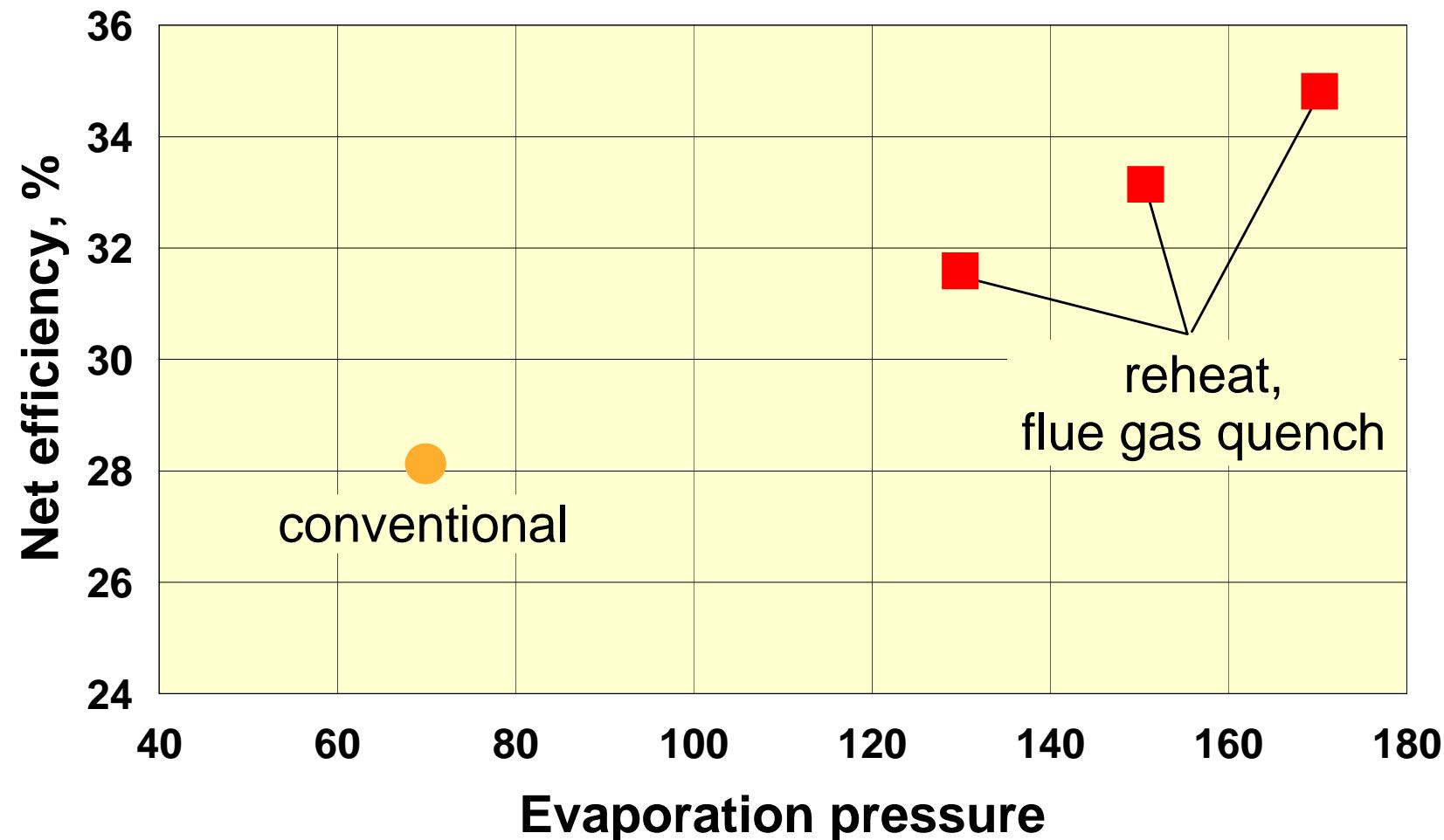


Main results: conventional vs RH with FGQ

design parameter		unit	plant configuration			
Assumptions	combustion power	MW	CONV	RH130	RH150	RH170
	evaporation pressure	bar	70	130	150	170
	reheat pressure	bar	-	25	25	25
	condensation pressure			0.07		
	steam temperature at SH outlet	°C		450		
	steam temperature at RH outlet	°C	-	450	450	450
	gas temperature at exit of radiative section	°C	650	673	688	694
	gas temperature at inlet of convective section	°C	650	650	650	650
	Flue gas generated on the grate		124.4	124.4	124.4	124.4
	FGR to combustion chamber	kg/s	21.9	21.9	21.9	21.9
Results	FGR to quench at exit of radiative section	kg/s	0.0	7.6	12.7	15.0
	Flue gas in convective section		146.3	153.9	159.0	161.3
	FGR, kg per kg at boiler outlet	%	15.0	19.2	21.8	22.9
	FGR, kg per kg generated on the grate	%	17.6	23.8	27.8	29.7
	Steam at HP turbine inlet	kg/s	66.04	60.45	60.55	60.65
	Gross power HP turbine	MWe	-	16.71	18.09	19.43
	Gross power LP turbine	MWe	-	54.09	56.44	57.67
	Total gross power	MWe	63.51	70.80	73.60	77.10
	Net Power	MWe	56.38	63.53	66.26	69.70
	Net extra power generated with RH, FGQ	MWe	-	7.15	9.88	13.32
Gross Electric Efficiency		%	31.75	35.40	36.80	38.55
Net Electric Efficiency		%	28.19	31.76	33.13	34.85



Efficiency vs P_{ev}





- Base estimate carried out with SteamPro / PEACE
- RH cases corrected for extended Inconel cladding + refractory coverage:
 - 100% of radiative section covered with refractory (1100 Euro/m²) or Inconel (3400 Euro/m²)
 - evaporator + high-temperature SH and RH (for a total of about 25% of total surface of convective section) completely covered with Inconel (2500 Euro/m²)
- Additional corrections to SteamPro/PEACE predictions for Electric systems, solid handling, buildings and civil works based on experience of major WTE built in Italy in the last decade

NOTICE: cost of convective section of boiler increases very substantially, but cost of radiative section tends to decrease (lower thermal power, smaller tubes)



Capital costs (Flue Gas Quench, Euro 2014)

	70	130	150	170
RH	No	Yes	Yes	Yes
Grate Combustor + Boiler	106,023,271	142,650,594	147,874,391	147,993,662
Flue gas treatment system	25,659,239	27,817,262	28,818,427	32,359,935
Steam Turbine	11,049,716	14,916,068	15,624,692	16,177,916
Heat rejection system	2,726,335	2,667,227	2,720,810	2,788,220
Other components of steam cycle	1,213,331	1,272,090	1,190,703	1,386,017
Electric system + transforms + DCS	7,659,061	8,309,219	8,554,490	8,857,999
Waste handling	3,177,930	3,177,930	3,177,930	3,177,930
Handling of solid residues	2,398,599	2,398,599	2,398,599	2,398,599
HVAC+Buildings	11,938,833	11,938,833	11,938,833	11,938,833
Balance of plant	1,337,969	1,342,847	1,353,852	1,375,690
Civil works, roads and construction	25,854,501	25,254,224	25,205,628	25,076,495
Mechanical works	76,418,032	65,640,222	62,291,223	58,480,012
Engineering and Plant startUp	9,780,023	11,144,403	11,197,343	11,224,896
Total plant and Civil costs	285,236,840	318,529,520	322,346,922	323,236,204
Contingencies 10%	28,523,684	31,852,952	32,234,692	32,323,620
Design, safety, testing, insurance, etc	21,392,763	23,889,714	24,176,019	24,242,715
Grand Total	335,153,287	374,272,186	378,757,634	379,802,540



Back-of-the-envelope cost assessment³⁶

Plant with RH, P_{ev}=170 bar, T_{SH}=T_{RH}=450°C, Flue Gas Quench

PRELIMINARY, CONSERVATIVE ESTIMATE

- Extra-power generation = 13.32 MW
- Extra electricity generated in 1 yr (7800 hrs) = 104 GWh
- Extra capital cost = 44.6 M€
- Assume Capital Carrying Charge 15%
- Add 4% per year of investment for O&M
- Thus, extra costs = $44.6 \text{ M€} \cdot 0.19 = 8.5 \text{ M€/yr}$
- Break-even value of electricity =
 $[8.5 \text{ M€/yr}] / [104 \text{ GWh/yr}] = 81.7 \text{ €/MWh}$

Conclusions

- Given the very unfavorable characteristics of the waste fuel, improving the performance of WTE plants poses extreme challenges
- For grate combustors plants fed only with waste, steam reheat seems an interesting option
- The introduction of RH calls for a comprehensive redesign of the whole integrated boiler. Flue Gas Quench allows limiting the size and the cost of the radiative section while keeping safe temperatures in the convective section
- Preliminary, conservative estimates show that with $P_{EV}=170$ bar and T_{max} of steam 450°C it is possible to increase net efficiency of over 6 percentage points
- For a 200 MW_{LHV} plant, the extra electricity generated with RH comes at a cost in the neighborhood of 80 €/MWh

**Thank you for your
attention !**



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