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Techno-Economic Analysis of Waste Heat Recovery with ORC from Fluctuating Heat Sources

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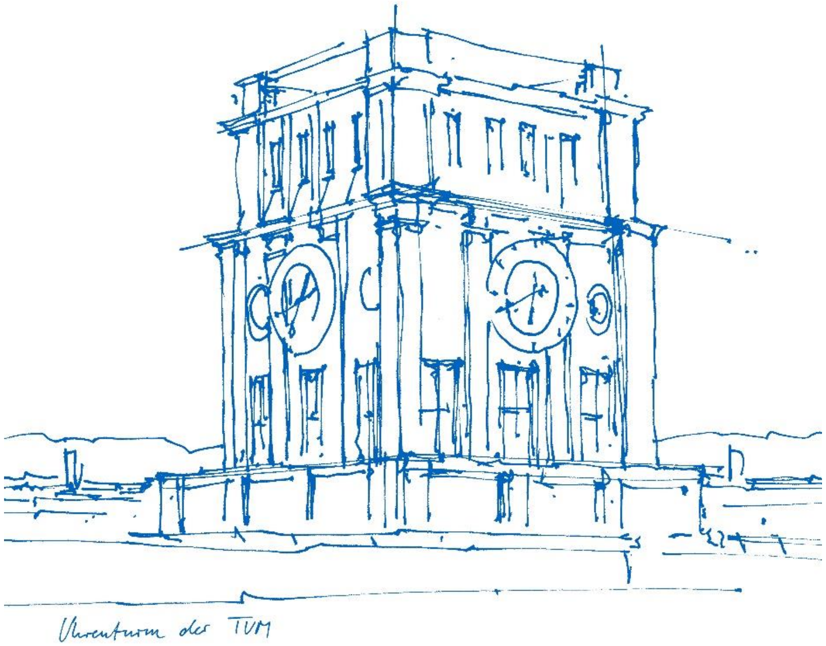


Milan, 13th September 2017

Outline

1. Waste heat from Heavy Industry
2. Waste Heat Fluctuations
3. Modelling and Methods
4. Results
5. Summary and outlook

1. Waste heat from industrial processes

Definition: “Waste heat is thermal energy (or heat), which is not used for the primary purpose of converting the raw material into a product.”

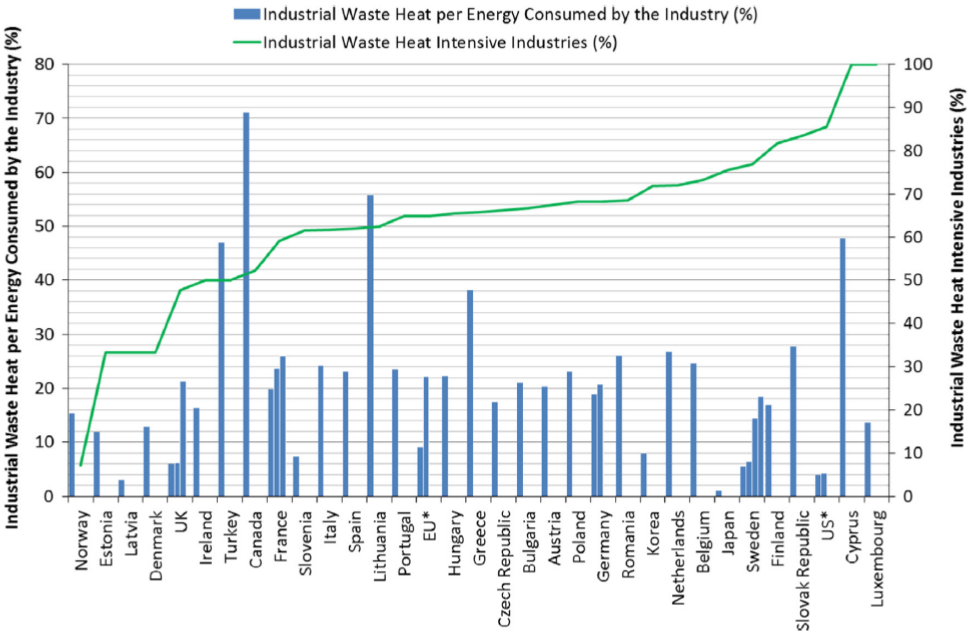


Figure: Miro, 2015.

Industrial waste heat can amount up to 70% of the industrial demand of a country (Canada)

EU27: 2708 PJ/a (9.1-22.2% industrial consumption)
Germany: 218-566 PJ/a (~12-30%)

1. Waste heat from industrial processes

Definition: “Waste heat is thermal energy (or heat), which is not used for the primary purpose of converting the raw material into a product.”

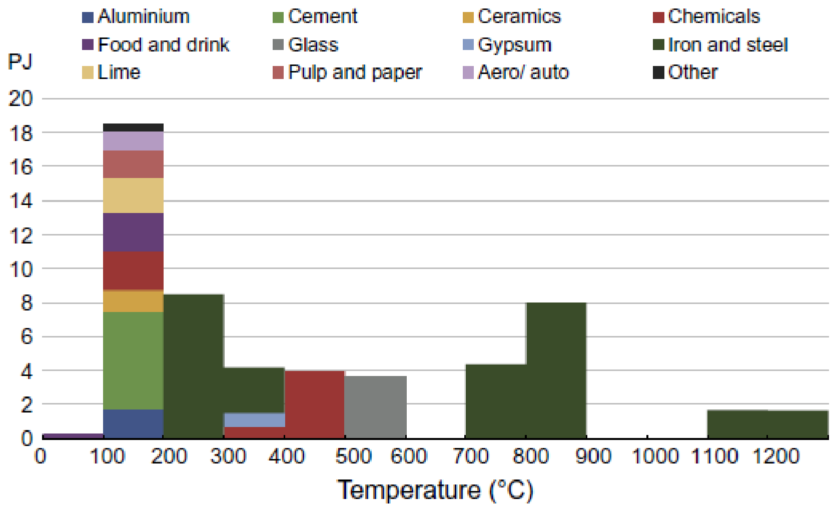


Figure: Hammond, 2014.

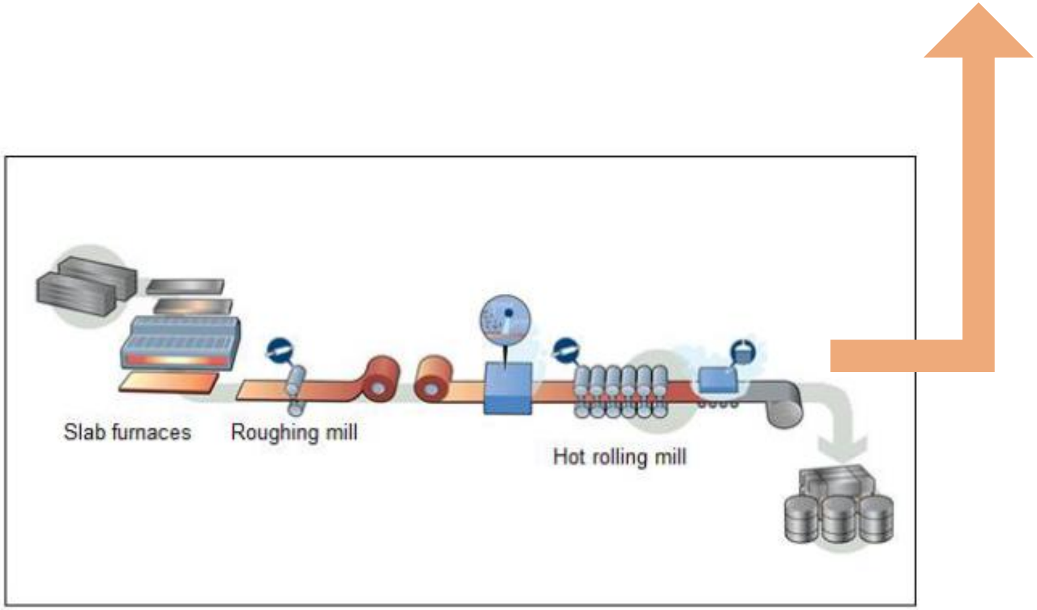
The available waste heat can be computed from:

$$\dot{Q} = \dot{m}\, c_p \left(T - T_{ref}\right)$$

Most important sectors:

- Cement
- Steel
- Non-ferrous metal (aluminium)
- Glass
- Chemicals

1. Where does waste heat come from?

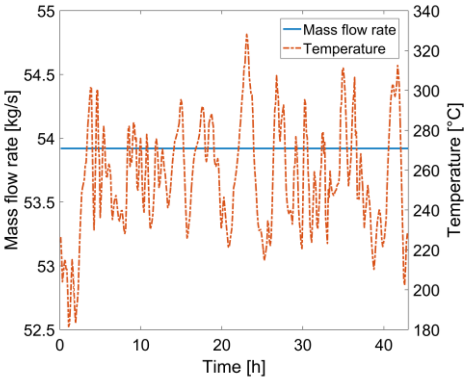


Waste heat
400°C

Rolling mill hot reheating furnace. Figure: De Freitas, 2014.

2. Heat source fluctuations

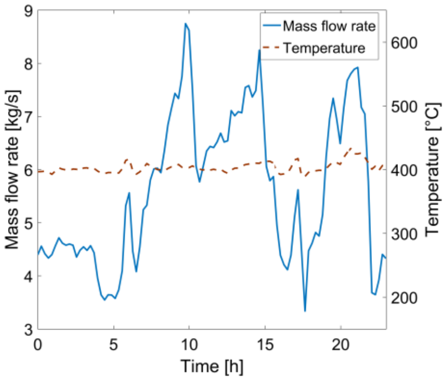
Cement industry



Fluctuating temperature

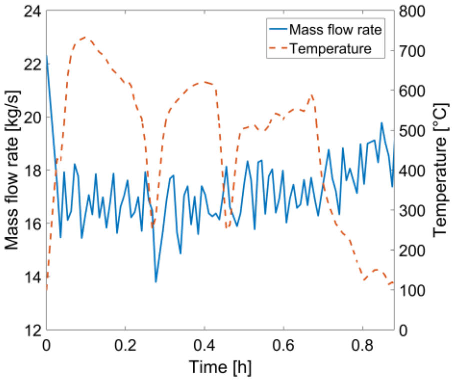
Profile: Legmann, 2002.

Steel: hot rolling mill



Fluctuating mass flow rate

Steel: electric arc furnace



Fluctuating temperature

Fluctuating mass flow rate

Profile: Brandt, 2014.

How should I design my system?

2. Design dilemma

For design → classical approach: fixed load point (classical nuclear plants for base-load)

Relatively easy, design based on single point

If the system operates for long-time in off-design (common ICE for vehicles, wind)

A trade-off has to be found

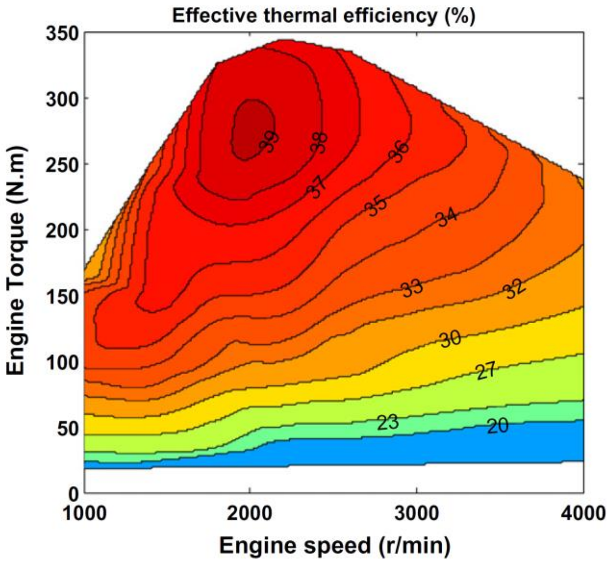
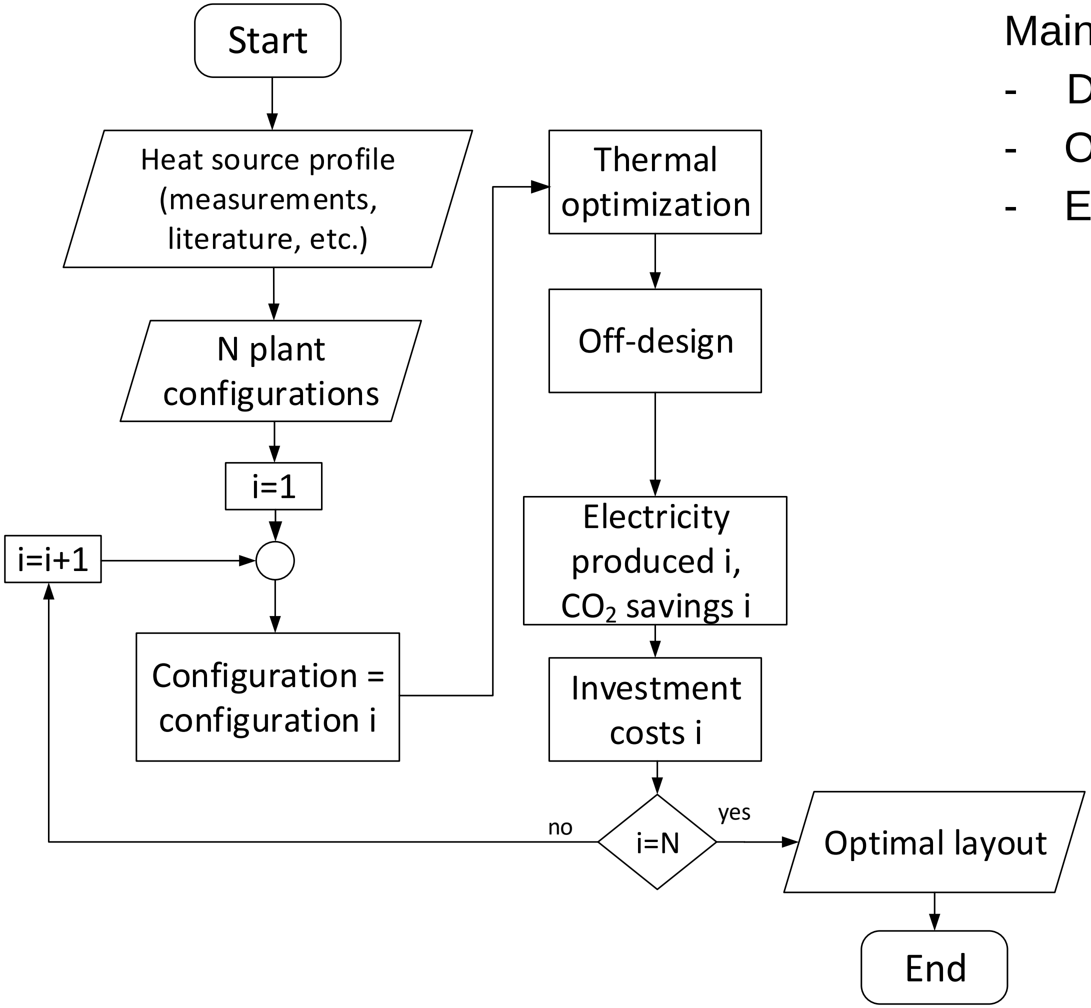


Figure: Zhang, 2013

3. Proposed procedure



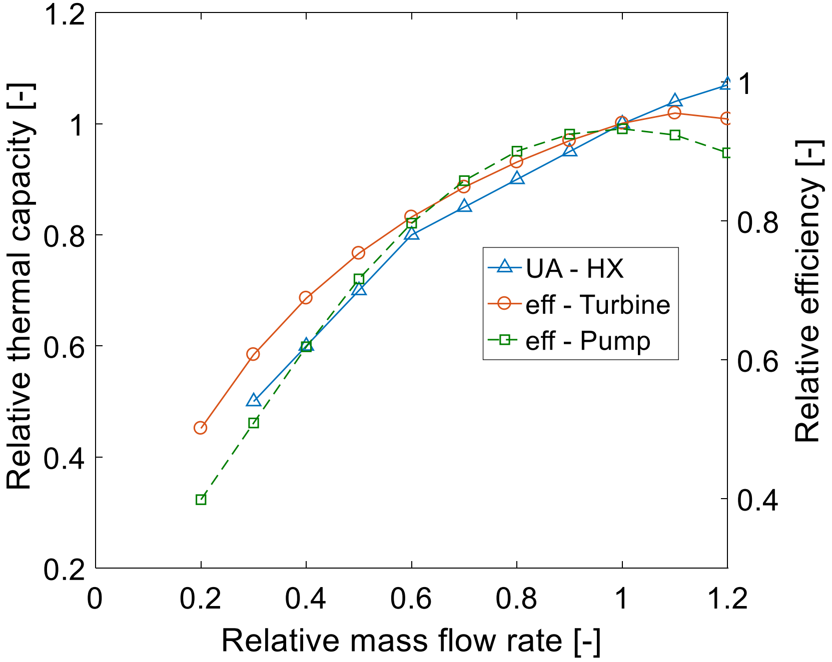
Main parts:

- Design
- Off-design
- Economics

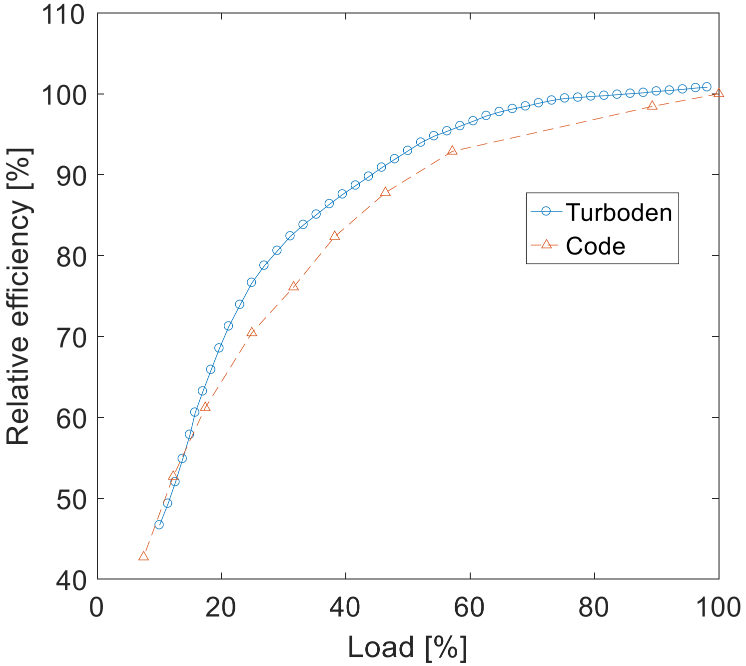
3. Off-design of ORC systems

When the load drops, the components are not working any more in the optimal point.

Correlations curves for off-design



Comparison with real system (qualit.)

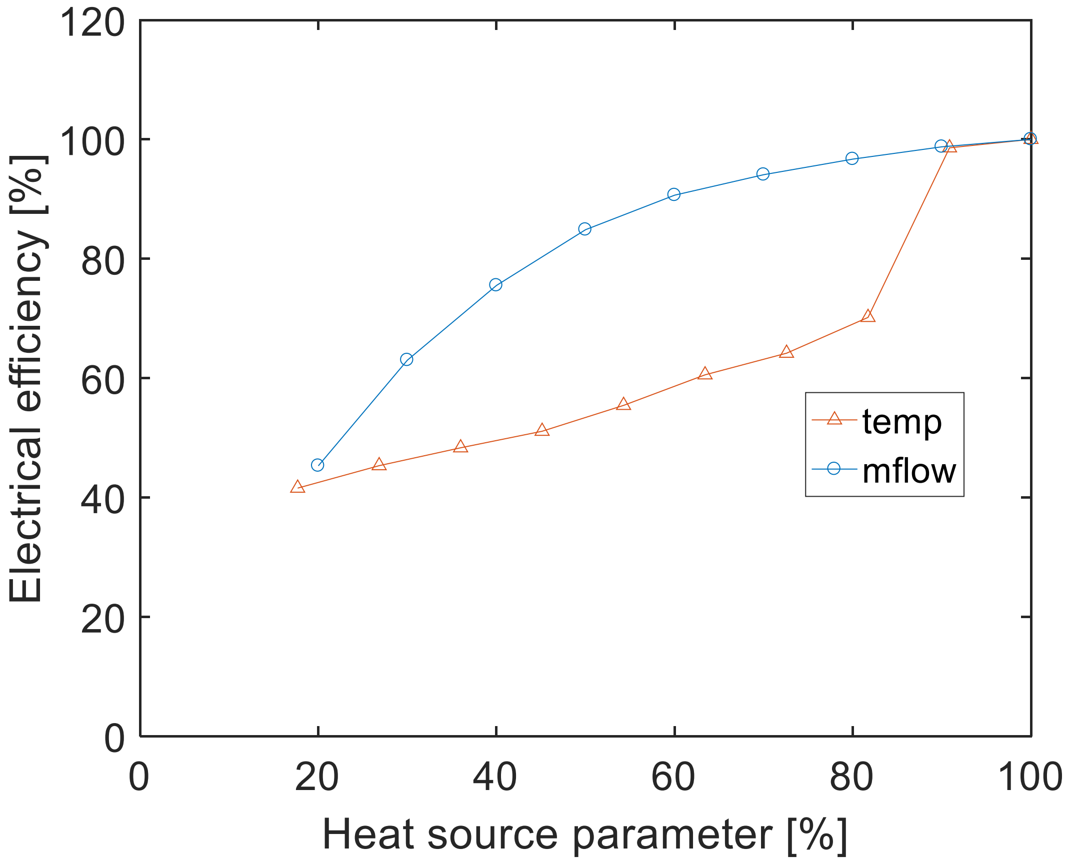


Turboden curve from: Turboden, 2017.

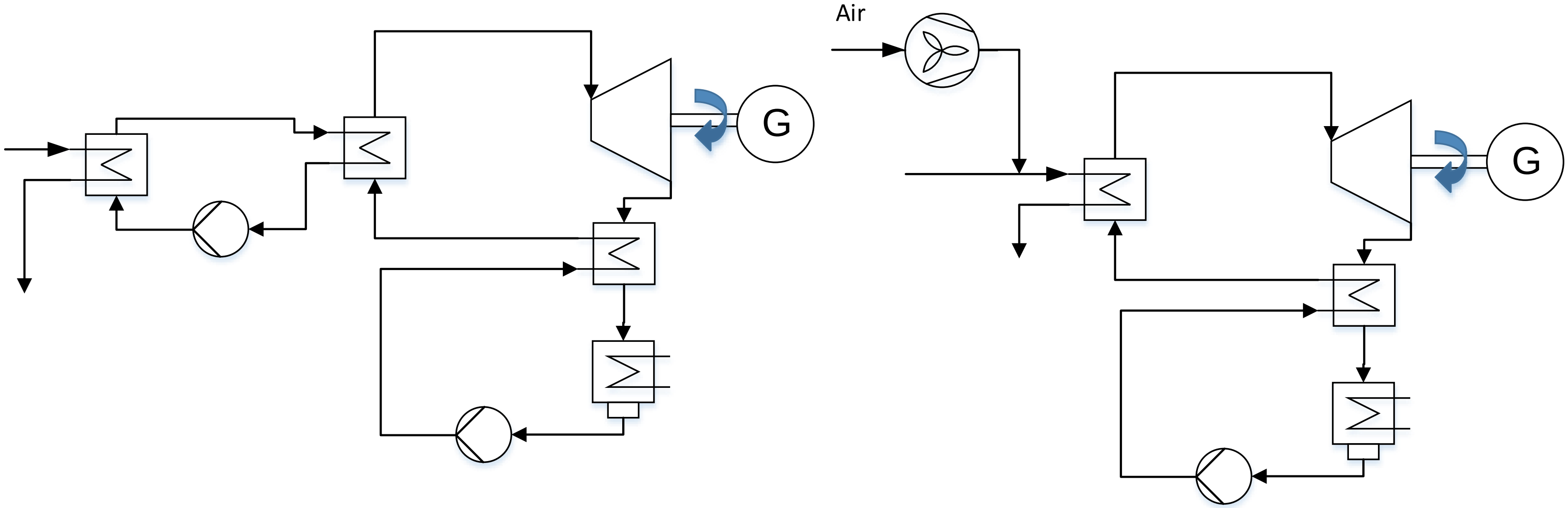
3. Off-design of ORC systems

When the load drops, the components are not working any more in the optimal point

Off-design in
temperature vs
off-design in
mass flow rate



3. Techniques to convert fluctuations in temperature into fluctuations in mass flow rate



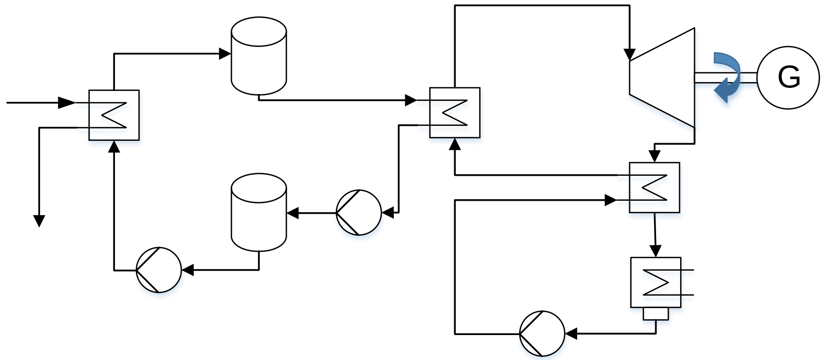
Temperature drops → lower Carnot efficiency

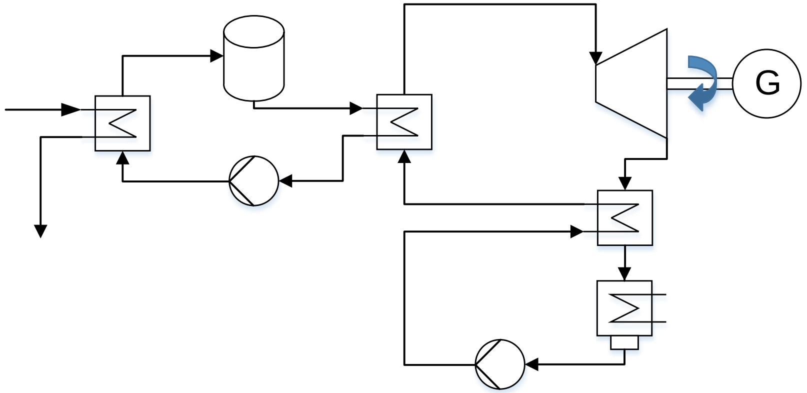
Additional components

But…

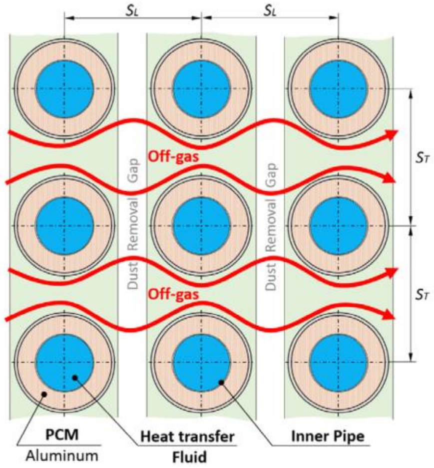
…better part-load

3. Storage options

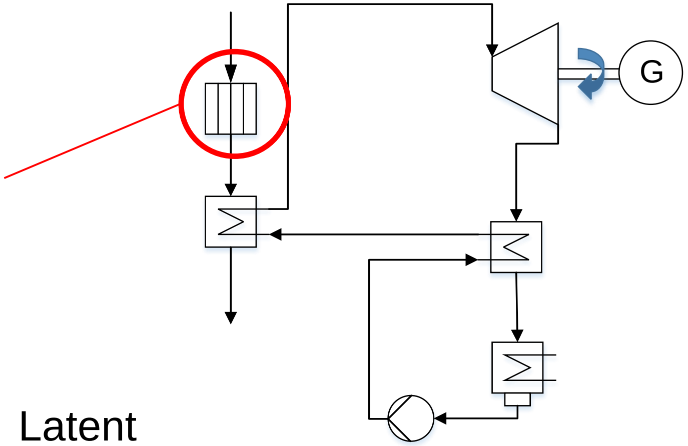




Sensible



Picture: Dal Magro, 2015.

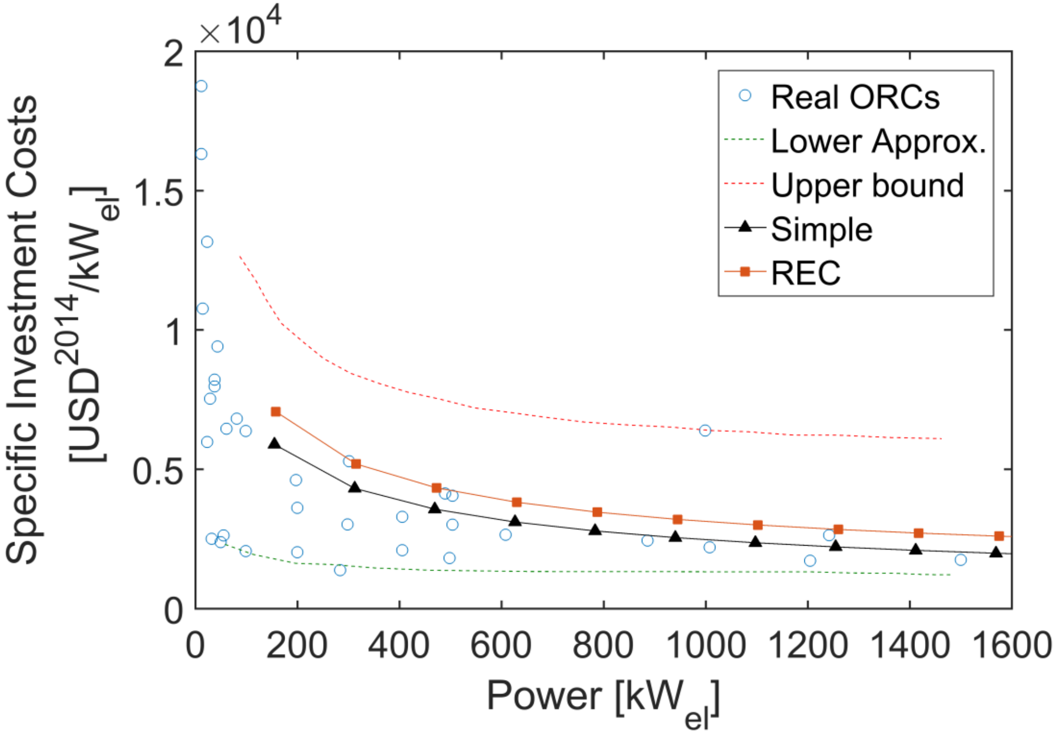


Latent

3. Economic model

Based on Turton (-25%/+40%), already used in several publications for ORCs

Correlations for costs related to heat exchanger areas, turbine power, pump power, etc.
Corrections for pressure and material



ORC values and bounds from Rettig, 2011.

3. Important figures

Electricity produced: $E_k = \bar{P}_k \, \Delta t$

CO_2-savings: $CO_2S = f \, E_k$

f = 535 tCO_2/kWh in Germany (source: Statista, 2016)

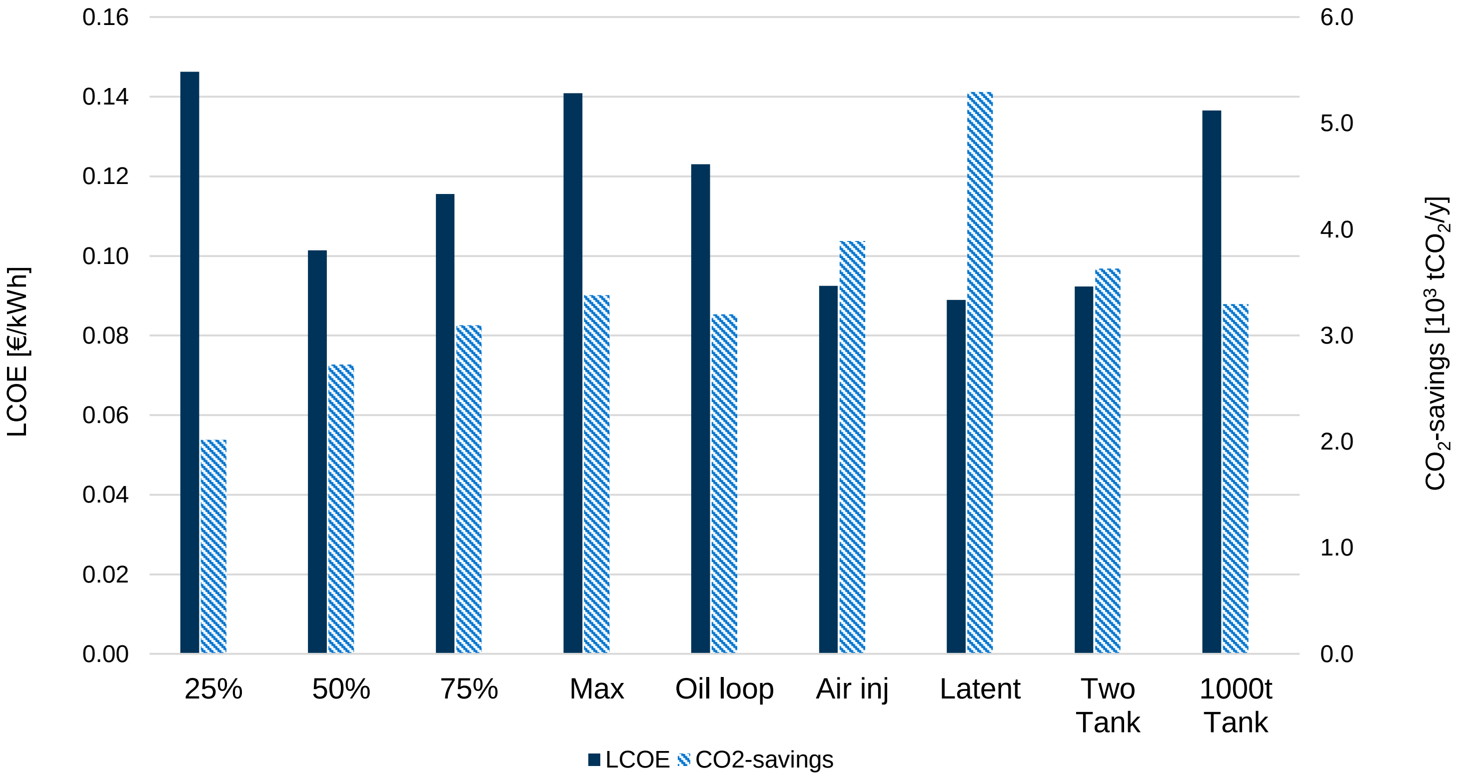
Levelized cost of electricity:

- interest rate i 4%
- number of cash flows N (10)

$$LCOE = \frac{\sum_{k=1}^{N} \frac{C_k}{(1+i)^k} + C_0}{\sum_{k=1}^{N} \frac{E_k}{(1+i)^k}}$$

1. No costs for fuel
2. Independent from electricity price!

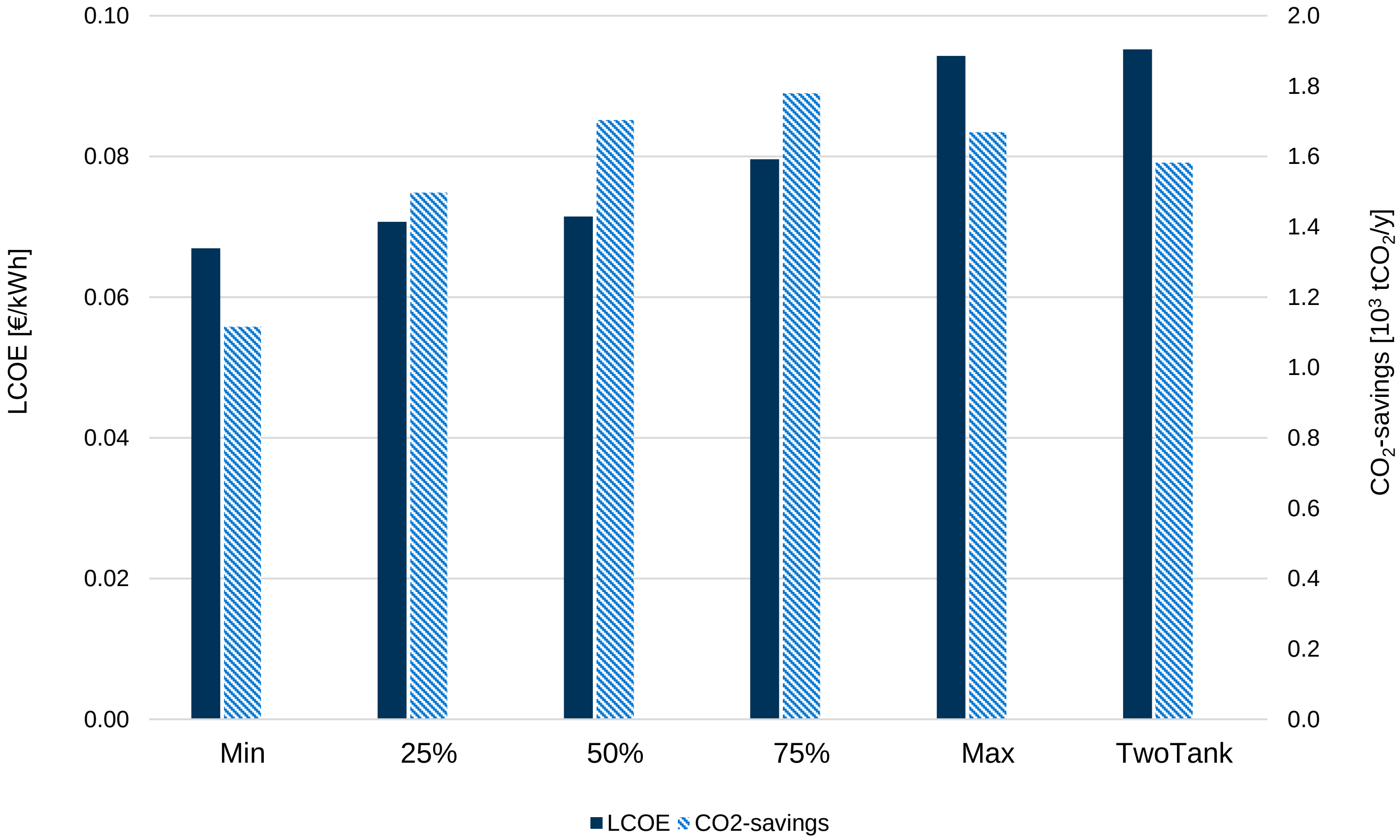
4. Results – Cement clinker (cooling air)



Lowest LCOE: Latent heat buffer

Highest CO$_2$-savings: Latent heat buffer

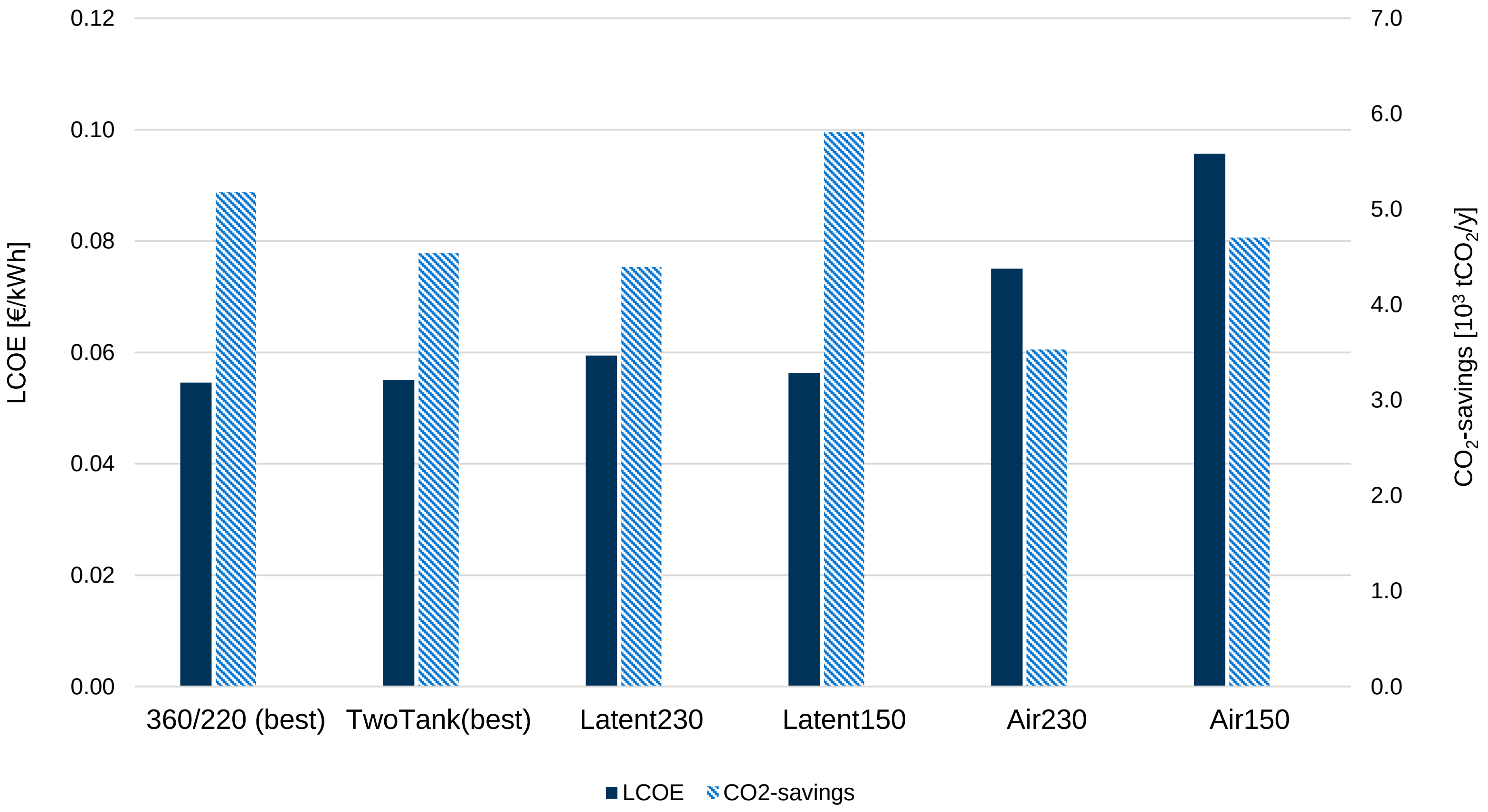
4. Results – Hot rolling mill



Lowest LCOE: Design for minimum source mass flow rate (rest bypassed)

Highest CO$_2$-savings: 75% CPD of source mass flow rate

4. Results – Electric Arc Furnace



Lowest LCOE: Latent heat buffer or direct evaporation (T50%M100%)

Highest CO_2-savings: Latent heat buffer

5. Summary

A **techno-economic** procedure for the design and analysis of ORCs subjected to **fluctuating heat sources** has been developed.

The model is based on **thermodynamic optimization** tools, investment **cost estimation** and correlation for ORC **off-design** behavior.

Different configurations **with and without storage** were analysed.

Temperature fluctuations affect **more** the performance of the ORC and cannot be easily by-passed.

No storage and **simple bypass** appears the most economic solution for fluctuating mass flow rate.

For fluctuating temperature, the **latent heat buffer** appeared a good solution both for the economic and the environmental perfomance of the waste heat recovery systems.

5. Future outlook

Analysis of additional profiles

More in-depth models of heat exchangers

Comparison of different working fluids in off-design

Development of dynamic models

Analysis of different control strategies

6. References

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Thank you very much for your attention.

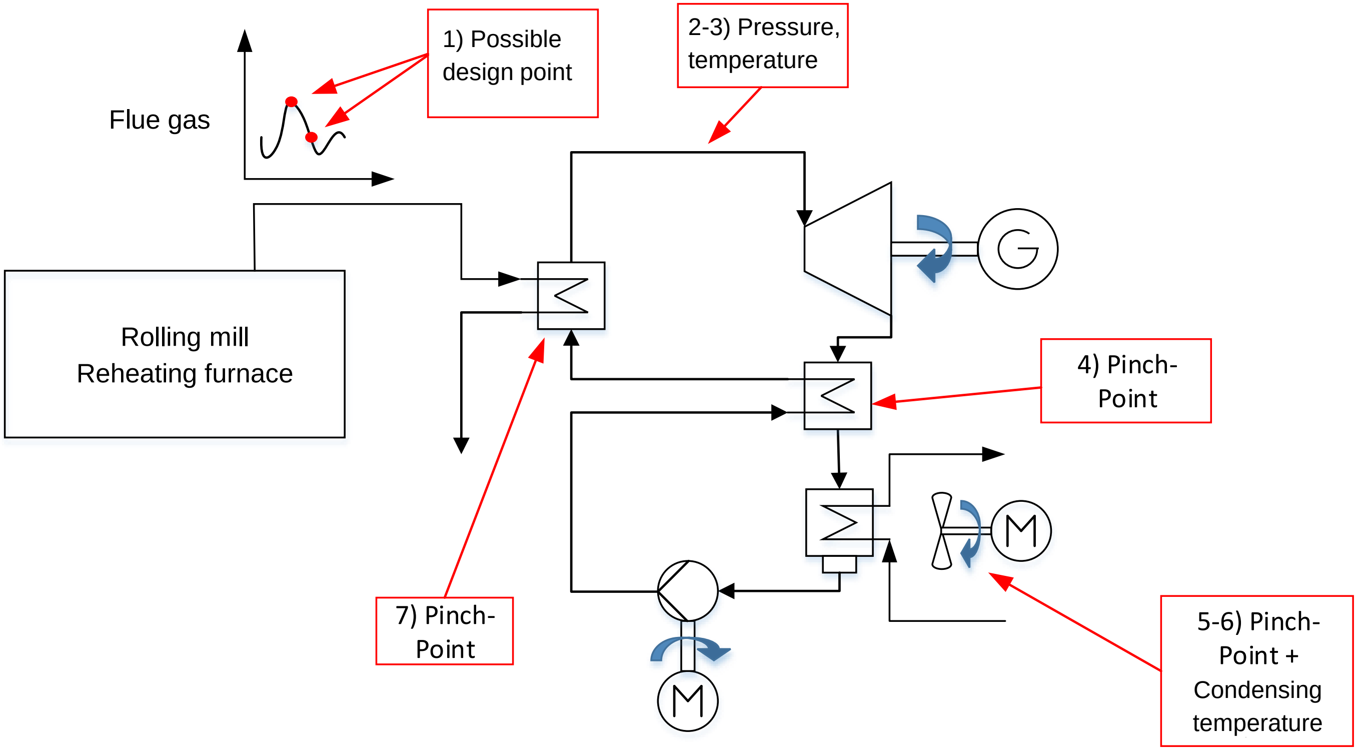
Assumptions – Thermodynamic design

Quantity	Unit	Value	Quantity	Unit	Value
Min. heat source temperature	[°C]	150	Turbine efficiency	[%]	75
Pinch-point	[K]	10	Generator efficiency	[%]	97
Pump efficiency	[%]	70	Recuperator effectiveness*	[%]	80
Pump motor efficiency	[%]	85	Condensation temperature	[°C]	30

*When used (for water, set to zero)

Output: evaporation pressure and superheating at nominal point

Design


Flue gas
1) Possible design point
2-3) Pressure, temperature
Rolling mill
Reheating furnace
4) Pinch-Point
5-6) Pinch-Point + Condensing temperature
7) Pinch-Point

Assumptions for heat storage

Storage	**Heat source**	**Medium**	**Temperatures (°C)**	**Quantity (t)**	**ORC working fluid**	**Notes**
Two-tank	Clinker cooling air	Therminol VP-1	220/92.5*	159.07	Pentane	If source temp. < 230°C, source bypass
	Flue gas HRF	Therminol VP-1	370/92.5*	17.87	Toluene	
	Flue gas EAF	HITEC®	400/225*	10.80	Toluene	If source temp. < 410°C, source bypass
Single tank	Clinker cooling air	Therminol VP-1	variable	1000	Pentane	
Latent heat buffer	Clinker cooling air	$LiNO_3$	254	70.44	MM	
	Flue gas EAF	50wt-NaCl/50-wt $MgCl_2$	450	9.96	Toluene	

(*temperature given as A/B: A: high temperature tank/B: low temperature tank)

Design data

Table A1. Thermodynamic optimization at design point (CC = Clinker Cooling, HRF = Hot Reheating Furnace, EAF = Electric Arc Furnace).

Case	Heat source temperature (° C)	Heat source mass flow rate (kg/s)	Working fluid	Turbine inlet temperature (° C)	Evaporation pressure (bar)	Condensation pressure (bar)	Electrical efficiency (%)	Net power output (kW)
CC 25%	237.1	53.9	Pentane	221.9	26.96	0.82	21.16	1017.9
CC 50%	254.8	53.9	MM	211.6	9.59	0.07	21.54	1246.7
CC 75%	277.1	53.9	MM	234.5	14.02	0.07	22.69	1598.6
CC Max	328.1	53.9	MM	259.6	15.51	0.07	23.49	2331.0
CC oil loop	220.0*	40.4*	Pentane	143.9	11.82	0.82	15.63	1554.0
CC Air inj.	220.0	82.5	Pentane	209.6	11.42	0.82	19.61	1156.1
CC latent	264.0	53.9	MM	219.6	10.90	0.07	21.91	1383.5
CC Two Tank	220.0*	23.1*	Pentane	210.0	11.83	0.82	15.81	898.9
CC Single Tank	214.1*	15.7*	Pentane	161.1	18.15	0.82	17.21	825.2

*Refer to heat source as oil/storage heat carrier

Design data

Table A1. Thermodynamic optimization at design point (CC = Clinker Cooling, HRF = Hot Reheating Furnace, EAF = Electric Arc Furnace).

Case	Heat source temperature (°C)	Heat source mass flow rate (kg/s)	Working fluid	Turbine inlet temperature (°C)	Evaporation pressure (bar)	Condensation pressure (bar)	Electrical efficiency (%)	Net power output (kW)
HRF Min	403.5	2.5	Toluene	328.0	33.01	0.05	29.37	260.8
HRF 25%	403.5	4.5	Toluene	328.0	33.01	0.05	29.37	367.6
HRF 50%	403.5	5.6	Toluene	328.0	33.01	0.05	29.37	436.8
HRF 75%	403.5	7.0	Toluene	328.0	33.01	0.05	29.37	541.8
HRF Max	403.5	9.5	Toluene	328.0	33.01	0.05	29.37	738.8
HRF Two Tank	370.0*	2.5*	Toluene	238.3	14.06	0.05	24.81	368.9

*Refer to heat source as oil/storage heat carrier

Design data

Table A1. Thermodynamic optimization at design point (CC = Clinker Cooling, HRF = Hot Reheating Furnace, EAF = Electric Arc Furnace).

Case	Oil hot temperature (° C)	Oil mass flow rate (kg/s)	Working fluid	Turbine inlet temperature (° C)	Evaporation pressure (bar)	Condensation pressure (bar)	Electrical efficiency (%)	Net power output (kW)
EAF 360/220 best	360	22.0	Toluene	344.9	13.54	0.05	24.77	826.2
EAF Two Tank	400	9.4	Toluene	352.7**	33.01	0.05	29.99	772.7
EAF Latent 230	460.0	22.3	Toluene	353.1**	33.00	0.05	30.37	1646.1
EAF Latent 150	460.0	22.3	Toluene	345.9	33.01	0.05	30.10	2177.4
EAF Air 230	450.0	37.8	Toluene	344.9	33.01	0.05	29.77	3531.2
EAF Air 150	450.0	37.8	Toluene	351.5**	33.00	0.05	30.02	2632.1

**Higher than the limit of 350° C, because of small tolerances in the code (error within 1%).

Economic assumptions

Interest rate i = 4%

Number of years = 10

Load hours 7000 h/y (EAF), 8000 h/y (cement, HRF)

Indirect and direct costs → 18% more for contingency and fees

Heat exchanger	Type	Material	U (W/m^{2}K)
Heat source/oil	U-tube	CS	80
Oil/evaporator	U-tube	CS	600
Heat source/evaporator	U-tube	CS	80
Recuperator	U-tube	CS	200
Condenser	Air cooler	CS	80

Component	Type	Material
Pump	Centrifugal pump	CS
Turbine	Axial gas turbine	CS
Compressor	Centrifugal fan	CS
Tank	API – fixed roof	CS (Process vessel)

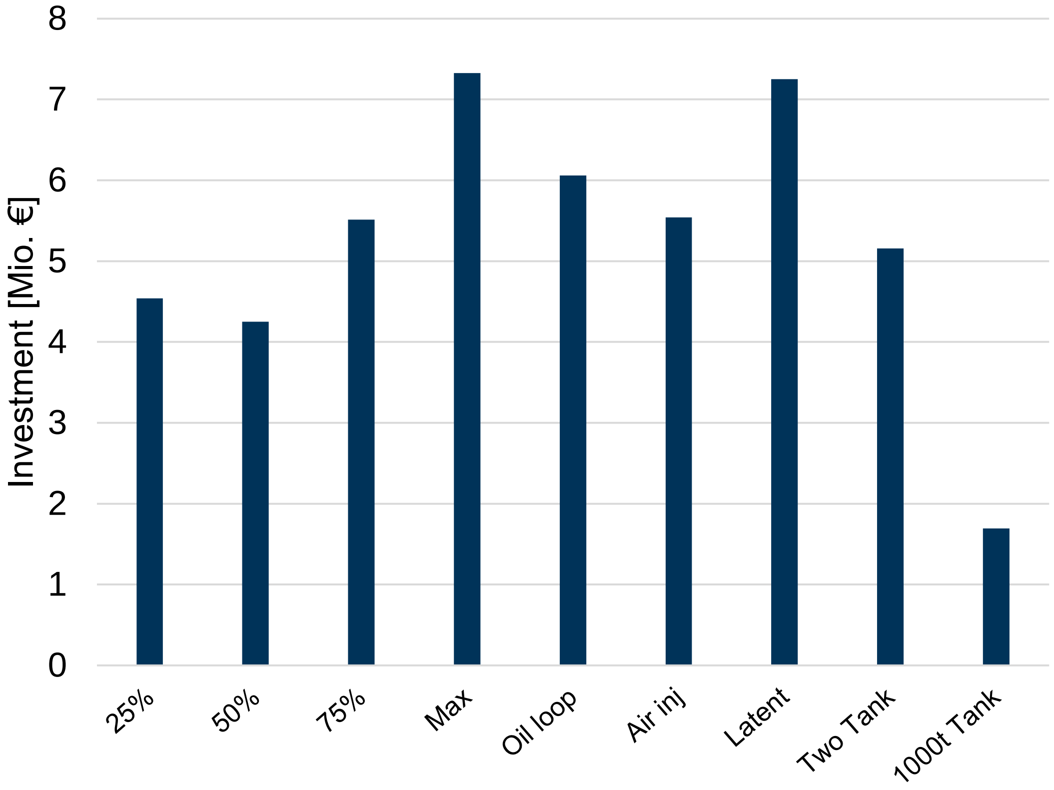
Economic assumptions

Material	Type	Unit	Cost	Quantity	Type	Unit	Cost
Therminol VP-1	Sensible	[€/kg]	1.60	$LiNO_3$	Latent	[€/kg]	8.00
HITEC® Heat Transfer Salt	Sensible	[€/kg]	0.74	50wt-NaCl / 50-wt $MgCl_2$	Latent	[€/kg]	0.14

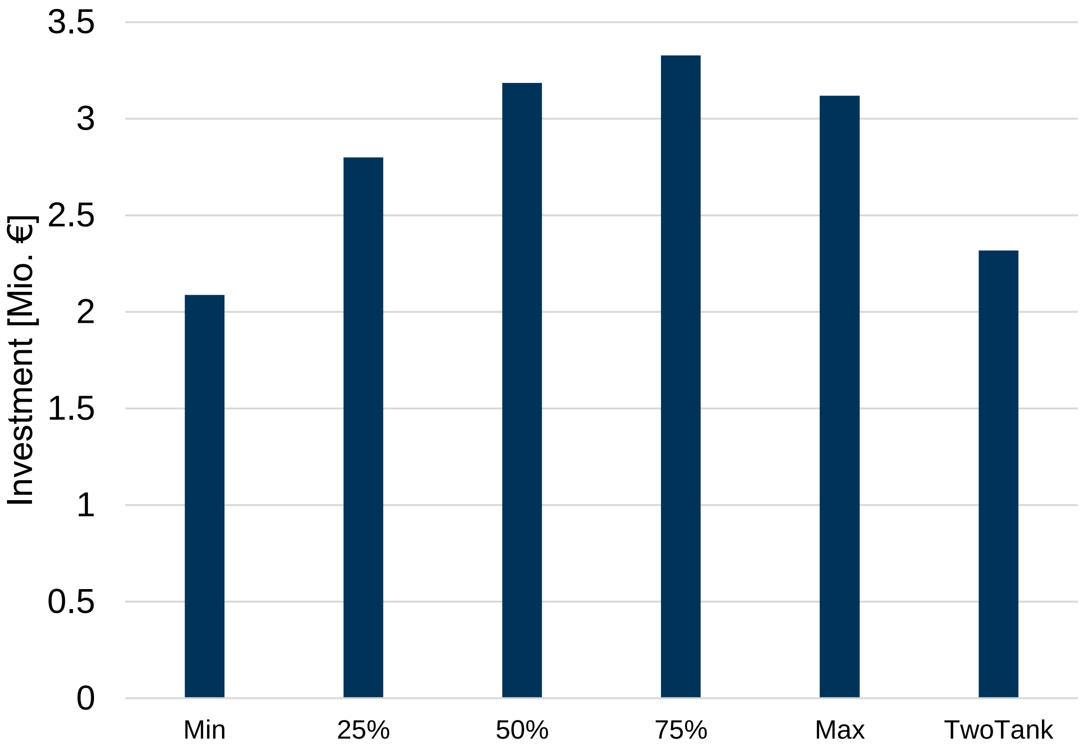
Pipe: 92.22 €/m

USD/EUR = 1.25

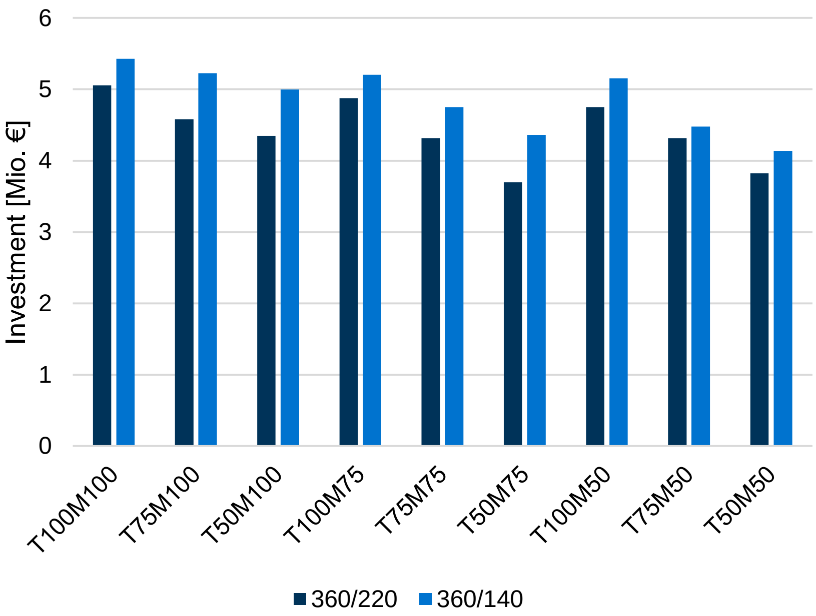
Investment Cement

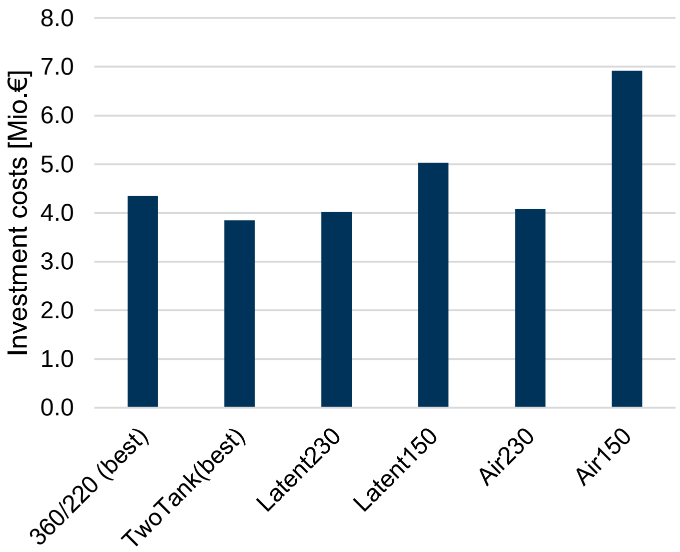


Investment Rolling mill



Investment EAF





EAF oil loop temperature: 360/220°C-340/150°C