Optimal sizing and operation of on-site combined heat and power systems for intermittent waste-heat recovery

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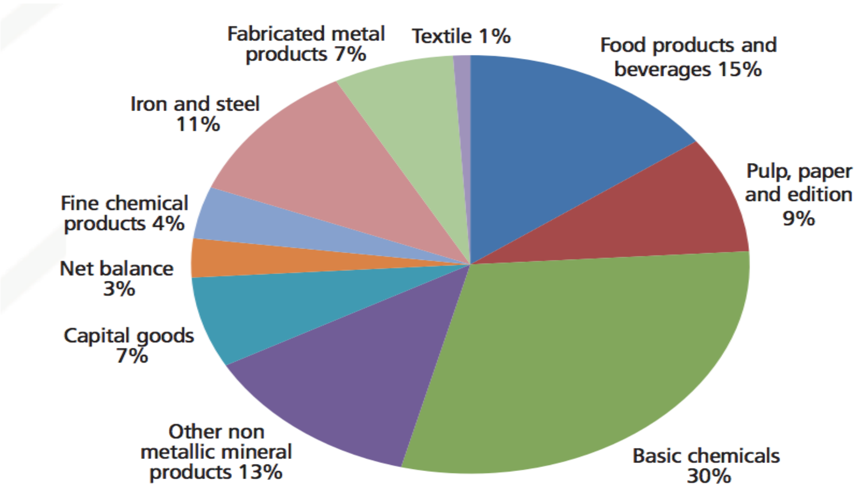
ORC 2017 -4th International Seminar on ORC Systems, September 13-16, Milan, IT

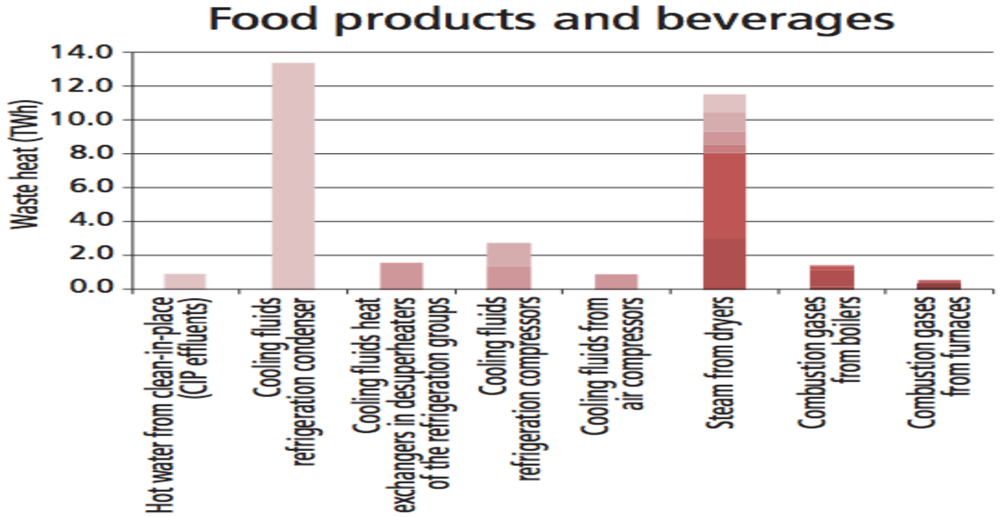
Outline

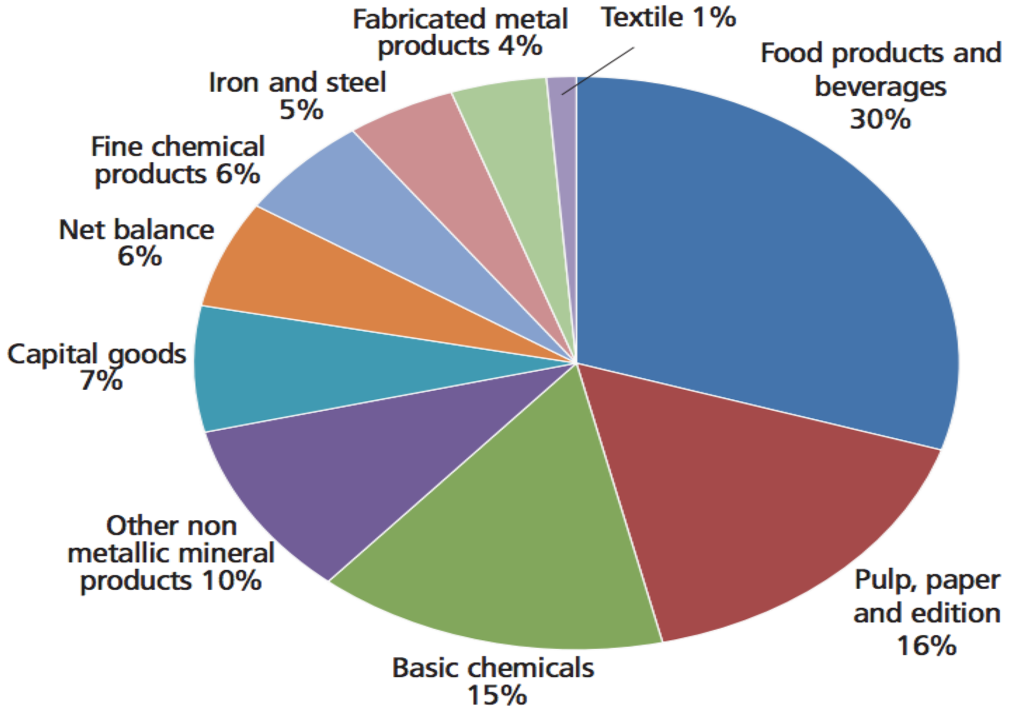
- Low grade heat recovery in food and beverage via ORC
- Case study: intermittent waste heat recovery in coffe roasting
- Comparison of investment strategies and key techno-economic factors
- Key findings and conclusions

Waste heat in food and beverage sector



Energy consumption by industrial sector



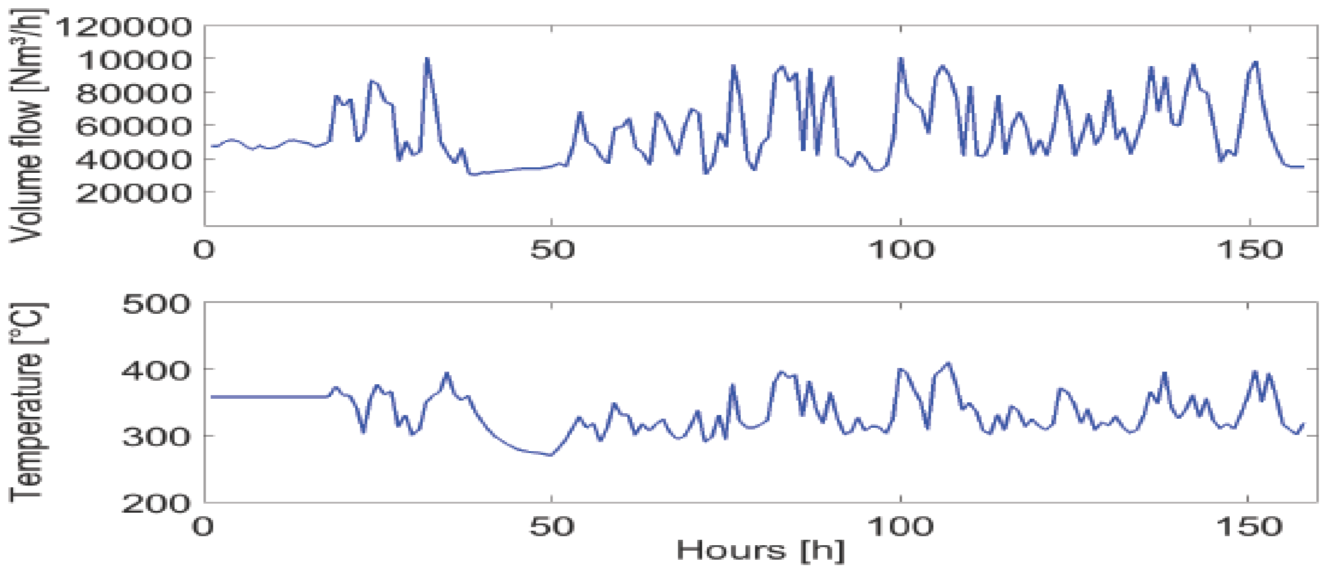


Waste heat by industrial sector

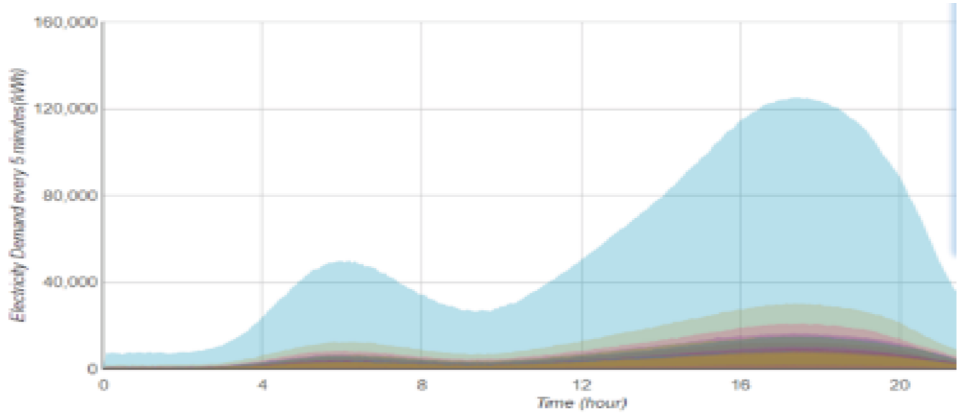
- Large potential for low-temperature waste heat recovery in food and beverage

Overview of waste heat in the industry in France," in ECEEE 2012 Industrial Summer Study, Brussels, 2012

Intermittent heat source vs. variable energy demand



Intermittent heat source

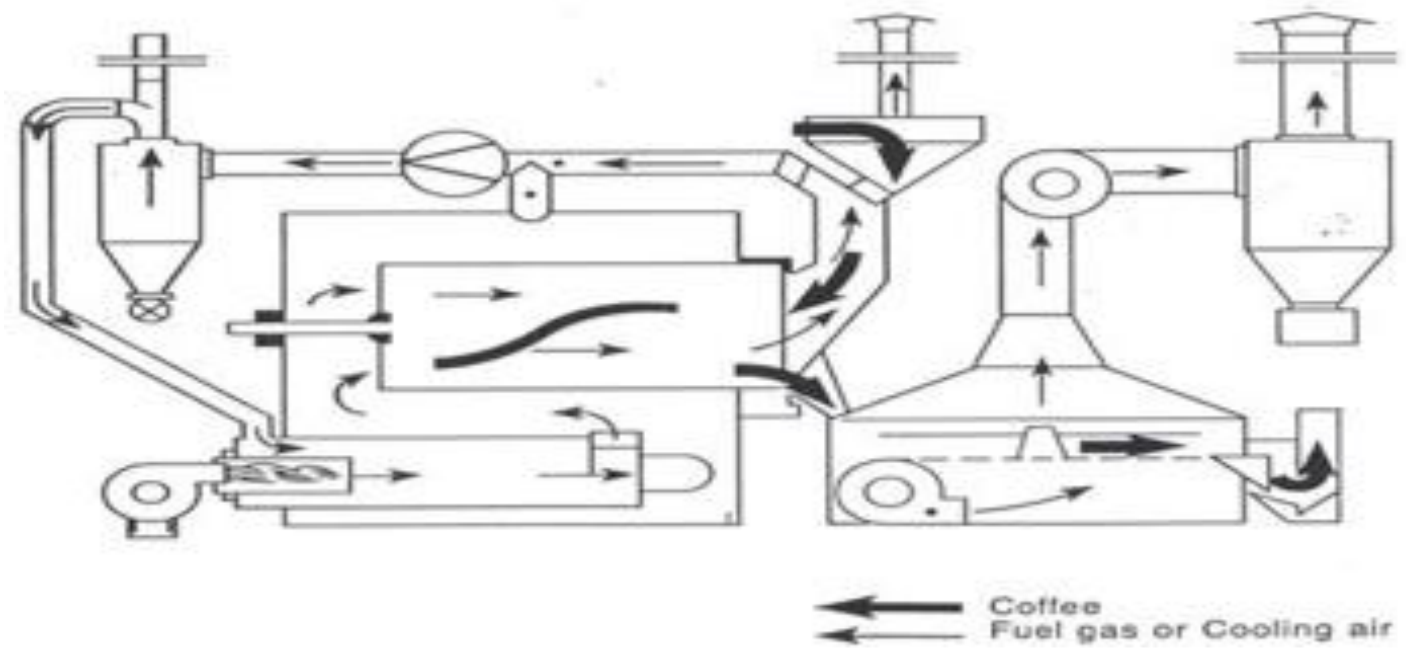


Variable energy demand

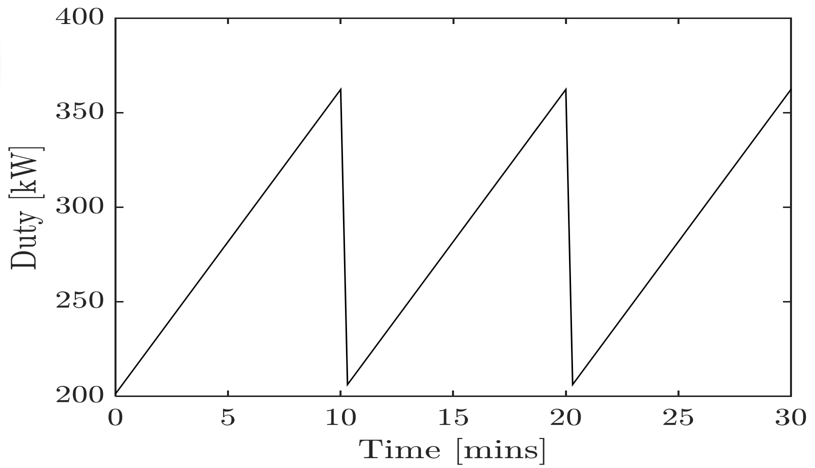
Challenges:

- Optimal system sizing and configuration
- Opportunities from storage, multi-fuel integration
- Optimal operation: baseload or load following?

Intermittent heat recovery: The torrefaction process



- Roasting capacity: 500 kg/hour
- Operation: 6 hours/day
- NG consumption: 7,000 GJ/year
- Modulating boiler size: 1 MWt



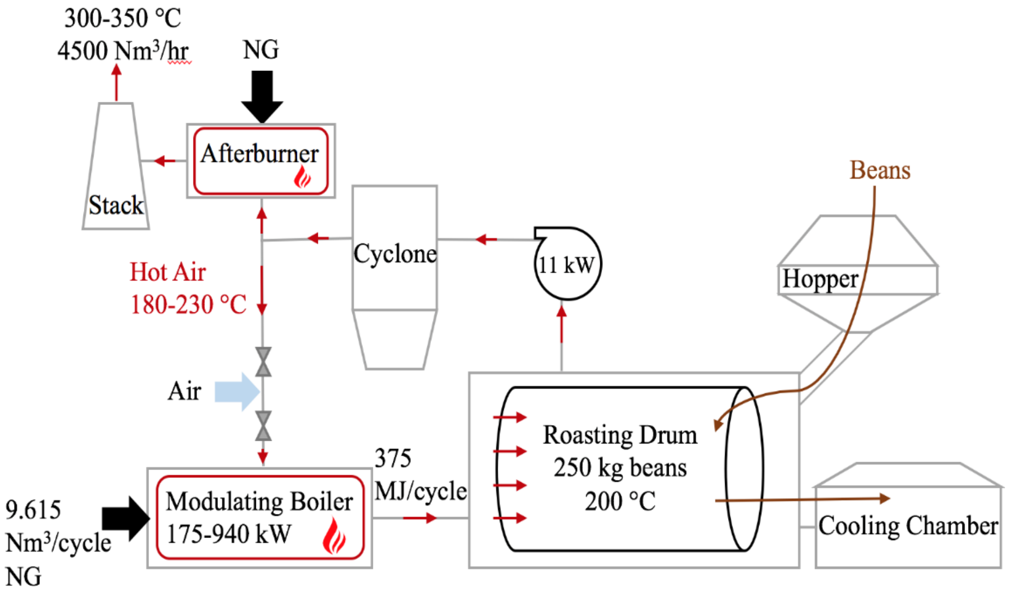
- **Modulating gas boiler for constant T gradient** during roasting
- Process intermittent (10 min torrefaction + 15 sec discharge)
- Post burner for VOC abatement in flue gases
- **T of flue gas discharged at the stack is high (330-350°C)**

Saicaf torrefaction process: Case studies definition

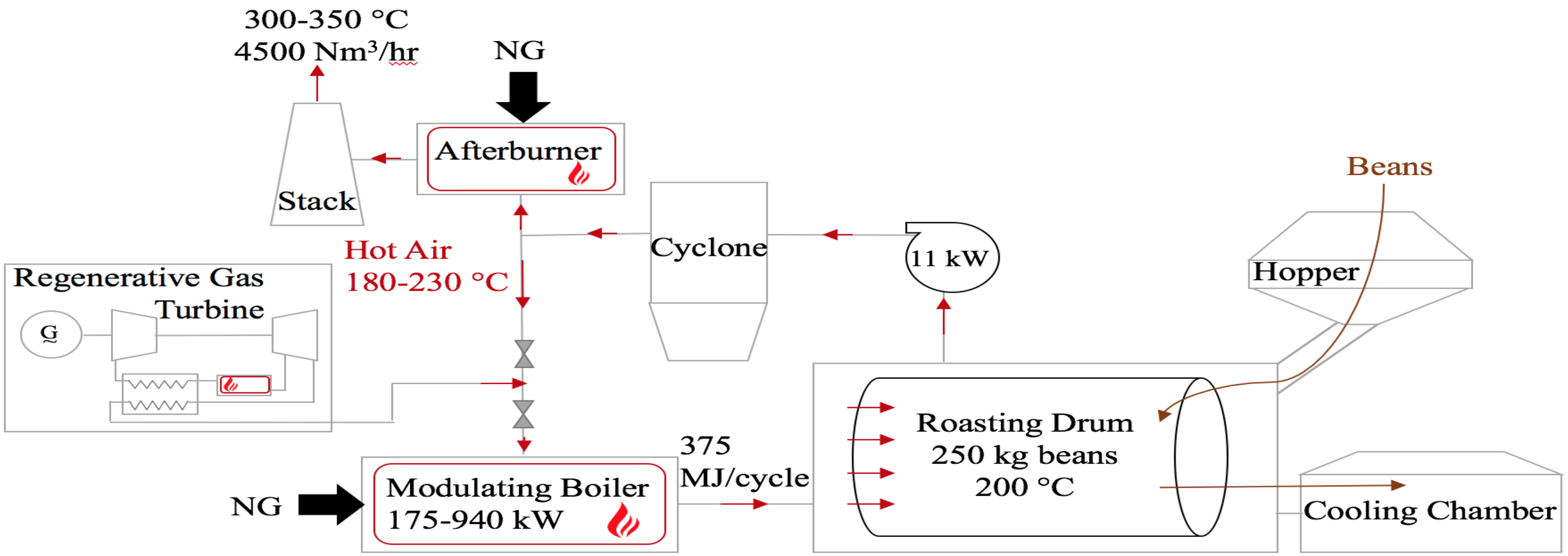
Case study 1: Regenerative gas microturbine for on site CHP – size 200 kWe (benchmark)

Case study 2: ORC fed by intermittent heat discharged by the process – size 26 kWe

Case study 3: Non-regenerative gas microturbine to match on site heat demand – size 200 kWe

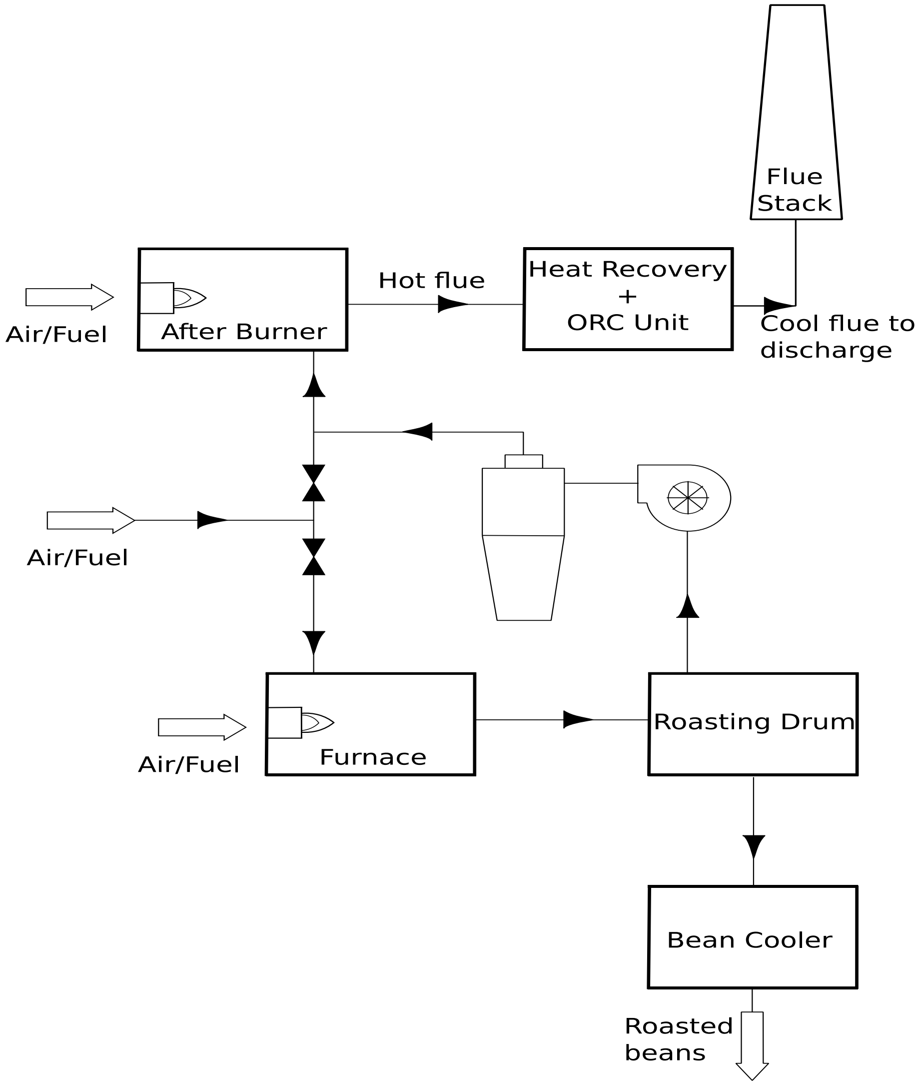


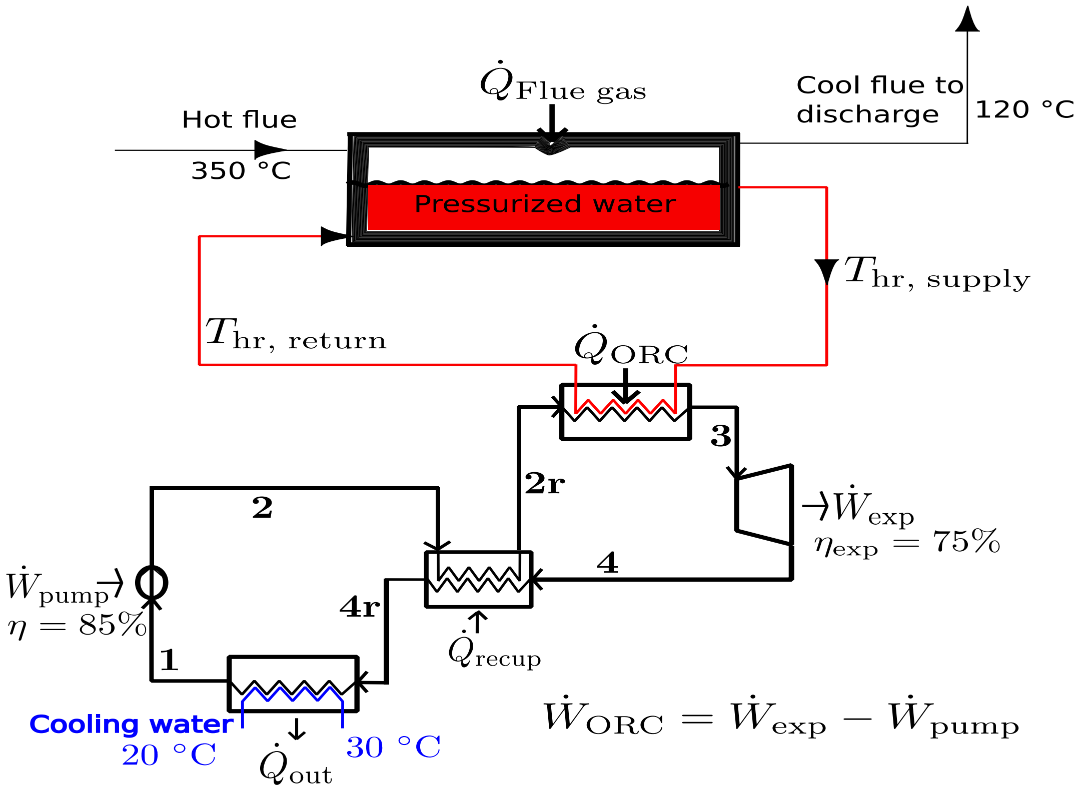
Case 1: Regenerative CHP-MGT



MGT size	Exhaust Flow Rate	Outlet Temperature	Recoverable Heat
200 kWe	1.3 kg/s	270 ℃	58.3 MJ

Case 2: Waste-heat recovery via ORC





$$\dot{W}_{\mathrm{ORC}} = \dot{W}_{\mathrm{exp}} - \dot{W}_{\mathrm{pump}}$$

$$m_{\mathrm{hr}} c_{\mathrm{p,hr}} \frac{\mathrm{d}T_{\mathrm{hr}}}{\mathrm{d}t} = \dot{Q}_{\mathrm{ORC}} + \dot{Q}_{\mathrm{hr}}(t)$$

$$\dot{Q}_{\mathrm{ORC}} = \dot{m}_{\mathrm{hr}} c_{\mathrm{p,hr}} \left(T_{\mathrm{hr,sup}} - T_{\mathrm{hr,ret}}\right)$$

Case 2: Waste-heat recovery via ORC

	$T_{hr,sup}$ = 120 °C					$T_{hr,sup}$ = 150 °C				
Working fluid	Butane	Pentane	R227ea	R245fa	R1234ze	Butane	Pentane	R227ea	R245fa	R1234ze
$\dot{W}_{ORC}$ (kW)	26.2	25.9	26.6	26.3	26.3	30.3	29.8	32.3	30.4	33.2
η_{ORC} (%)	9.07	8.99	9.21	9.10	9.13	10.5	10.3	11.2	10.5	11.5
P_{evap} (bar)	11.1	4.0	23.4	8.8	24.5	16.2	5.5	27.8	13.6	34.5
P_{cond} (bar)	3.73	1.14	6.84	2.46	7.52	3.73	1.14	6.84	2.46	7.51
$\dot{Q}_{ORC}$ (kW)	288	288	288	288	288	288	288	288	288	288
$\dot{Q}_{out}$ (kW)	262	263	262	262	262	258	259	256	258	255
$\dot{Q}_{recup}$ (kW)	44.8	43.1	58.3	42.8	31.9	11.9	20.1	98.7	11.6	45.7

Case 3: Non-regenerative CHP-MGT

Replacement of existing modulating boiler and set up of inline afterburner

	Case 3 compared to Case 1
Turbine outlet temperature	Higher
Electrical efficiency	Lower
NG consumption	Higher

- Unitary cost similar to Case 1 as afterburner controls cost similar to MGT regenerator
- Overall costs depends on gas/electricity price ratio

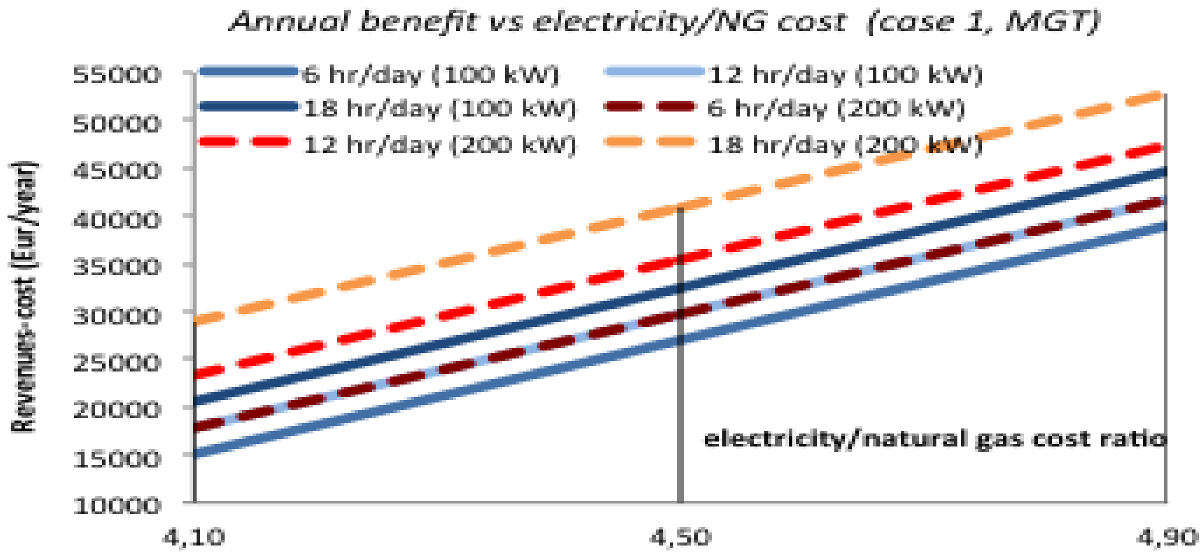
Technoeconomic analysis

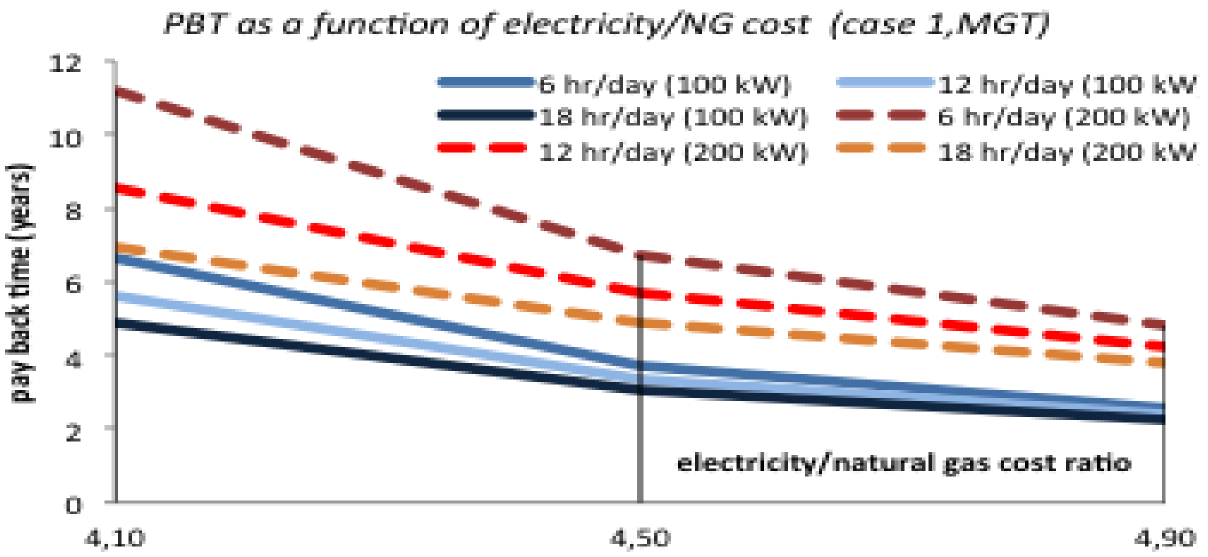
	Case 1	Case 2	Case 3
Plant size (kWe)	200	26	200
NG saved (Nm^3/cycle)	1.65	-	10.28
Electricity generated (kWh/cycle)	33.33	4.3	33.33
NG consumption (Nm^3/cycle)	11.31	-	19.90
Saving (Eur/cycle)	5.65	0.65	8.96
Total cost (fuel +O&M) (Eur/cycle)	4.75	0.06	8.06
Balance (Eur/cycle)	0.9	0.59	0.9
Investment (Eur)	200,000	120,000	180,000
Payback time (cycles)	222,200	203,400	200,000
Payback time (6 hours per day operation) (years)	23.7	21.7	21.3

Key results – 1

Case study 1: Natural gas microturbine

•Profitability increases with electricity/natural gas cost ratio and production capacity
•Can better match electricity demand at higher production capacity



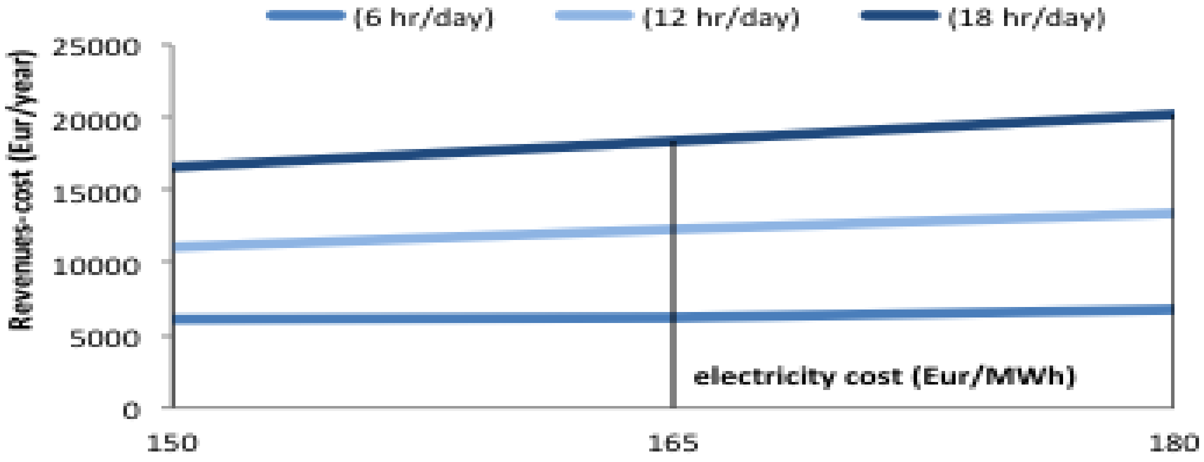


Key results – 2

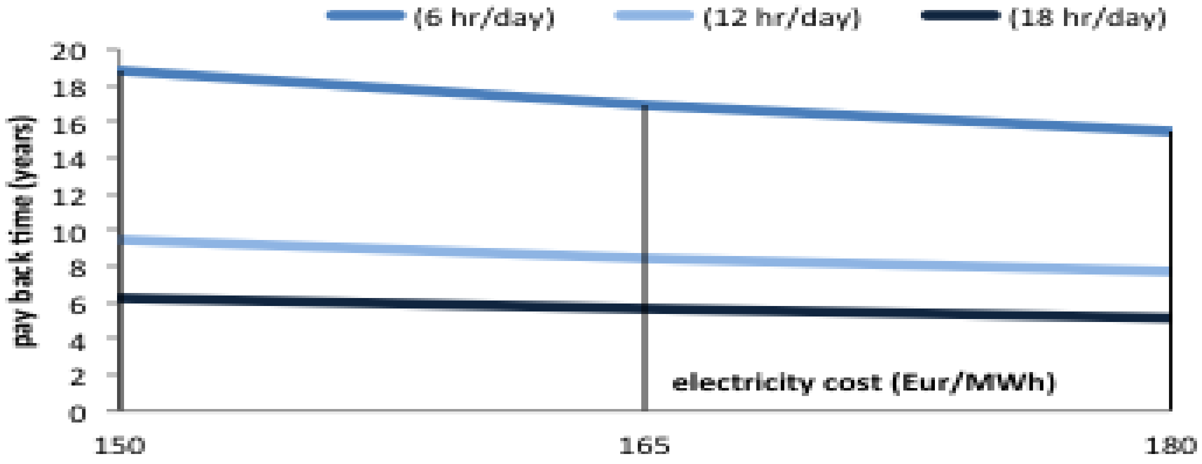
Case study 2: Intermittent waste heat recovery via ORC

•Highly influenced by production capacity
•At high production capacity, MGT is more profitable than ORC

Annual benefit vs electricity cost-case 2 ORC



PBT (years) as a function of electricity cost-case 2 ORC



Conclusions

- Low-grade waste-heat recovery from food processing has large potential and ORC is a promising technology (working fluids, cycle configurations)

- Waste-heat recovery from coffee roasting via ORC is profitable only at very high production capacity, otherwise on site MGT based CHP is more competitive

- Integration of on-site CHP via gas microturbine and intermittent waste heat recovery via ORC should be explored, to increase whole system flexibility and enhanced demand response strategies

- Optimal coupling of demand and supply is a key factor: matching intermittent heat source and variable demand could maximize benefits

Thank you!

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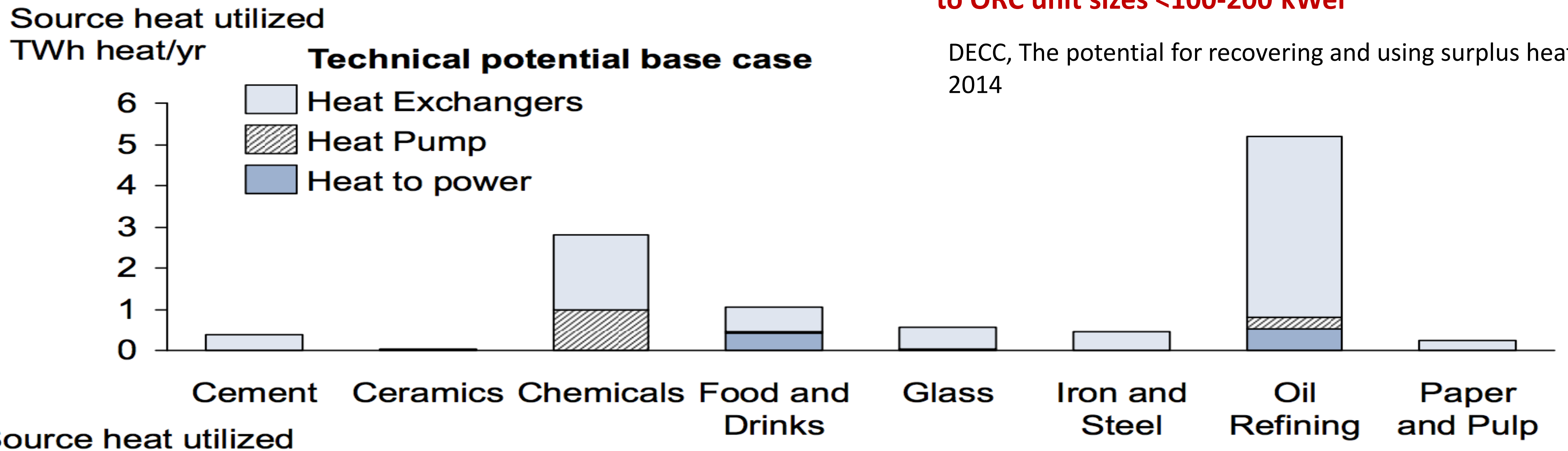
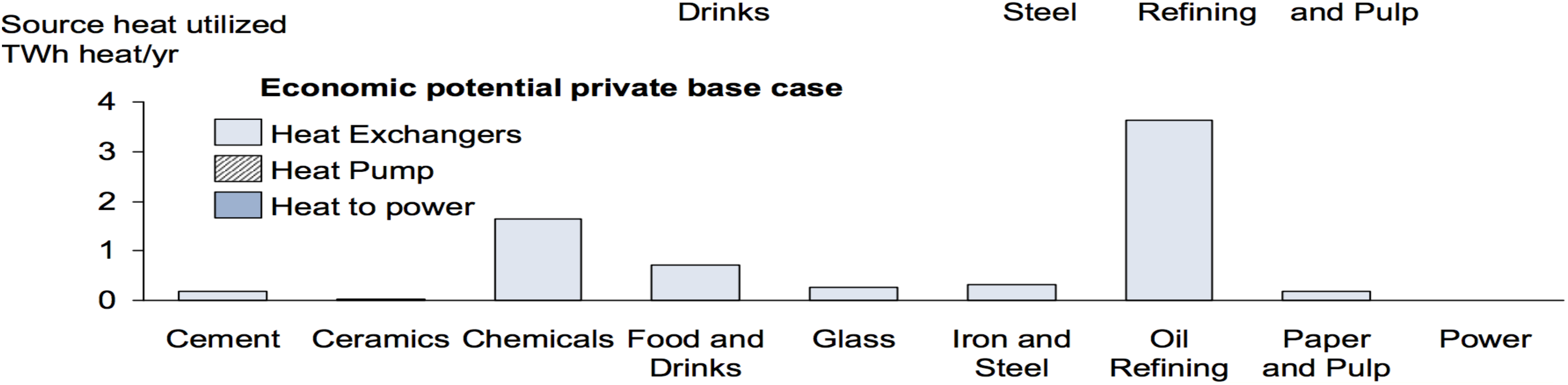
Waste heat recovery options

~70% of industrial sites have streams with <1 MWth corresponding to ORC unit sizes <100-200 kWel

DECC, The potential for recovering and using surplus heat from industry, 2014





ORC technology

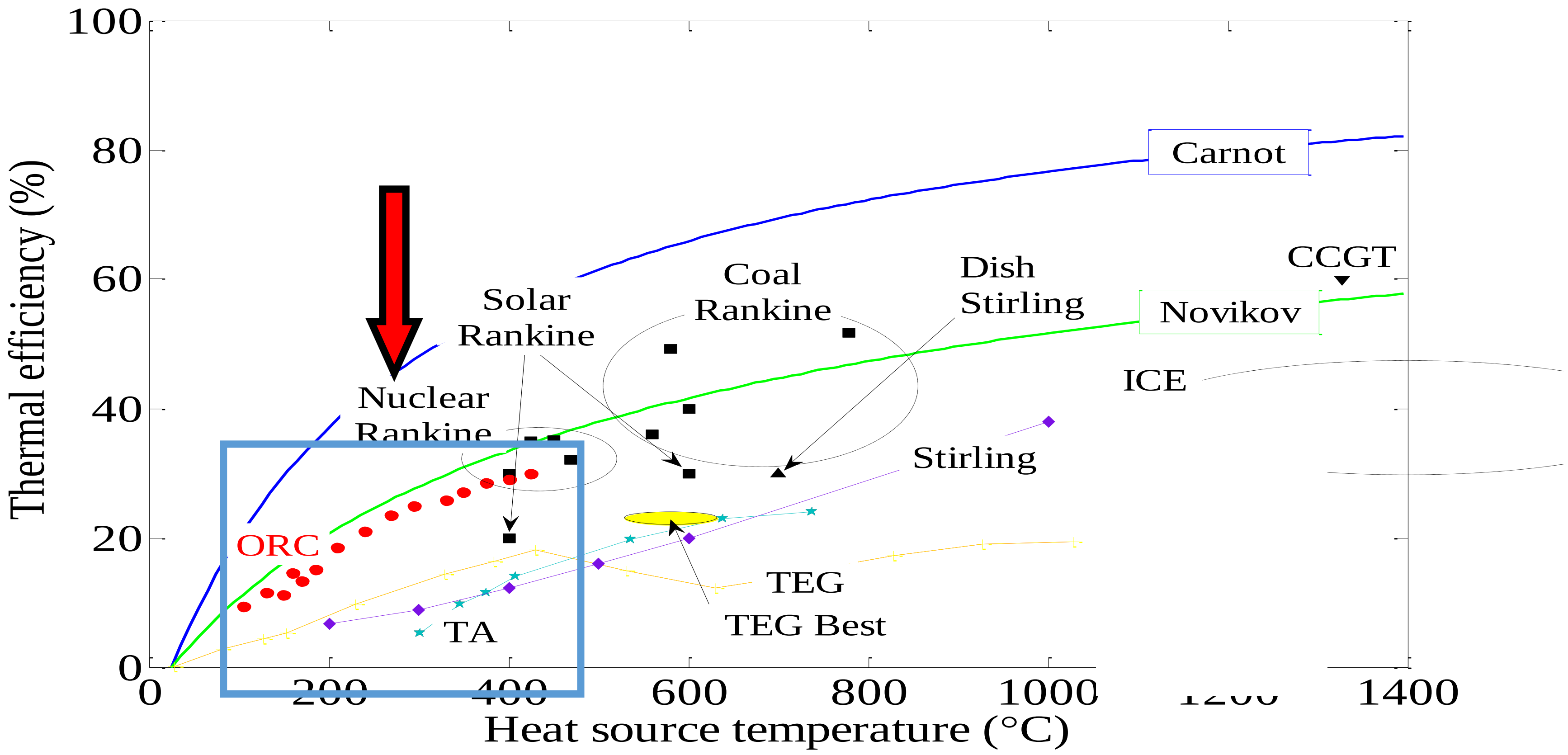
•low- to medium-grade heat (below 100 °C to 300-400 °C)

•ORC systems significantly outperform competing options: thermoelectric generators (TEGs), Stirling and thermoacoustic (TA) engines.

•Efficiencies in excess of 25% are achievable at higher temperatures (i.e., above 300 °C).

•~600 plants currently in operation worldwide and a cumulative capacity of 2 GW.

•Commercially available systems are much larger than those proposed here (up to 100-200 kWel).

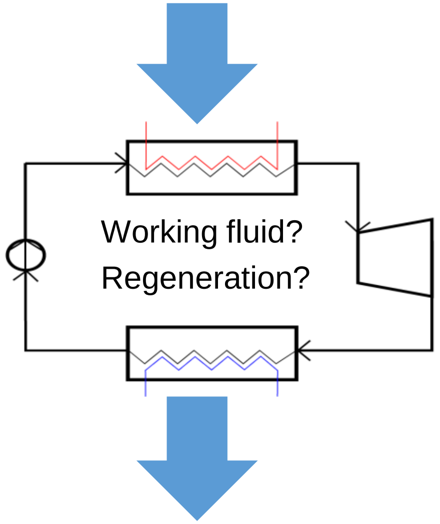


ORC Systems

- Standard operation with 100-300 ºC heat gives ~8-25% thermal efficiency, ~5-10 yr payback
- **Levelised energy cost (LEC) over 25 years = ~Eur30-40/MWh** for **ORC**
  - **~Eur100-200/MWh** for **renewables**
  - **~Eur50-100/MWh** for **conventional power generation**

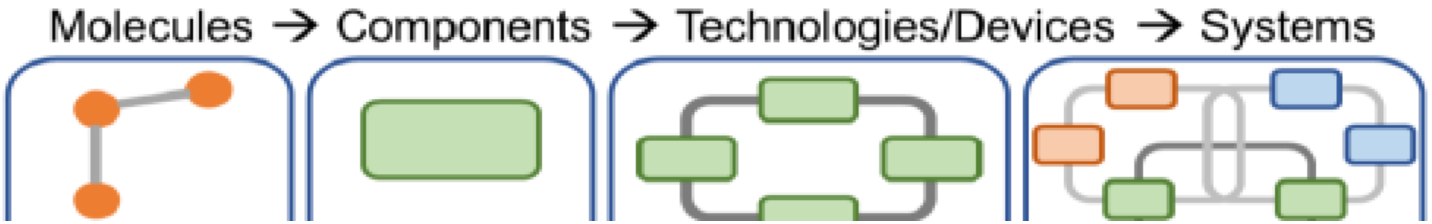
ORC technology and research challenges

Heat sources: waste-heat, geothermal, solar, CHP, biomass, bottoming cycles



Heat sinks: Cooling water, ambient air, lower grade heat demand

- increase the **efficiency** of the ORC (working fluids, cycle configurations)
- design **cost** optimal ORCs (cost components modelling, learning curves, trade-offs and and thermo-economic analyses
- optimal **coupling** of demand and supply: part load operation, matching intermittent heat source and variable demand
- **whole systems integration**: multi-fuel energy sources, thermal storage, energy networks integration and demand response strategies



ORC thermo-economic optimization

Purchase Cost Correlations:

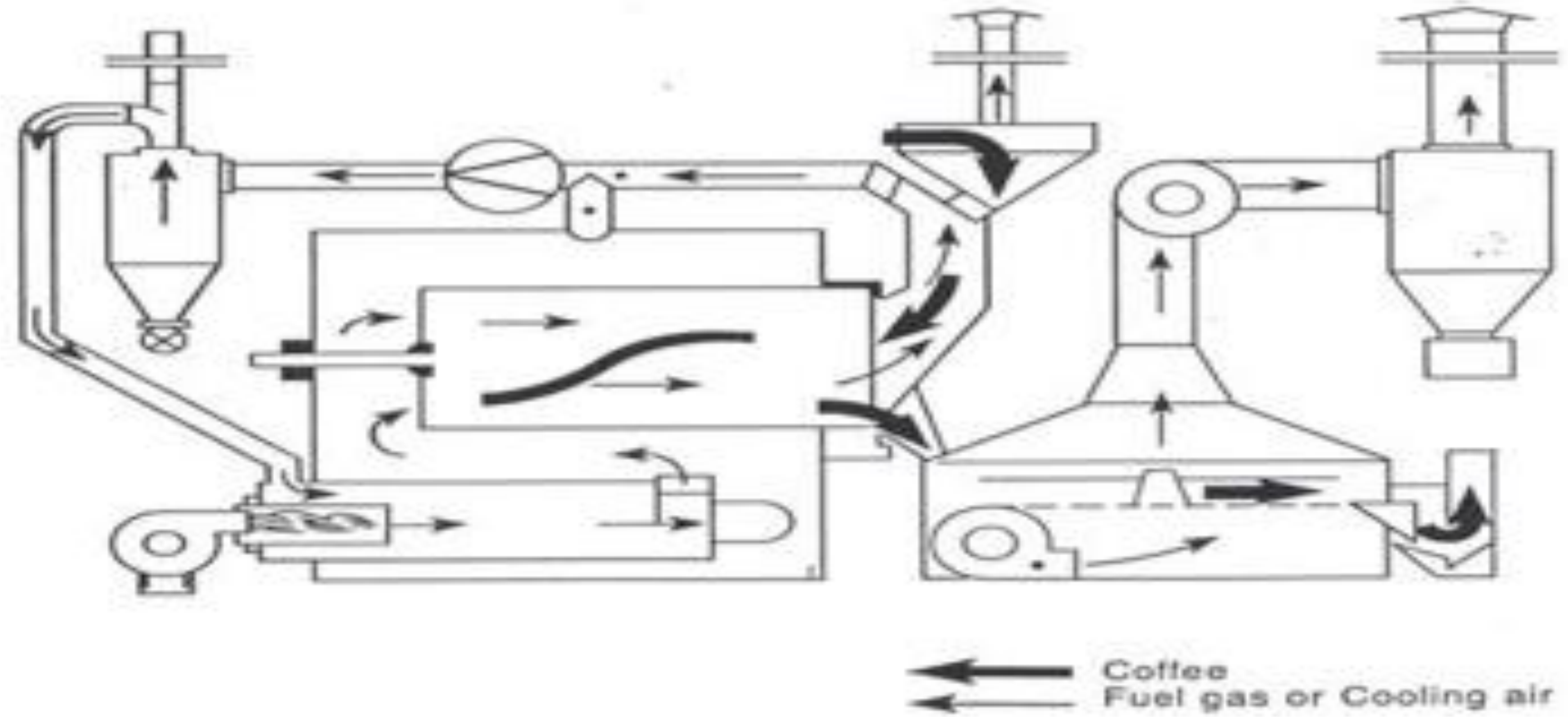
- ❑ Originate from the chemical industry plant cost estimations
- ❑ Steps:
- ✓ Calculate basic cost
- ✓ Estimate impact of materials, pressures etc. on the basic cost
- ✓ Estimate purchase cost
- ✓ Account for installation, contractors fees etc. in the bare module cost
- ✓ Calculate total cost – Lang Factors are used x1.18

- ❑ Seider 2003 or 2009 $$C_p^0 = F \exp(K_1 + K_2 lnA + K_3 ln^2 A)$$

- ❑ Turton 2001 $$C_p^0 = F\ 10^{(K_1 + K_2 log_{10} A + K_3 {log_{10}}^2 A)}$$

- A: The specific parameter for which its correlation is designed (area, pressure, volume flow rate etc.)
- Ki: Values from Tables for different components
- F: Factors to account for different pressure, materials, etc. (Correlations for those F factors also exist)

Intermittent heat recovery: the coffee torrefaction process



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Operation 6 hours/day
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Modulating boiler size 1 MWt

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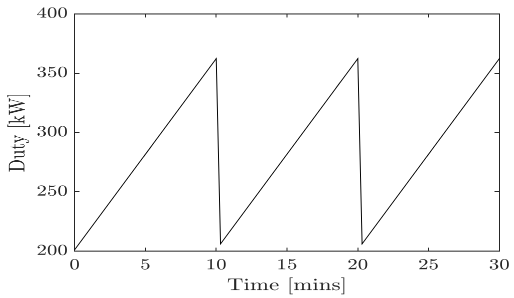

Duty cyce of thermal storage coupled to ORC and fed by the intermittent heat source

Saicaf torrefaction process: case studies definition

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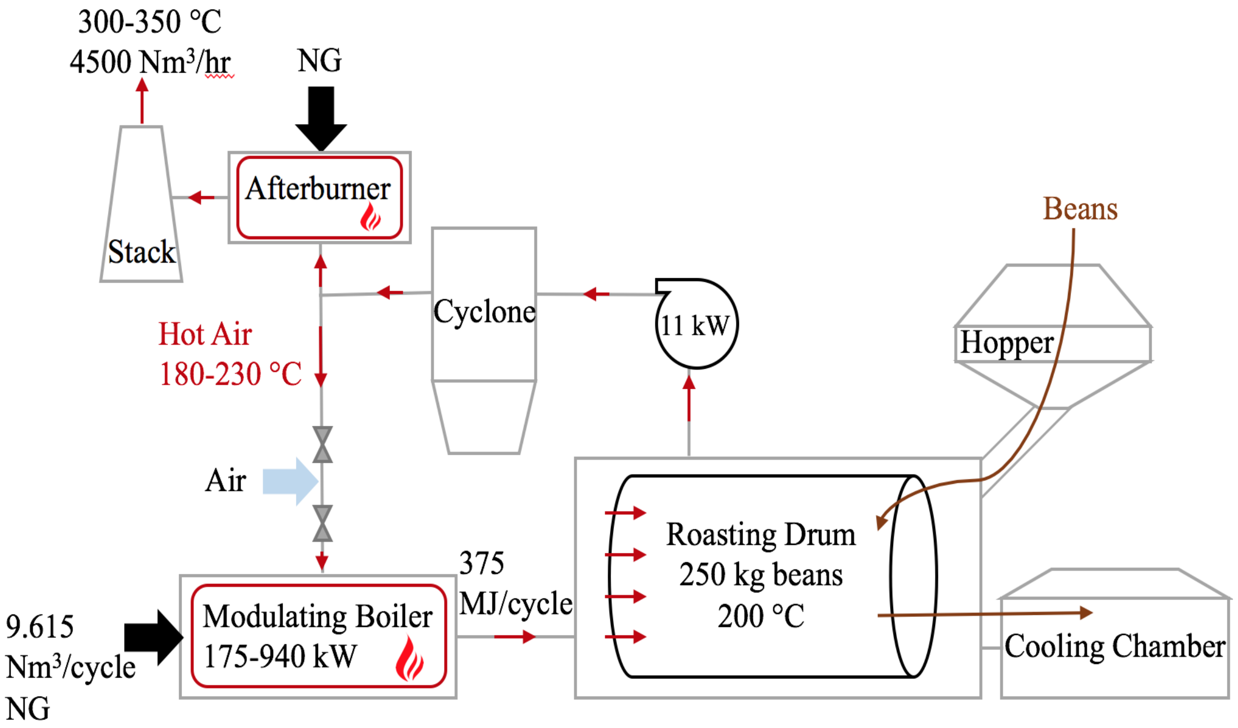
Case study 2: ORC fed by intermittent heat discharged by the process – size 26 kWe
Case study 3: not regenerative gas microturbine to match on site heat demand – size 200 kWe (reduced electric efficiency but higher heat availability for torrefaction process)



Main Conclusions

- Low grade waste heat recovery from food processing has large potential and ORC is a promising technology (working fluids, cycle configurations)
- Cost is the main barrier, and cycle configurations with max efficiency often present highest costs – thermoeconomic optimization required
- Waste heat recovery from coffee roasting via ORC is profitable only at very high production capacity, otherwise on site MGT based CHP is more competitive
- Integration of on site CHP via gas microturbine and intermittent waste heat recovery via ORC should be explored, to increase whole system flexibility and enhanced demand response strategies
- optimal coupling of demand and supply is a key factor: matching intermittent heat source and variable demand could maximize benefits
- multi-fuel energy sources, thermal storage, energy networks integration and demand response strategies are crucial to facilitate penetration of these technologies