Technical and economical experiences with large ORC systems using industrial waste heat streams of cement plants

2. ORC-Symposium - 6. November 2015- HSLU

Hochschule Luzern - Technik & Architektur Horw

Urs Herzog - Holcim Technology Ltd

LafargeHolcim

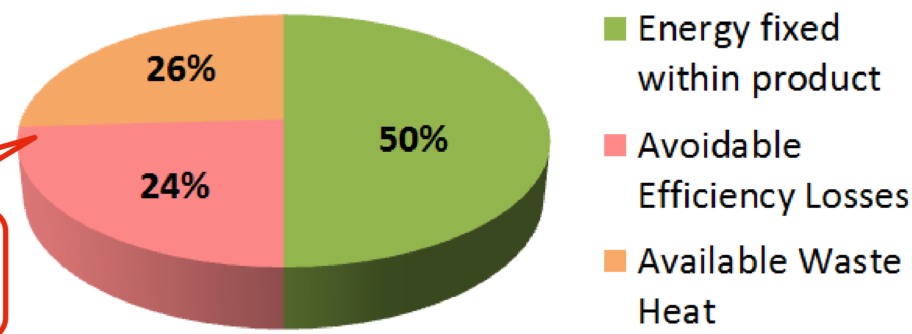
Agenda

- Waste Heat Streams and Potential for Waste Heat Recovery in Energy Intensive Industries (EI-Industry)
- Waste Heat to Power (WHP) Option in Cement Industry
- Holcim ORC - WHP Projects - Key Data
- ORC-WHP Experiences made / Learning’s
- Economics
- Findings & Conclusion

There exist a significant potential in industry sectors worldwide to improve energy efficiencies and valorize waste heat streams

- Studies[1)] estimate that 20-50% of all energy inputs into industrial process leaves in the form of waste heat.
- The global total final energy consumption of the industry was 107 EJ in 2011[2)]
  - Overall efficiency is estimated to be ~ 50%
  - The total saving by applying Best Available Technology (BAT) is estimated to be 25 EJ (= 24%)
  - The rest is considered to be wasted as heat streams in solid, liquid and gaseous forms at different temperatures levels (25 – 800 °C)

Total Energy Consumption
World Industry; 107 EJ /yr [2)]



Industrial Waste Heat Streams

1) Energetics and US DOE, 2004
2) M. Bendig 2015, (IEA 2004e)

Petroleum & coal, chemical, iron & steel and non-metallic mineral product gave highest waste heat usage potential

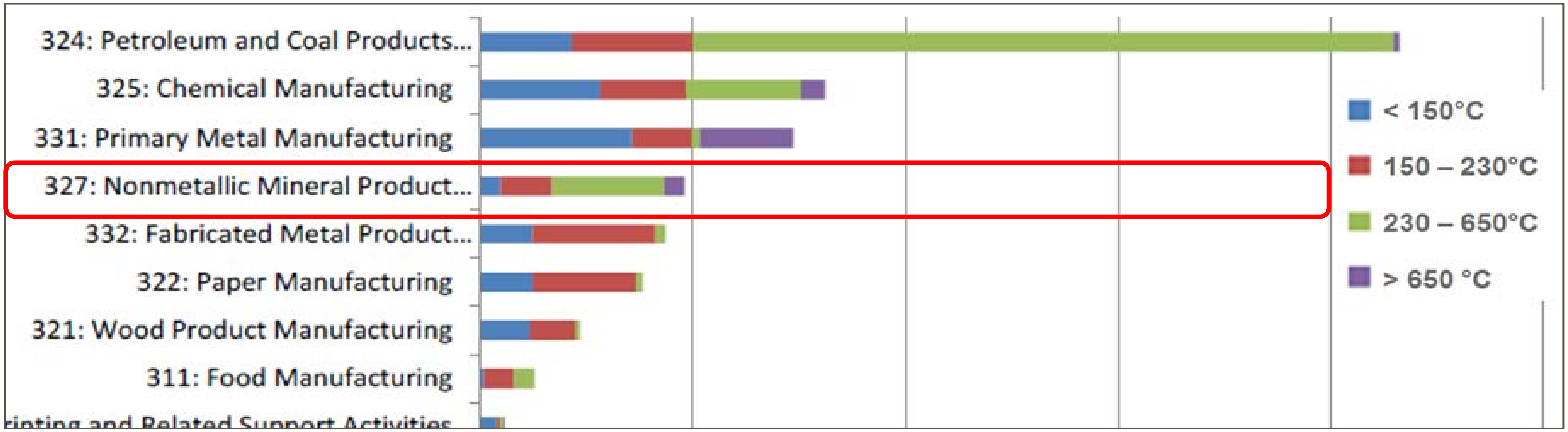
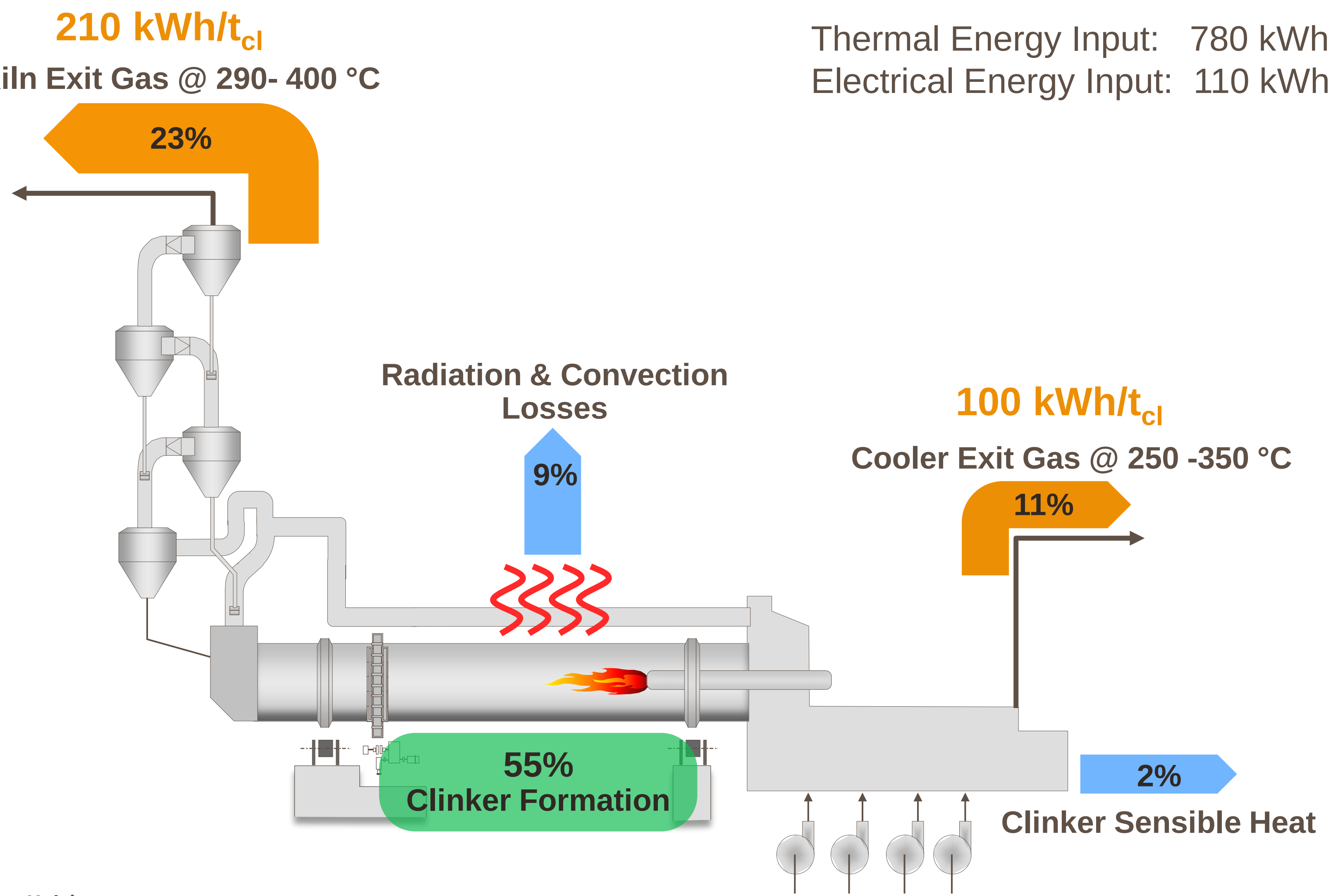


Fig: US industries; manufacturing sector waste heat Inventory (list not exhaustive)
(source: ICF International study 2015 [4)])

- Largest potential is within Petroleum & coal products; Majority of waste heat stream is on temperatures above 230°C
- The 4 top potential industries have a significant waste heat streams with temperatures above 230°C
- Waste heat valorization potential in Cement as part of "Non-Metallic Mineral Products" will be presented in more details

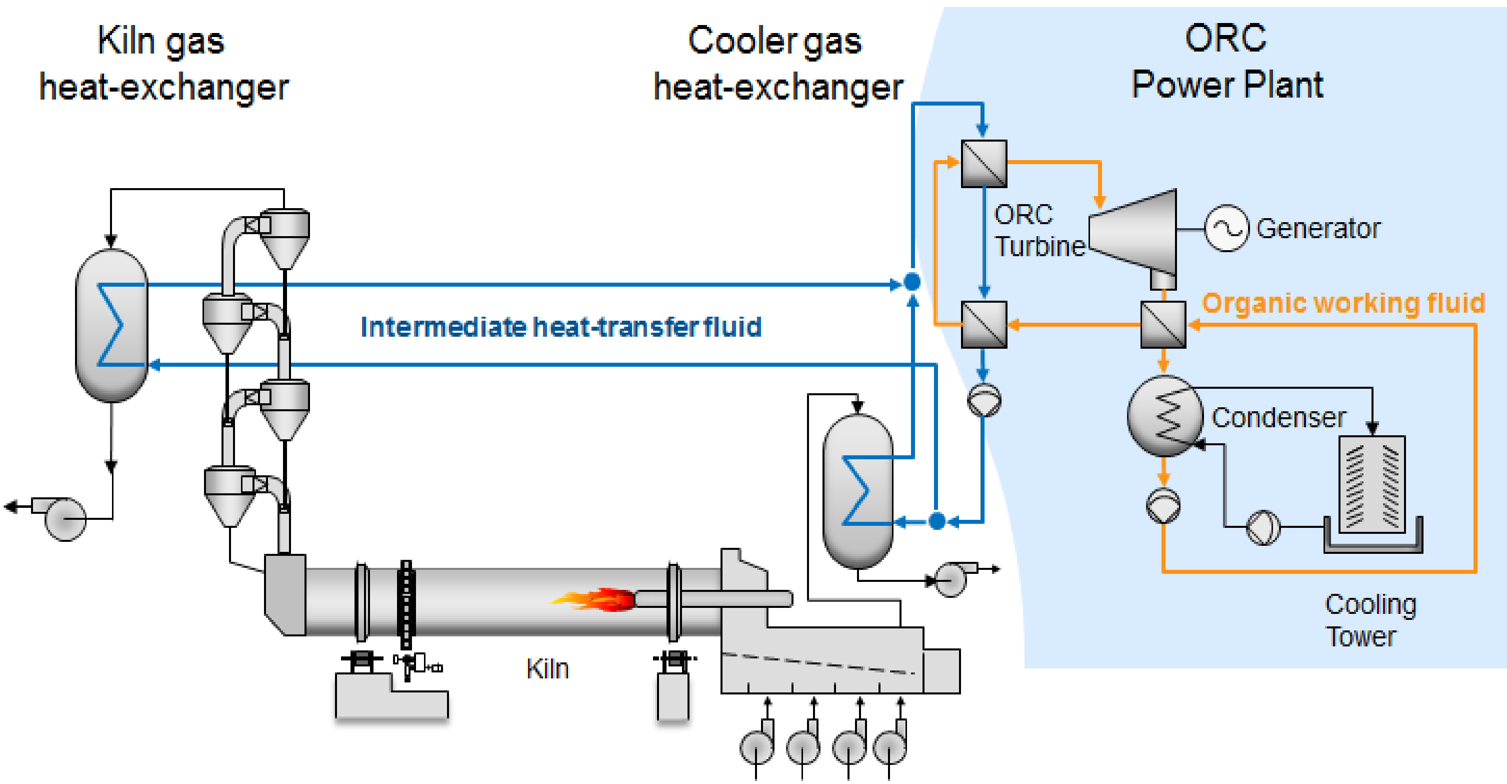
Energy Flow Diagram of a cement plant clinker burning kiln
Thermal Energy Input & Waste Heat Streams

Thermal Energy Input: 780 kWh / tcem
Electrical Energy Input: 110 kWh / tcem



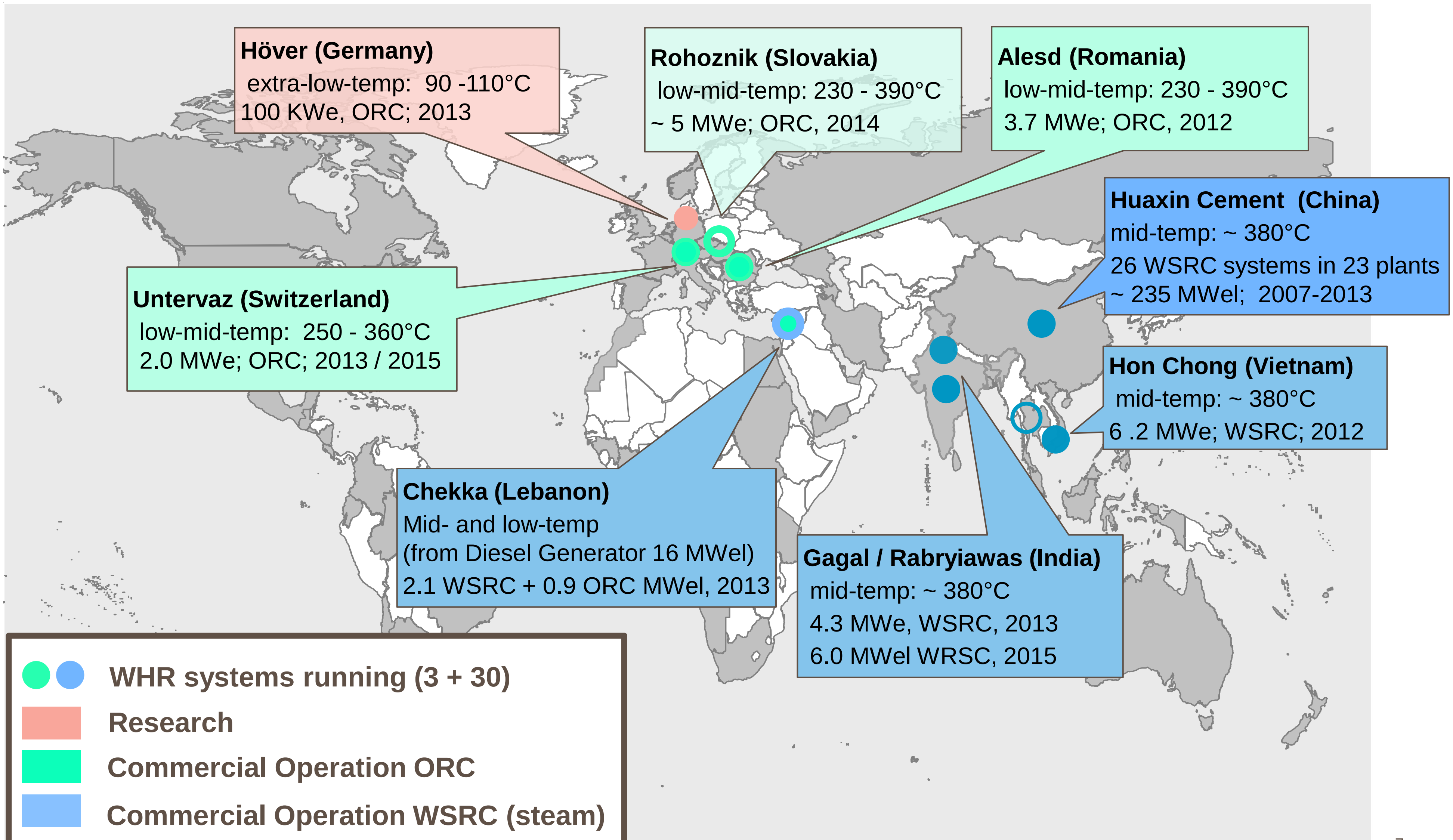
Cement kiln Waste Heat to Power (WHP) Systems mostly use Water-Steam-Rankine Cycle (WSRC). -- For temperatures < 300°C Organic-Rankine Cycle (ORC) is the better option.

- Momentary ~ 900 WHP system are running worldwide (highest number in China)
  - Majority of systems using steam turbines (WSRC) at temperatures > 350°C
- Average yield of WHRP in cement is ~ 30-40 kWh_{el}/t_{cl}
- Less than 10 WHP system using ORC concept with the objective to use low temperature waste heat streams



- Two heat-exchangers designed for high dust load (cleaning system)
- Two intermediate heat transfer loops (either thermal oil or pressured water)
- ORC cycle with recuperator (hydrocarbon, silicone or refrigerator fluid)
- Air or water (evaporation) cooled condenser

In the field of Waste Heat to Power, Holcim gained experiences from numerous commercial operating and research projects
(since 2008 Holcim build more than 35 WHP plants)



In 2012 Holcim Romania commissioned the world first ORC-WHP power plant using kiln and cooler gas streams

Kiln exhaust
Heat-exchanger 2

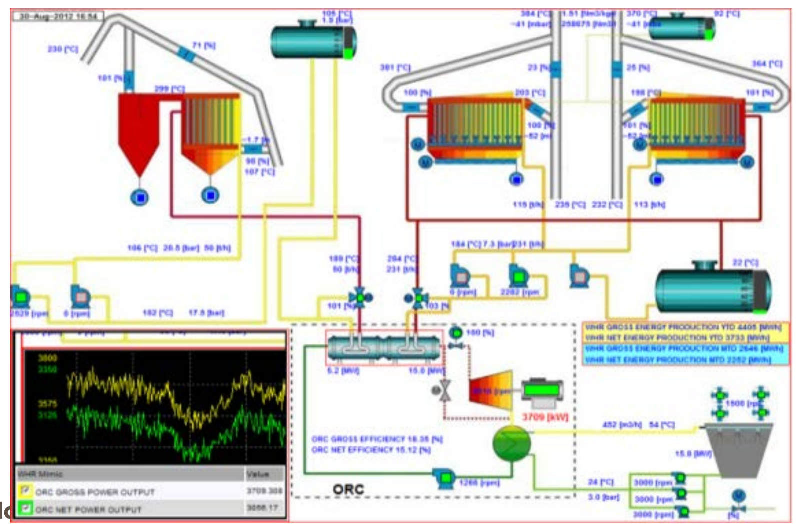
Cement kiln system with two exhaust gas heat-exchangers

Kiln exhaust
Heat-exchanger 1

ORC-WHR power plant with 4 MWel (gross) power output

ORC power plant building

ORC power plant with evaporator, recuperator and condenser



ORC Flow Sheet
three heat sources:

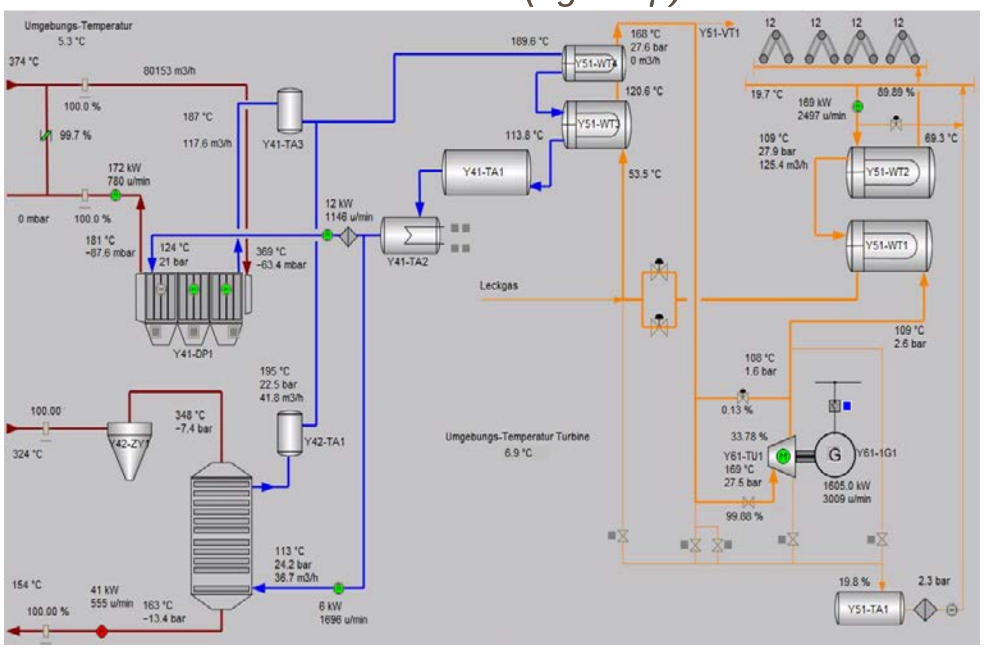
- kiln exhaust exit 1 (left)
- kiln exhaust exit 2 (right)
- cooler air exit

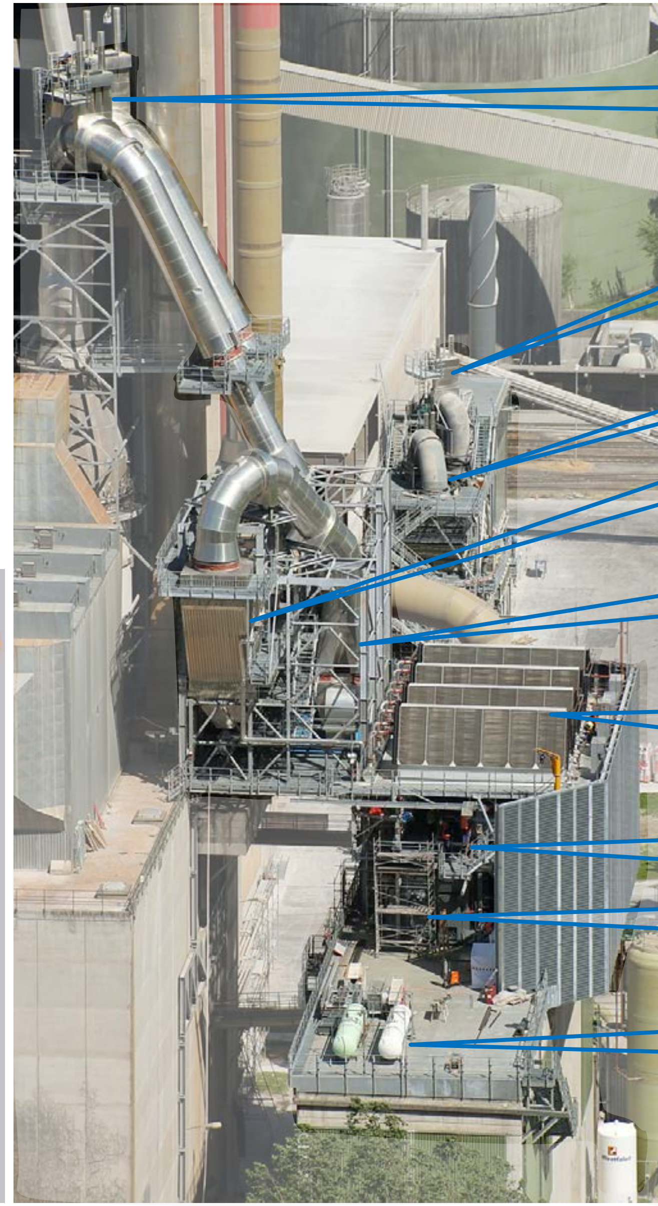
Holcim Switzerland commissioned 2013 / 2015 a “roof-top” ORC-WHP power plant using kiln and cooler gas streams

Cement kiln WHP system with two heat sources:

- kiln exhaust
- cooler air

ORC Flow Sheet
with two gas heat-exchangers *(left)*
ORC fluid pre-heater and evaporator *(middle)*
ORC turbine & generator *(right bottom)*
and Air cooled condenser *(right top)*



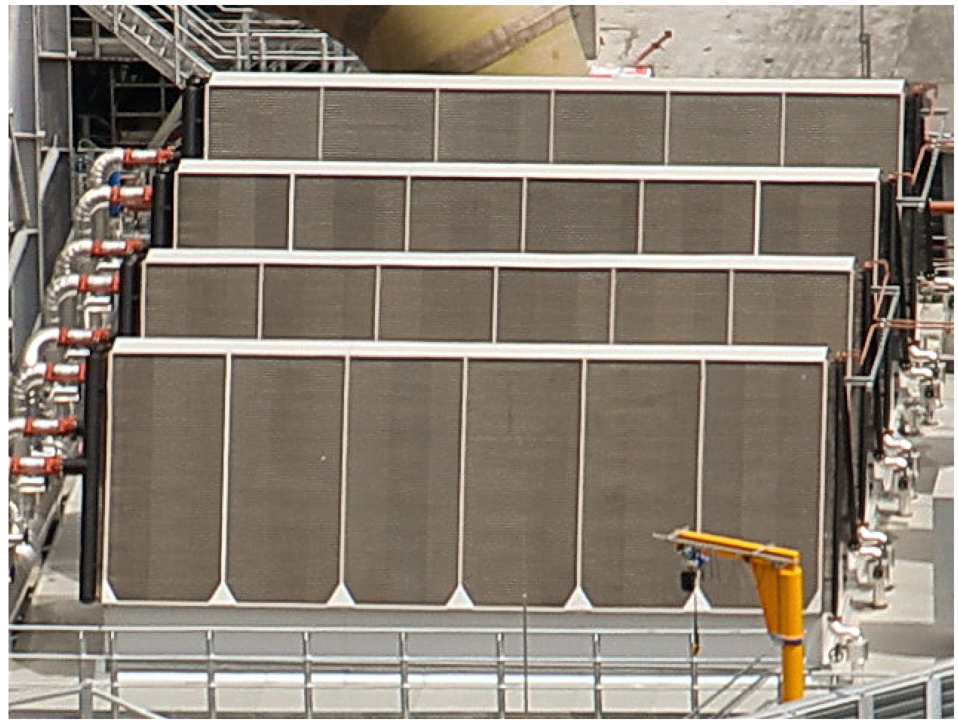


Untervaz WHP ORC-WHR power plant with 2.3 MW_{el} (gross) 1.9 MW_{el} (net) power output

Horizontal gas-flow pre-heater
HEX bare tubes with dust rapper

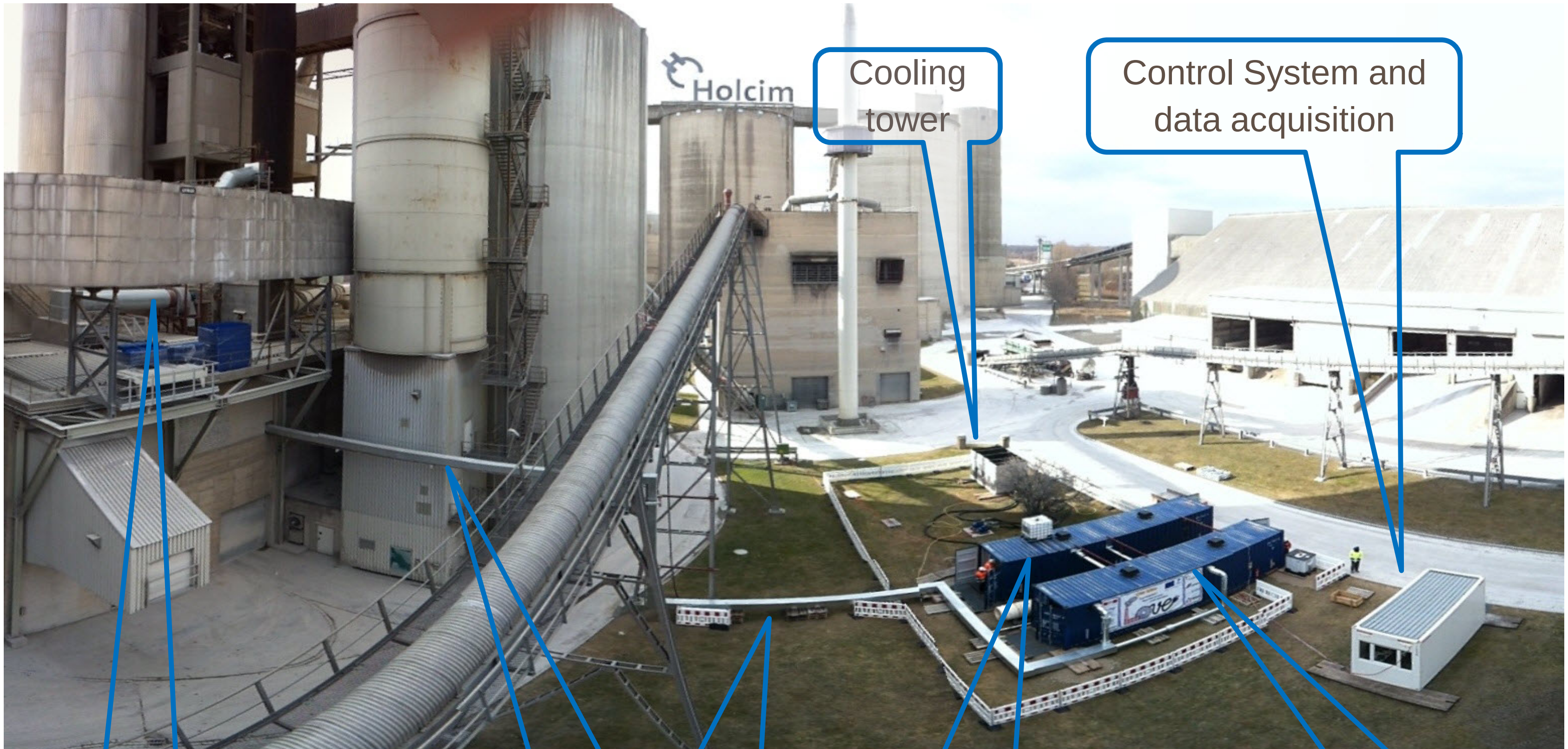
Air Cooled Condenser (four modules)

- no water consumption; no plume
- noise issue; higher aux. consumption (4x48kW)



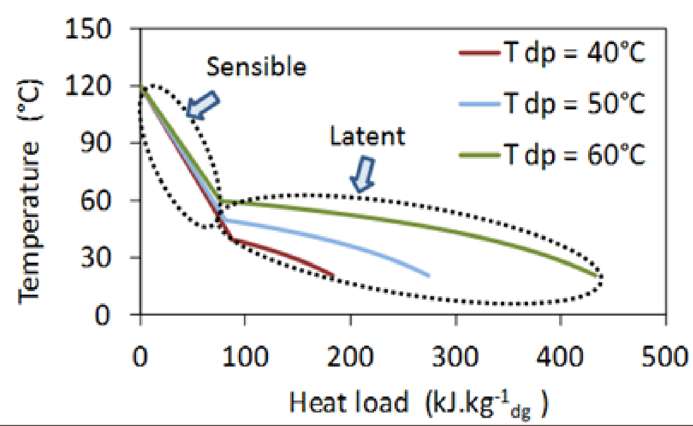
Höver cement plant extra-low heat WHP research pilot (2013) EU FP7 program: "LOVE" project

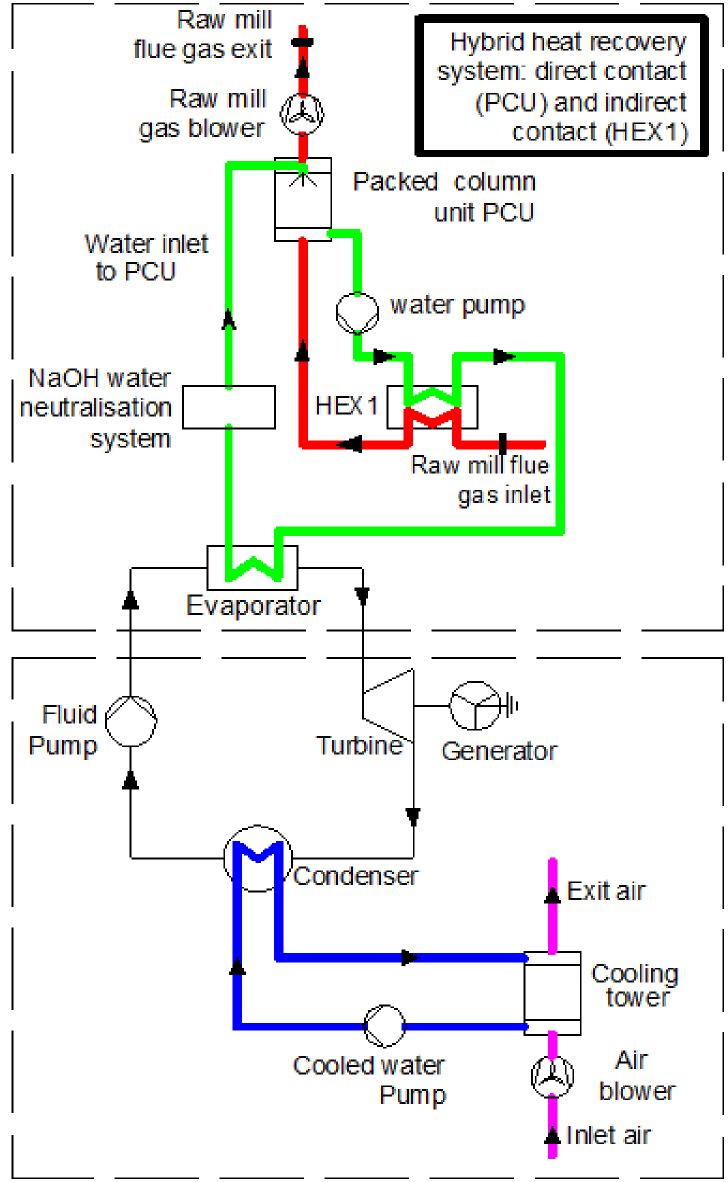
"Low-temperature heat valorization towards electricity production" (waste stream gas temperature < 120°C)



Hybrid heat-exchanger *(patented)* to extract latent heat at extra-low temperatures from wet exhaust gas

➢ **Heat load availability**





Heat Recovery and ORC System Parameter of WHP installed by Holcim (2008 to 2015)

Plant	Type / Size Inlet Temp	Heat-Exchanger Make / Type Cleaning / Spare Cap.	Heat-Transfer Coupling	ORC turbine Make / Type / Stages/ Gear / Axe-sealing	ORC fluid Evaporation-temp / Gross Eff	Cooling
Alsed; Romania	Commercial 4 MW_{el} 230 / 390°C	*JFE* H-cross-flow Hammering >100% reserve	Thermo-Oil Press-Water Serial	*Turboden* Axial, Multi-Stg Gearless Oil sealing	Silicone-oil (MM) ~ 240°C 19.3%	Wet Water-evaporation
Untervaz; Switzerland	Commercial 2.3 MW_{el} 250 / 360°C	*HTA* H-cross-flow Hammering 60% reserve	Press-Water Parallel	*Atlas-Copco* Radial, Single-Stg Gear N2 sealing	Isobutane = 140-160°C ~ 16-17%	Dry Air cooled
Rohhoznik; Slovakia	Commercial ~ 5 MW_{el} 310 / 360°C	*Transparent* V-parallel-flow Hammering >100% reserve	Thermo-Oil Parallel	*Turboden* Ax-Rad, Multi-Stg Gearless Oil sealing	Cyclo-pentane ~ 210°C ~ 21%	Wet Water-evaporation
Höver; Germany	Research 100 kW_{el} < 120°C	*Armines* Direct-condensing self-cleaning	Water	*Cryostar* Radial, Single-Stg Gearless Variable-speed hermetic housing	R 245fa (R1234yf) = 64°C !! 5.9-6.2 %	Wet Water-evaporation

Experiences made with ORC type WHP systems

- Performance of ORC Systems
  - Exhaust gas input temperatures: 360 – 390°C
    - Efficiency (gross) 16 - 21%; depending on HEX, ORC system and fluid
    - Internal (captive) consumption ~15% - 20% (water-steam system ~ 7%)
    - Extra-low temperature system with 105°C gas temp. → Eff = 6%
  - Reliability / Availability
    - All WHP plant have a high availability: 96-98%
      - Heat exchanger design is crucial (heat transfer area and dust removal system)
  - Operation:
    - Operation & Maintenance Cost = 2.4 €/MWh;
      - Fully automatic operation (no additional shift personnel)
      - Water cooling systems need chemical additives and regular water analysis

- System Cost / Cost of power produced
  - Investment cost: 3'300 – 4'500 k€/MW (extreme = 5500 €/MW)
  - Power cost (LCOE): 81 – 109 €/MWh

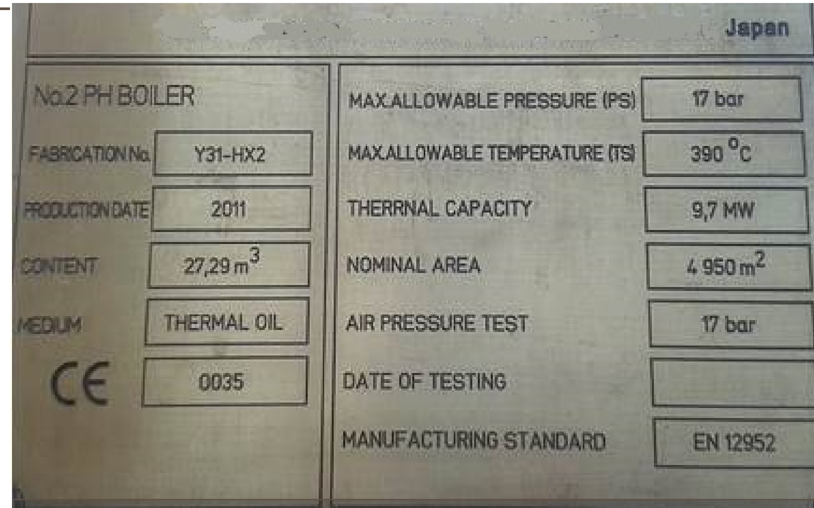
Issues / Learnings (1)
Overall Efficiency / Complexity / Cost Driver

- Gas Heat-Exchanger (HEX) & Heat Transfer
  - Proper design (cross-flow) and sufficient exchanger surface (+ 100% reserve)
  - Adequate dust removal (hammering) and transportation system
  - Heat Transfer Loop: Non-pressured system preferred (Thermal-oil)
    - Best Option: Avoid Heat Transfer Loop (Direct heat concept)
- Turbine type
  - Multi-Stage expander (to fully use available pressure level)
    - Good part-load performance (WHP source vary widely – in contrast to geo-thermal plants)
  - Low rotation / gearless
  - Oil / liquid turbine-axe sealing (avoid addition N2 system)
- ORC fluid
  - Select fluid to match temperature level (supplier-design)
  - Flammable fluid (hydrocarbons) require EX-Design

- Cooling
  - Water-evaporation Systems (Wet) are more effective, need less energy and are lower in cost compared to Air Cooled Condenser - but they need water chemicals and regular care

Issues / Learnings (2)
Exhaust Gas Heat-Exchanger (HEX) Size & Design

- "Japanese" Design:
  Thermal capacity: 9.7 MW
  Exchanger Area: 4950 m^2
  Specific Area: 0.5 m^2 / kW



- "German" Design:
  Thermal capacity: 10.4 MW
  Exchanger Area: 3110 m^2
  Area reserve: 60 %
  Specific Area: 0.3 m^2 / kW

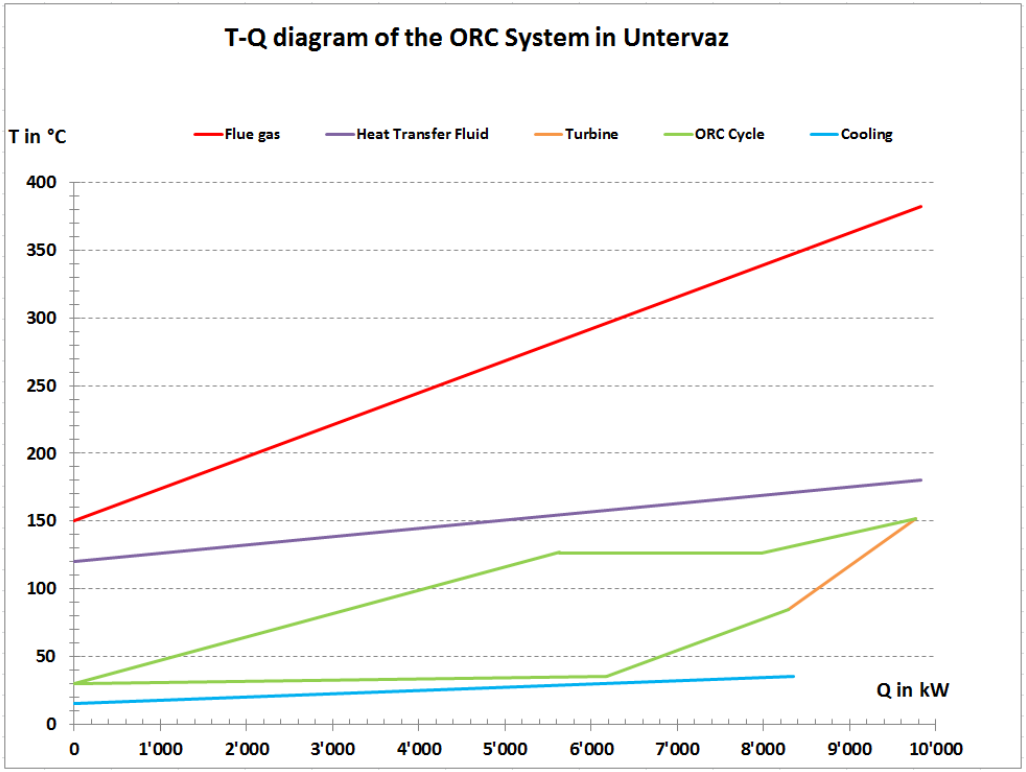
Innovationen für erhöhte Wirtschaftlichkeit und Umwelt

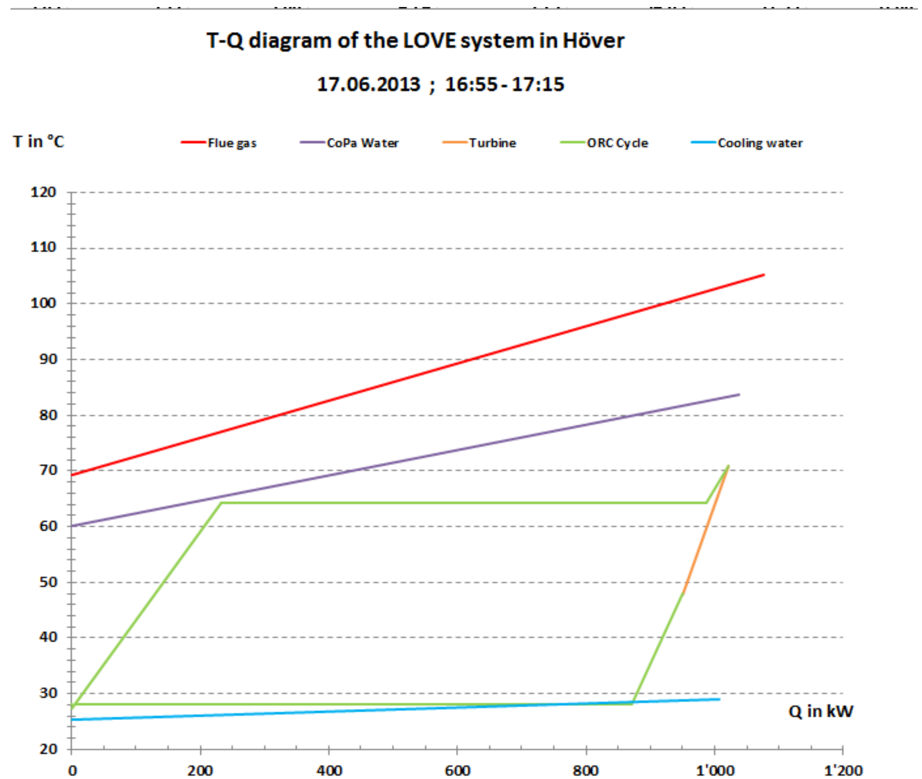
Technische Daten für Abluft-Wärmetauscher: WT-A/HW /

Betriebszustand / Abluft-Wärmetauscher			Saubere Heizflächen
Betriebspunkt			Design
Abgasmassenstrom (50 kg/sec.)	kg/h		179.909
Abgasvolumenstrom	Nm^3/h		117.000
Abgastemperatur am Eintritt	°C		370
Abgastemperatur am Austritt	°C		160
Abgasdruckverlust	mbar		12,5
Wärmeleistung	**kW**		**10.410**
Heißwassertemperatur am Eintritt	°C		130
Heißwassertemperatur am Austritt	°C		192
Heißwasserüberdruck	bar		20
Heißwassermassenstrom	kg/h		139.130
Heißwasservolumenstrom im Mittel	m^3/h		153
Heißwasserdruckverlust	m Fl. S.	ca.	40
Wärmedurchgangskoeffizient	$W/m^2{*}K$		64,9
Heizfläche inkl. Reservefläche	m^2		3.110
Heizflächenreserve	%		60

Issues / Learnings (3)
Maximal use of available Energy

- Loss of Exergy
  - Some system design results in high Exergy Loss (do not use available temperature level)





- Gas Inlet temperature is quit high but HEX heat transfer coefficient is low and Isobutane fluid properties do not match very well
- Gas Inlet temperature is extra-low; HEX heat transfer coefficients are OK – but fluid with gliding evaporation temperature (azeotrope mixture) would be more adequate

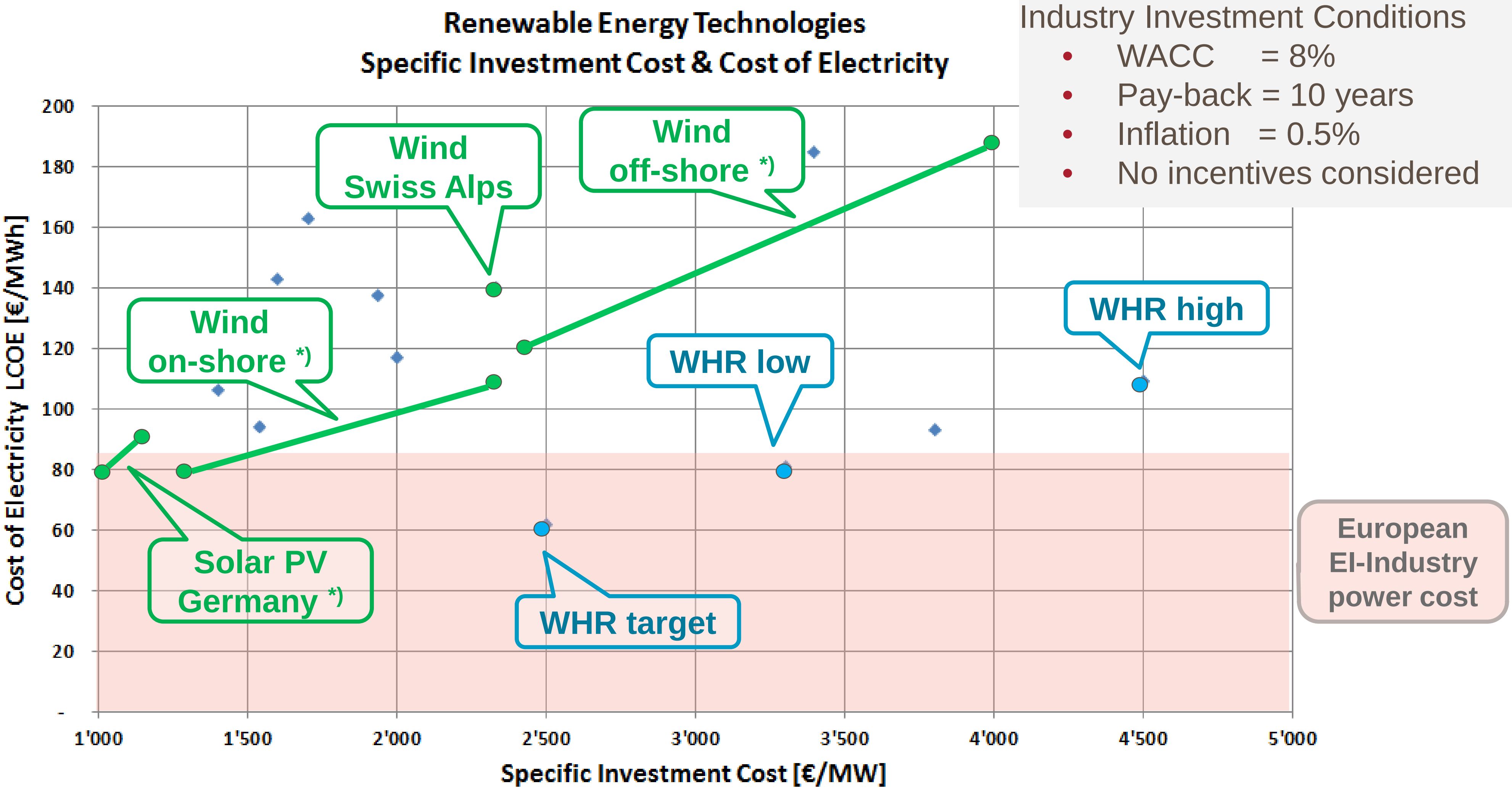
Economics

- **I'm an engineer:**
  - **I want to develop solutions –**
    but it must be economical

Prof. Dr. Lino Guzzella; President ETH Zürich

"Quote: Zürich 21.08.2015; Swiss-US Energy Innovation Days"

WHP generated power has slightly lower cost compared to "standard" Renewable Energy production cost – – but WHP is not eligible for "RE Incentives"



Industry Investment Conditions

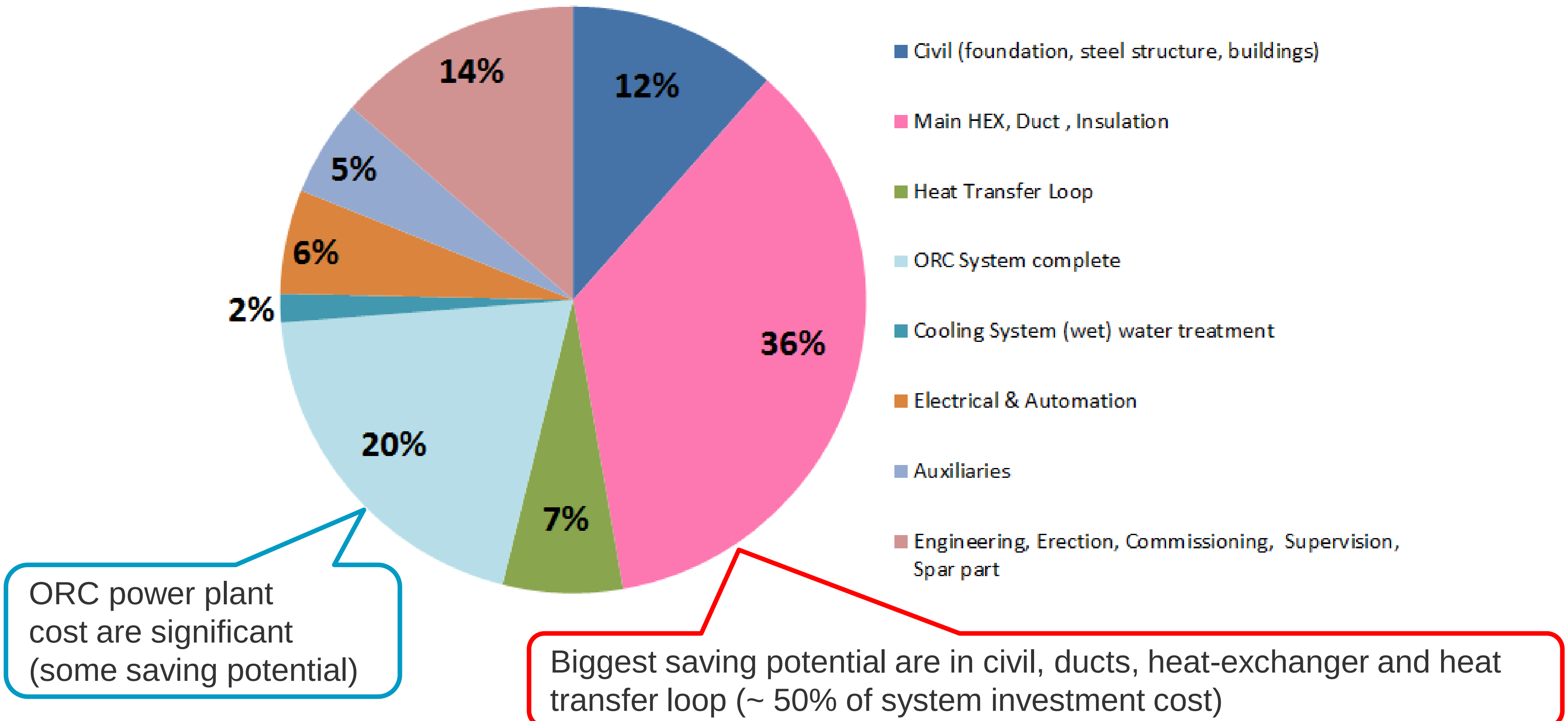
- WACC = 8%
- Pay-back = 10 years
- Inflation = 0.5%
- No incentives considered

*) Sources: Fraunhofer ISE, Stromgestehungskosten Erneuerbare Energien, Studie November 2013,

WHP System Investment Cost contributes for 96% of the resulting electricity price

- O&M cost are marginal (3 - 4%)
- **Cost reduction measures must focus in lowering investment costs**

WHP-ORC System Cost Split



Findings and Conclusion

- ORC based mid-temperature WHP in cement plants proved to work well and are economic viable for power prices > 90 €/MWh
  - Innovations are required to further reduce investment cost
    - Apply simple design (location, duct work, cooling, auxiliaries, etc.)
    - Use modular, standard and mass-produced components
- Design, installation and operation are crucial for high performing applications
  - Use experiences made (Industry has learned from good and bad practices)
  - Comprehensive modeling and simulation tools are required to:
    - determine best systems design
    - define optimal system parameters for all possible operation points (part-load performance is crucial for WHP applications)
- *In the near future, WHP in EI-Industry will compete with Renewable Energy Systems, mainly Solar PV (Fraunhofer ISE)*

LafargeHolcim