Waste heat recovery via Organic Rankine Cycle:
Results of a ERA-SME Technology Transfer Project

Ing. Bruno Vanslambrouck

UGent Campus Kortrijk
Research Group Thermal Energy in Industry (TEI)

Presentation based on results from research, supported by IWT

ASME ORC 2013
2nd International Seminar on ORC Power Systems
October 7th & 8th, 2013 De Doelen, Rotterdam, The Netherlands

Presentation overview

UNIVERSITEIT GENT

CAMPUS KORTRIJK

Content of this presentation is based on main project results of:

- TETRA-IWT project (2007-2009):

Waste heat recovery via ORC on renewable energy applications

15 members in the User Group, 5 case studies

- TETRA-IWT project within the European ERA-SME framework (2010-2012):

Waste heat recovery via Organic Rankine Cycle

German partner: Hochschule für Technik, Stuttgart
36 members in the Flemish User Group, 7 in the German one
9 case studies in Flanders

Presentation overview

Topics:

- Project goals
- Steam versus ORC
- Economic evaluation tool incl ORC module database
- Case studies
- Some conclusions
- ORC test rig @ Ugent Campus Kortrijk

Steam versus ORC

UNIVERSITEIT GENT

CAMPUS KORTRIJK

Gross cycle efficiency ORC with regenerator vs simplified steam cycle

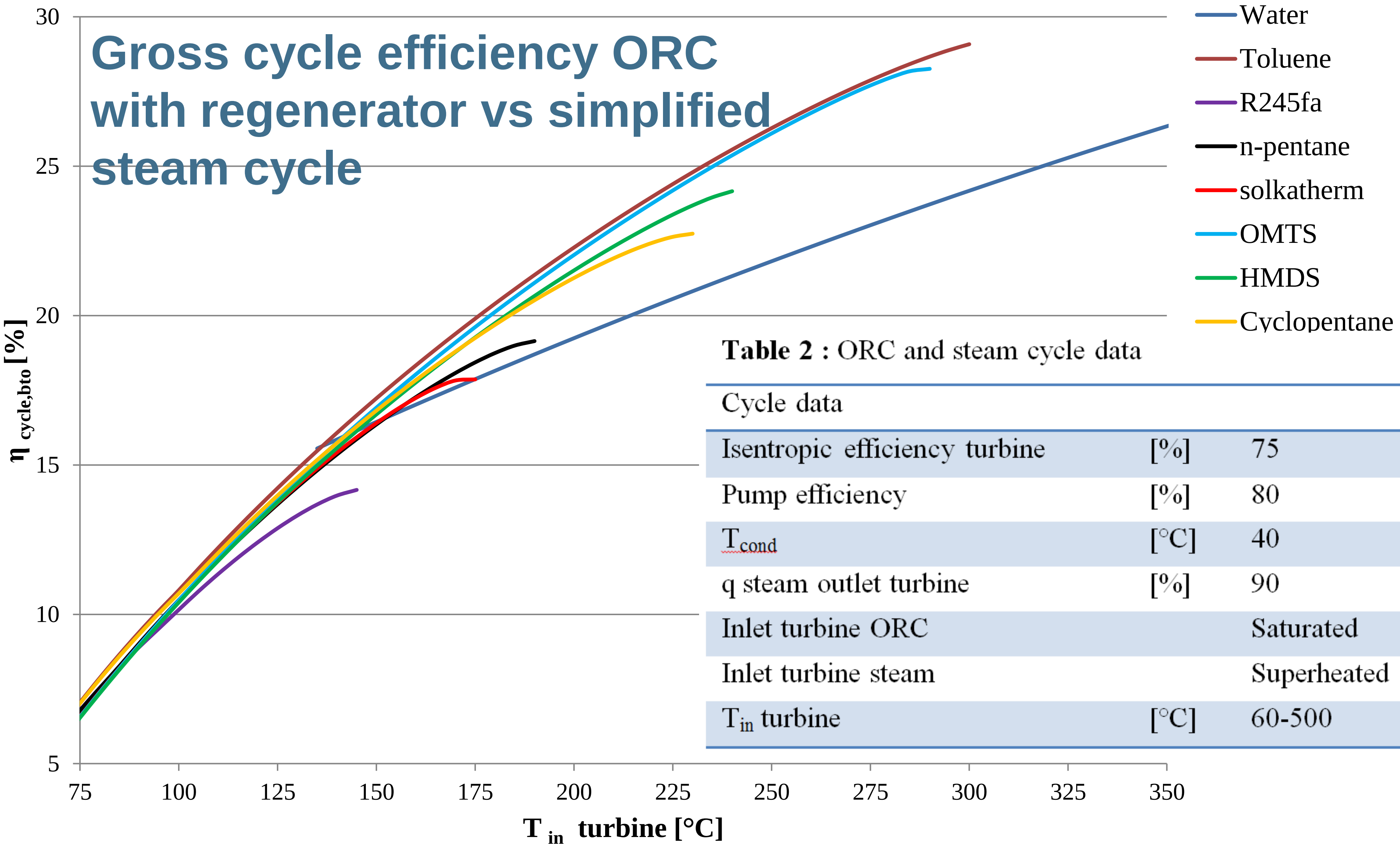
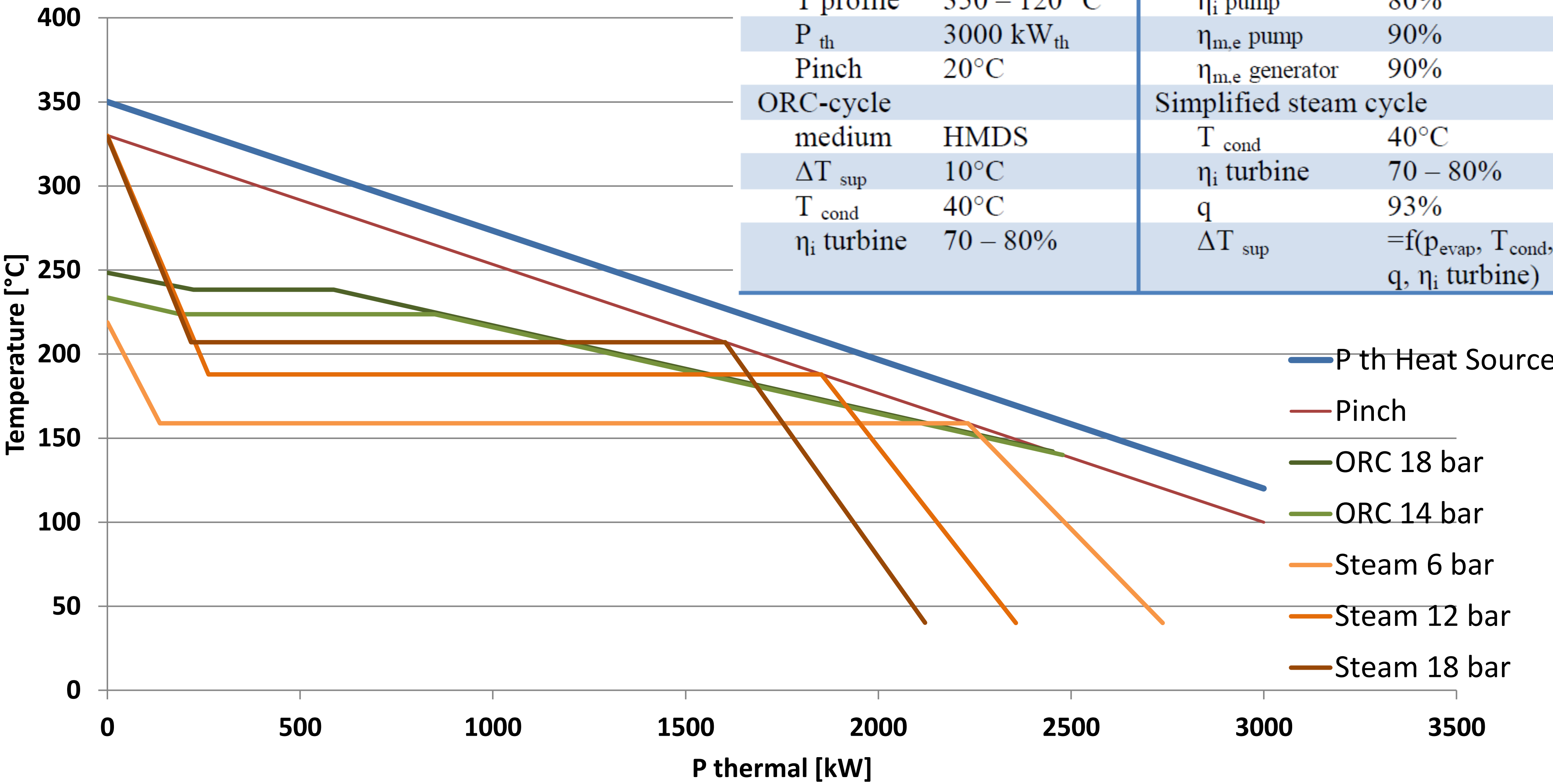


Table 2 : ORC and steam cycle data

Cycle data		
Isentropic efficiency turbine	[%]	75
Pump efficiency	[%]	80
T_{cond}	[°C]	40
q steam outlet turbine	[%]	90
Inlet turbine ORC		Saturated
Inlet turbine steam		Superheated
T_{in} turbine	[°C]	60-500

UNIVERSITEIT GENT CAMPUS KORTRIJK

Matching profiles ORC - steam



Parameter data

Waste Heat source :		Components	
T profile	350 – 120 °C	η_i pump	80%
P $_{th}$	3000 kW$_{th}$	$\eta_{m,e}$ pump	90%
Pinch	20°C	$\eta_{m,e}$ generator	90%
ORC-cycle		Simplified steam cycle	
medium	HMDS	T $_{cond}$	40°C
ΔT $_{sup}$	10°C	η_i turbine	70 – 80%
T $_{cond}$	40°C	q	93%
η_i turbine	70 – 80%	ΔT $_{sup}$	=f(p$_{evap}$, T$_{cond}$, q, η_i turbine)

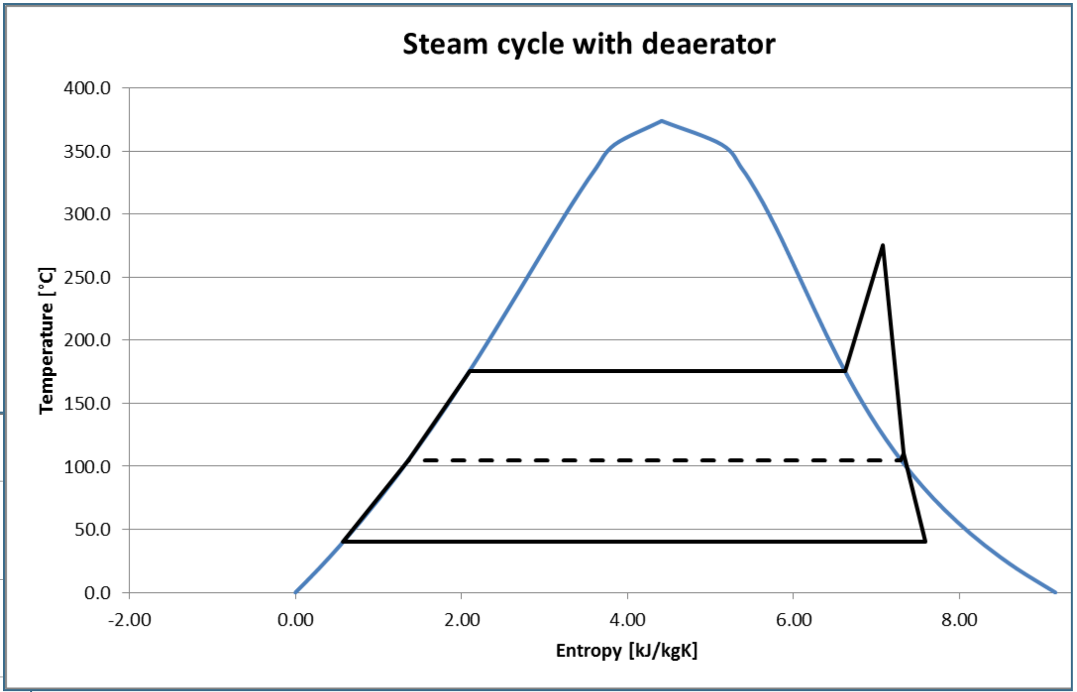
Results for a steam cycle and ORC (HMDS) for different parameters

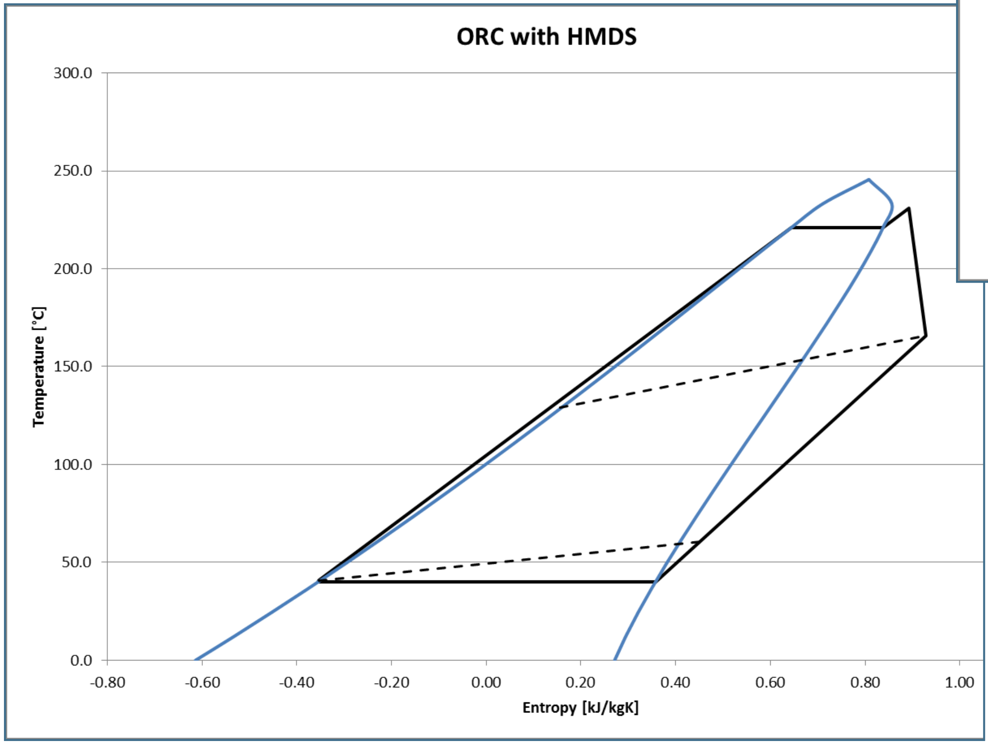
(good match with existing ORC-modules)

Case	η_i turb [%]	p_{evap} [bar]	T_{sup} [°C]	$\eta_{cycle,bto}$ [%]	$\eta_{cycle,nto}$ [%]	$P_{gen,bto}$ [kW_e]	$P_{gen,nto}$ [kW_e]	$P_{th,reco}$ [kW_{th}]
O_1	70	14.0	234	20.4	19.7	506	488	2479
O_2	70	17.6	248	21.3	20.4	509	487	2388
O_{opt}	**70**	**14.9**	**239**	**20.7**	**19.8**	**513**	**492**	**2478**
S_1	70	6.0	219	16.1	16.0	440	439	2737
S_2	70	12.0	272	18.5	18.5	442	441	2386
S_3	70	18.0	305	19.9	19.9	426	424	2134
S_{opt}	**70**	**7.9**	**320**	**17.6**	**17.6**	**454**	**453**	**2572**
O_3	80	14.0	234	22.6	21.9	574	556	2540
O_4	80	17.6	248	23.6	22.7	578	556	2452
O_{opt}	**80**	**16.3**	**244**	**23.3**	**22.4**	**583**	**561**	**2505**
S_4	80	6.0	267	18.7	18.7	509	508	2715
S_5	80	12.0	330	21.6	21.5	509	508	2357
S_{opt}	**80**	**7.9**	**320**	**20.2**	**20.1**	**519**	**518**	**2571**

Steam versus ORC

- **Automatic presentation of ORC and steam cycle on Ts-diagram**





Economical evaluation tool

UNIVERSITEIT GENT

CAMPUS KORTRIJK

Database ORC modules

- Standard modules of all ORC constructors
- Technical data of ORC modules
- Economical data : ORC module prices

Characteristics Heat Source

- Thermal power P_{th}
- Temperature profile
- Dew points

Selection criteria

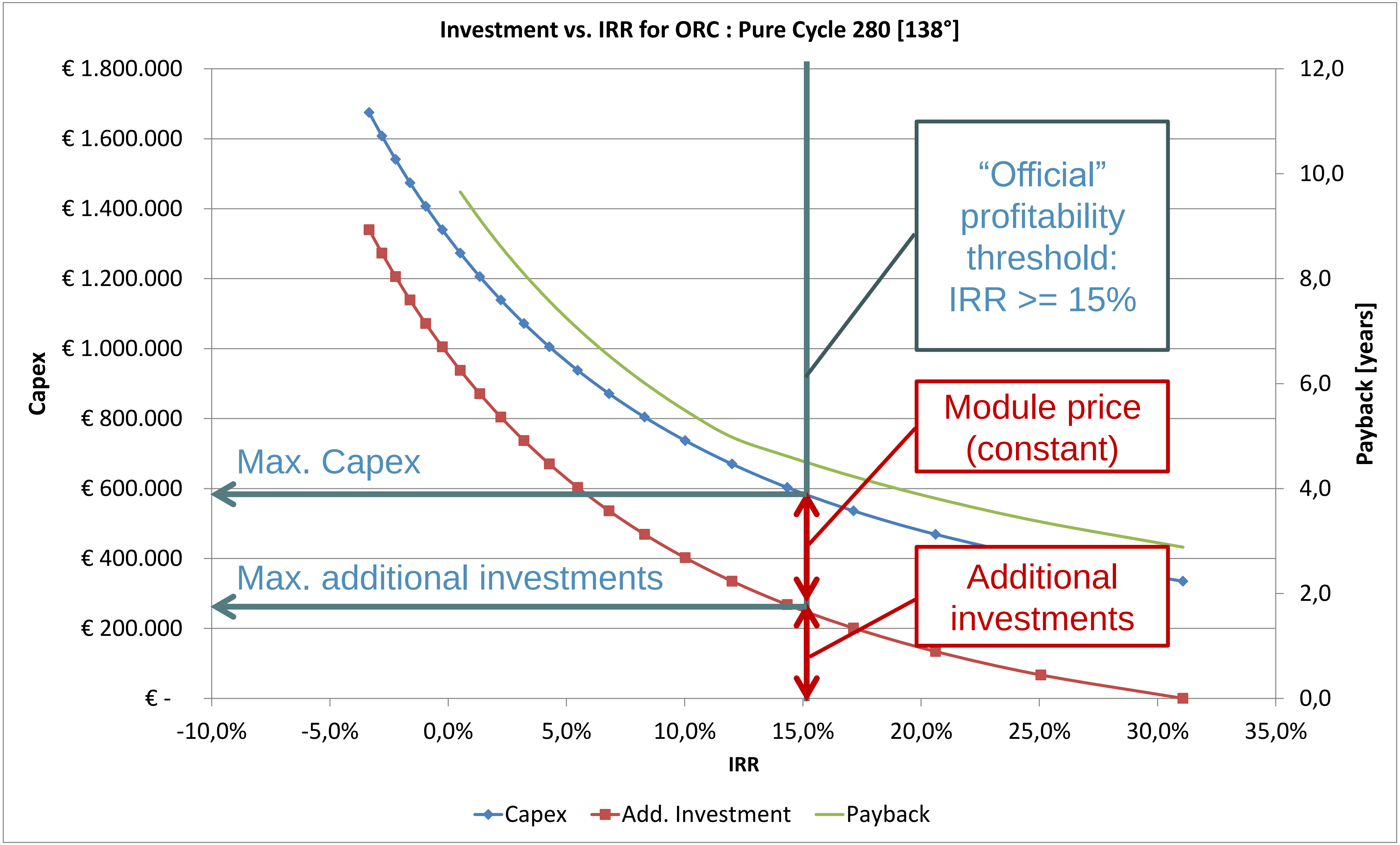
- T_{max}
- P_{th}

List of suitable ORC modules

Technical data ORC modules

- Thermal input : P_{th}, T_{in}, T_{out}
- Cooling water : P_{cw}, T_{in}, T_{out}
- Performance : gross/net P_{el}, η_{el}
- ORC medium
- Expander type
- …

Economical evaluation tool



Case studies

Cases within 1st TETRA-project (2007-09 on renewable energy):

Case 1: Landfill gas engines (3 x 1,1 MWe)

Case 2: Biogas engines (373 kW, later + 500kWe)

Case 3: Bio-oil engine (250kWe)

Case 4: Combustion grate cooling biomass boiler
(0,5-2,5MWth @~120-140°C)

Case 5: Biogas engines (930 & 1130 kWe)

UNIVERSITEIT GENT

CAMPUS KORTRIJK

Case 1: Landfill gas engines on a site with decreasing gas production

(calculations situation 2009)

Year	Total net electric power, MWe	Available waste heat, MWth
2004	5,85	7,67
2005	4,78	6,26
2006	4,28	5,61
2007	3,56	4,67
2008	3,33	4,36
2009	3,04	3,98
2010	2,82	3,69
2011	2,62	3,43
2012	2,43	3,19
2013	2,26	2,96

UNIVERSITEIT GENT

CAMPUS KORTRIJK

Case 1: Adapted ORC modules, proposed by the selection tool

(calculations situation 2009)

Supplier	Model	Thermal input LT, kW_{th}	Thermal input HT, kW_{th}	Net power, kWe
Maxxtec	AD 315	0	1665	242,8
Tri-o-gen	1 module	0	760	150
Tri-o-gen	2 modules	0	1520	300
Köhler und Ziegler	2 modules	1180	1360	300
Köhler und Ziegler	3 modules	1770	2040	450
Infinity Turbine	IT80	727	0	80
Infinity Turbine	IT250	2273	0	250
Calnetix	WHG125	674	0	100
BEP Europe	250kWe	2100	0	250
PWPS	Pure Cycle 280	2670	0	225

Case 1: Economical outcome

Specific situation because of decreasing gas production → limited project life time !

IRR presented solutions: 15 – 40% for 5 year use
23 – 45% for 10 year use
Pay Back Time: 2 – 4 years

Based on E-price = EUR 35/MWh (to supply to the grid)
Green Certificates : EUR 106/cert (1 per MWh E-production)

Other cases gave comparable results, except cases 2 and 3 where no adapted modules (to small) were found at that time.

Case studies

Cases 2nd TETRA-project (2010-12 on industrial, non renewable waste heat):

Case 1: Waste heat valorisation on a incinerator plant

Case 2: Heat recuperation on a CO-afterburner in foam glass production

Case 3: ORC on furnace exhaust and cooling water in a steel wire plant

Case 4: Study of heat recovery on a 41 MW gas turbine of a paper mill to become + 5% RPE savings within the frame of CHP-certificates

Case 5: ORC on low pressure steam and hot gases in a chemical plant

Case 6: Heat recuperation in an automobile paint shop

Case 7: Waste heat recuperation (exhaust gases + cooling water) on a walking beam furnace of a steel production plant

Case 8: Exhaust heat recuperation on a clay grain production plant

Case 9: Low temperature waste heat use in a water cleaning plant

Case 2: Foam glass production plant

Exhaust gases @ ca 740°C from CO afterburning (4 burners, grouped per 2) of waste gases from foaming installation (glass is reheated in an oxygen free area)

Distance between 2 groups: ca 150 m

Outlet gas temperature, °C	Waste heat available, kW
100	3098
120	3008
140	2917
160	2826
180	**2735**

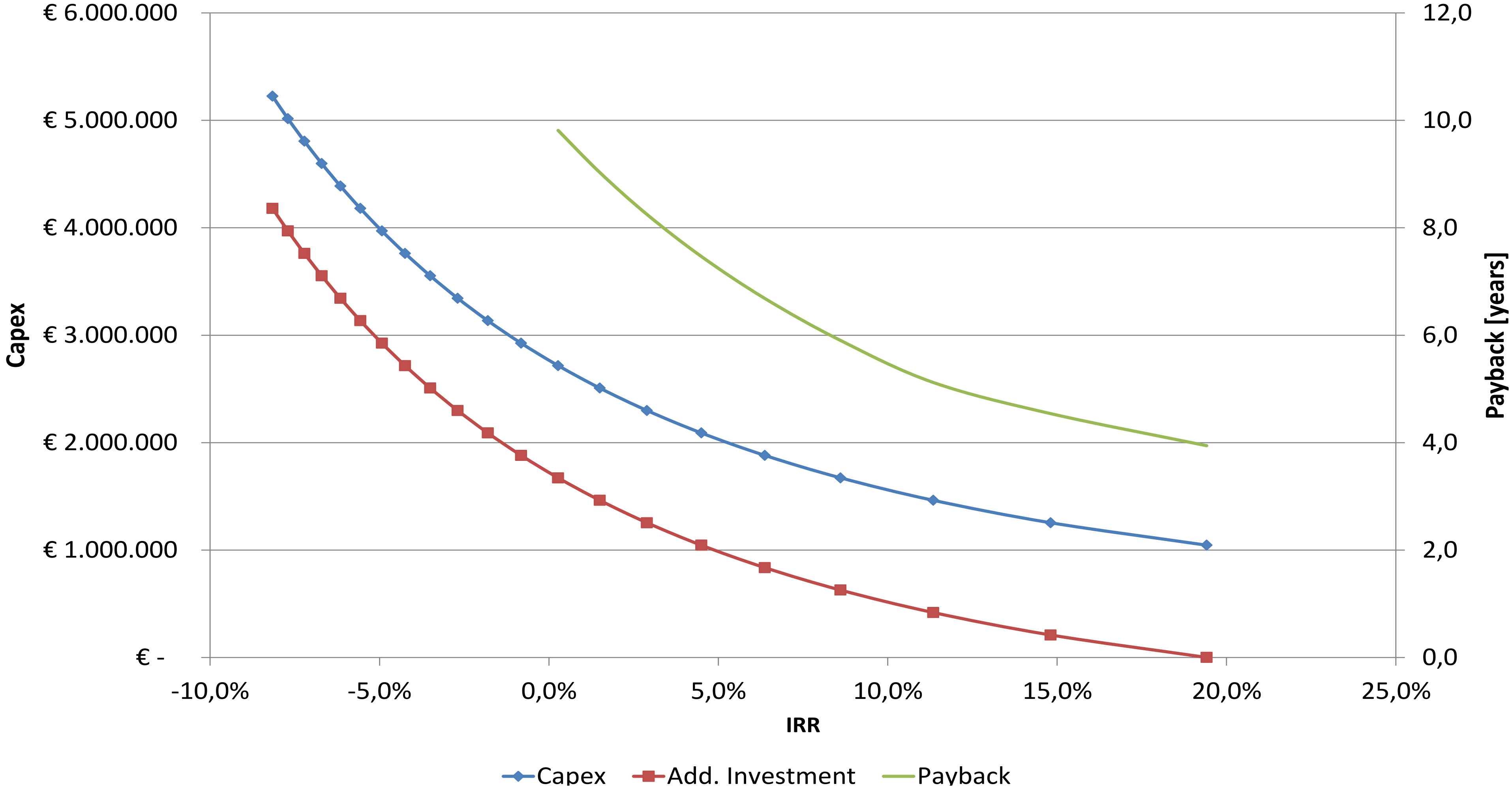
Solution 1: Turboden TD 6 HR split (ca 510 kWe, no full load)

Data N°	44	
ORC Module	T 6 HR	
Constructor	Turboden	
Number of ORC	1	
Expected IRR	15	%
Price ORC-unit	€ 1.045.000	
$P_{el,bto}$ ORC-unit	567	kWe
$P_{el,nto}$ ORC-unit	510	kWe
Electr. Prod.	4110	MWh/year
Profits Electricity	€ 328.815	€/year
Maintenance costs	€ 34.912	€/year
GSC	€ -	€/year
Additional profits	€ -	€/year

Capex	€ 1.245.000
Opex	€ 20.000
Depreciation	€ 249.000
IRR	15,0%
Δ criterium	0,0%
Add. investm.	€ 200.000
Payback	4,5

Direct evaporating not allowed (to hight t°, risk on silicon oil cracking).
Connection between 2x 2 chimneys via thermal oil circuit required: high integration costs…

Solution 1: Turboden TD 6 HR split (ca 510 kWe, no full load)



Case studies

Solution 2: 2x Triogen 165 kWe (2x 900 kWth needed: ok), no connection between the 2 chimney groups

Reference: Triogen ORC with direct evaporation, fed by waste heat from two sources

Solution 2: 2x Triogen 165 kWe

IRR max = 12,5% if integration costs are zero…, so not economical under defined conditions

Data N°	41	
ORC Module	Tri-O-gen 165 kWel	
Constructor	Tri-O-Gen	
Number of ORC	2	
Expected IRR	15	%
Price ORC-unit	€ 900.000	
$P_{el,bto}$ ORC-unit	330	kWe
$P_{el,nto}$ ORC-unit	330	kWe
Electr. Prod.	2660	MWh/year
Profits Electricity	€ 212.763	€/year
Maintenance costs	€ 26.004	€/year
GSC	€ -	€/year
Additional profits	€ -	€/year

Capex	€ 900.000
Opex	€ -
Depreciation	€ 180.000
IRR	12,5%
Δ criterium	2,5%
Add. investm.	€ -
Payback	4,9

Case 4: Paper mill

Old (1997) 41 MWe CHP **to renew**: based on a gas turbine (LM6000 GE), heat recovery as steam @ 14 bar. Exhaust gas outlet 120-130°C.

By integrating additional E-production (+25%) and/or realizing 5% increase of RPE, this CHP can be considered as "renewed" and CHP-certificates are to obtain for a new period (as a new one). Economically very attractive.

To realize this a steam turbine or ORC, using exhaust heat, is to integrate. The condensor heat must be used in order to realize additional energy savings.
Since the heat must be available as 5 bar steam, a **back pressure steam turbine** (inlet 80 bar-550°C with cofiring) was the best choice to reach the goals.

Case 5: Chemical plant (Proviron Basic Chemicals-Ostend)

Within a chemical process, about 30 000 ton/year of low pressure steam (2,5 barg) is released.
So far, this steam was expanded into the atmosphere without heat (and treated water) recovery (estimated thermal power: ~ 2,4 MW).

Via contacts within our project user group, this became a field test case for BEP Europe since this was the first build 250 kWe module and the location was close to the company.

From our selection and evaluation tool, following results has been found:

Proviron
a human and ecological approach to chemistry

Case Proviron (low pressure steam):

Data Heat Source	Case 2	Units
Type Heat Source	Steam	
Qmin	3	Ton/h
Qmax	5	Ton/h
Tmin	100	°C
Tmax	140	°C
pressure	3.5	bar (a)

Thermal Power		
Library Medium Heat Source	IF97	
Density	1.907	kg/m^3
Conversion factor	3.6	
$\dot{M}$ min	0.83	kg/s
$\dot{M}$ max	1.39	kg/s
h max,Heat Source	2732	kJ/kg
h min,Heat Source	419	kJ/kg
Δh Heat Source	2313	kJ/kg
$P_{th\ heat\ source}$ min	1927	kW_{th}
$P_{th\ heat\ source}$ max	3212	kW_{th}

Case Proviron (continued):

Project parameters	(Energy Benchmarking Covenant)			Profits		
Project lifetime	10	years		Additional profits	0	€/year/ORC-unit
Depreciation	5	years (linear)		Demi - water	0	€/ton
Residual value	0	€/ORC-unit		WKK Certificates		
Tax rate	34	%		Year 1	0	€/ORC-unit
				Year 2	0	€/ORC-unit
Availability				Year 3	0	€/ORC-unit
	90	%		Year 4	0	€/ORC-unit
or	7884	hours		Year 5	0	€/ORC-unit
Energy Prices				Year 6	0	€/ORC-unit
Electricity				Year 7	0	€/ORC-unit
	80	€/MWh		Year 8	0	€/ORC-unit
Evolution factor				Year 9	0	€/ORC-unit
	0	%/year		Year 10	0	€/ORC-unit
GSC						
	0	€/MWh	(Green Certificates)			

Calculate IRR

Case Proviron (continued):

N°	MODULE	CONSTRUCTOR	Temp Heat Source High [°C]	Q IN ORC [kW_{TH}]	Max number of ORC	Net Efficiency ORC [%]	Net electric P_{el} ORC-unit [kWe]
9	ET250	BEP Europe	140	2 150	1	10%	213
30	IT 250	Infinity Turbine	110	2 197	1	10%	213
36	K&Z 375kWe	Kohler& Ziegler	135	2 500	1	13%	320
88	Pure Cycle 280 [138°]	Turboden (Pratt&Whitney)	138	3 120	1	8%	252

ORC module price per kW_{el} : 850 – 1300 (2700) €/kW_{el}

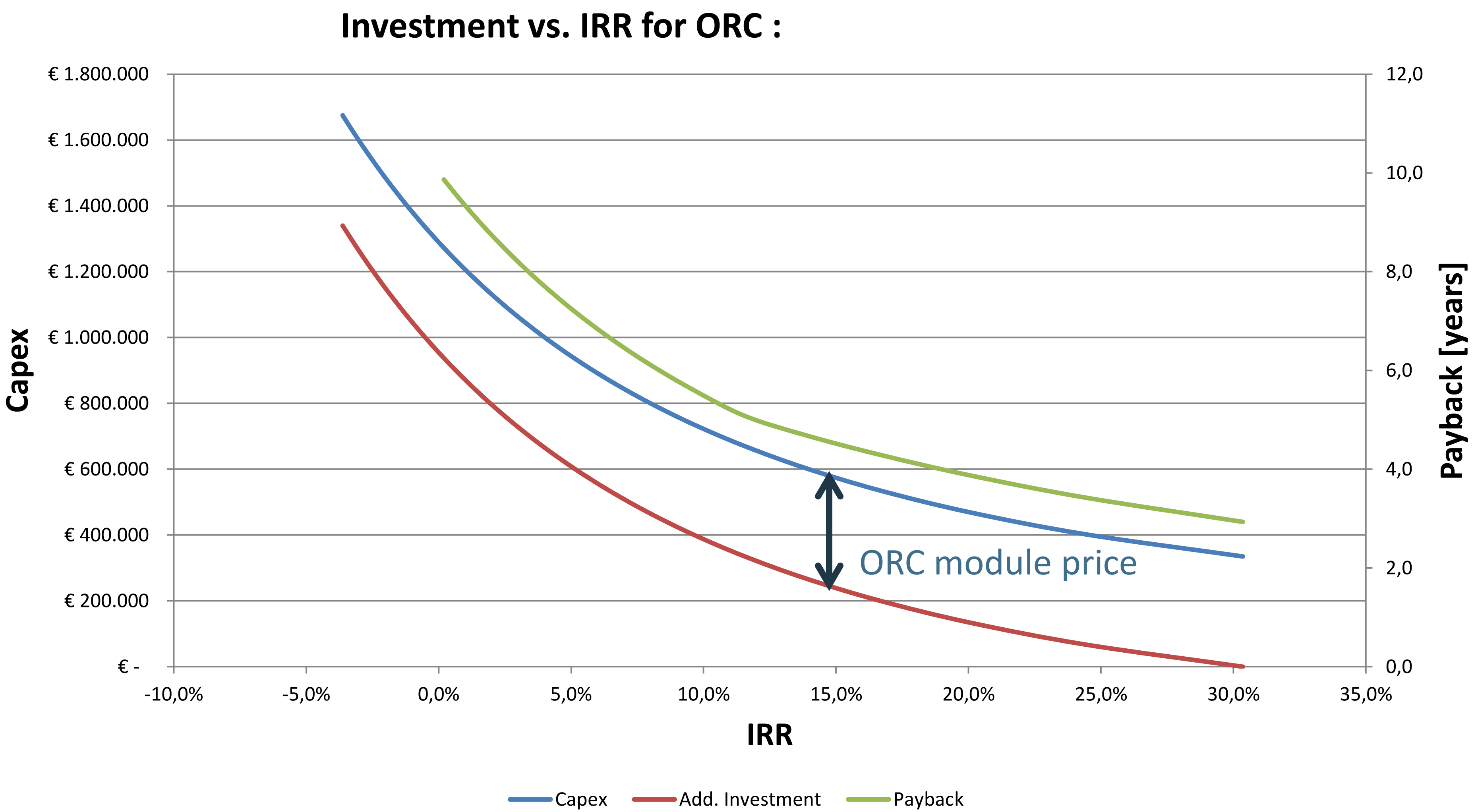
Calculated IRR : (4,5%) 12,2% - 17,5%

Payback : 4 – 5 years (with a “standard” rated integration cost)

Additional investments :

- Direct connection to steam network
- Cooling circuit + dry cooler
- Connection to electricity grid

Case Proviron (continued):



Case Proviron (continued): realisation

250 kWe module from the ORC 4000 series

E-RATIONAL

VALUE FOR HEAT

Case 7: Expanded clay grains production plant (Argex-Burcht)

Expanded clay grains are produced in a drum furnace.
App 100 000 Nm³/h dust containing exhaust air is leaving at **250°- 280°C**. By cooling down to 180°C (above dew point), ca **3.3 to 3.7 MWth** is to recover. This could fed an adapted ORC of app 400 - 600 kWe

Realisation:
3 Clean Cycle modules (GE Energy) ordered.

Case studies

Case Argex (continued): solution

GE Energy (United States):
(earlier Calnetix Power Solutions)

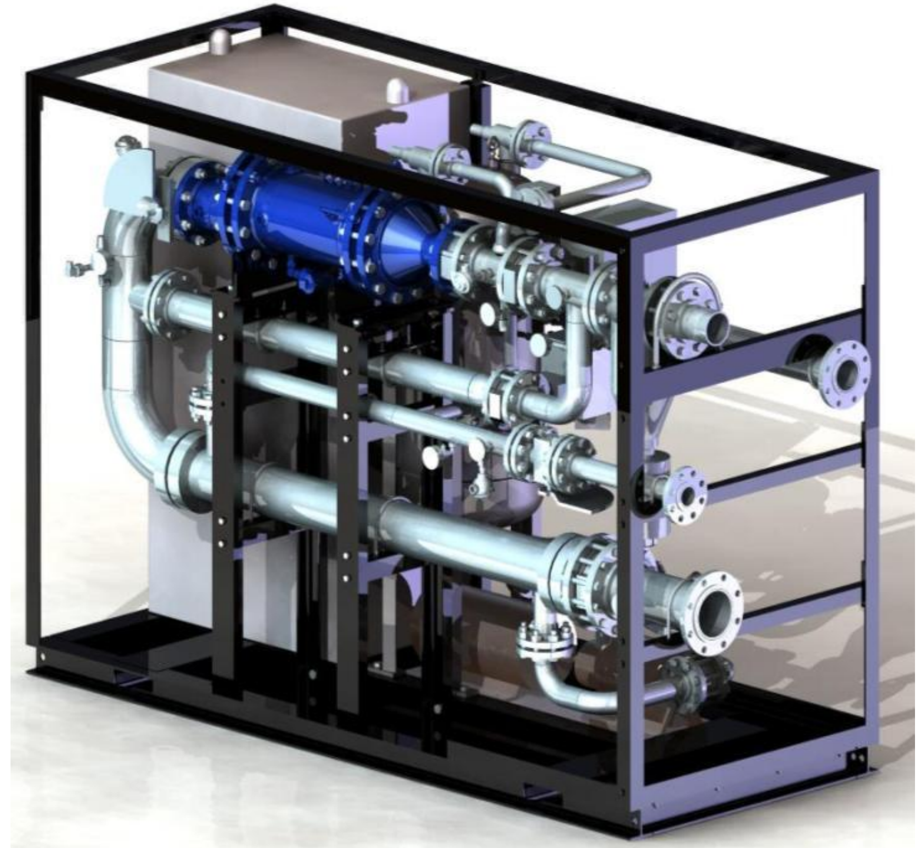
Clean Cycle 125

Output: 125 kWe gross (about 100 kWe net)
Evaporation/condensing t°: 121/21°C

Adapted heat sources: 980 kWth needed
Steam from 124°C
Hot water from 143°C
Hot gases from 204°C (cooled down to 149°C)

Electrical efficiency: 10-11%

Alternator	High speed, permanent magnet
Turbine	Single stage radial expander turbine
Bearings	Magnetic frictionless
Refrigerant	R245fa (Non-ozone depleting)



Case studies

UNIVERSITEIT GENT
CAMPUS KORTRIJK

Main factors determining technical/economical feasibility:

Heat source type:

- LP-steam: huge amount of latent heat available at constant temperature, direct connection to ORC-evaporator
- Hot water or oil: also direct connection possible, sometimes contamination of water with particles, fibers…
- Flue gas: direct evaporation (sometimes), waste heat recovery unit mostly needed, attention to dew point corrosion, dust ….

Cooling:

- Availability on site (river, excess capacity on existing coolers) ?
- Use of condenser heat required for CHP certificates?

Electricity production:

- Own consumption or grid injection ? → price ca EUR 80 versus EUR 40/MWh
- Green- or CHP certificates → **(needed) additional benefit**

UNIVERSITEIT GENT CAMPUS KORTRIJK

Conclusion about cases concerning non renewable waste heat:
Economical feasibility is **problematic**, except if waste heat source is directly connectable (steam, hot water) with the ORC **AND** economical expectations are realistic (f.i. IRR min = 15%; PBT about 4 year acceptable)

Case on hot gases in the reach of 700-800°C and > 2 MW didn't meet this expectations...

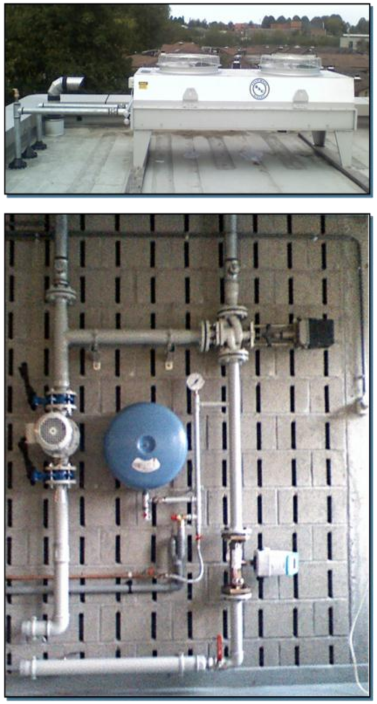
ORC test and demo facility

UNIVERSITEIT GENT

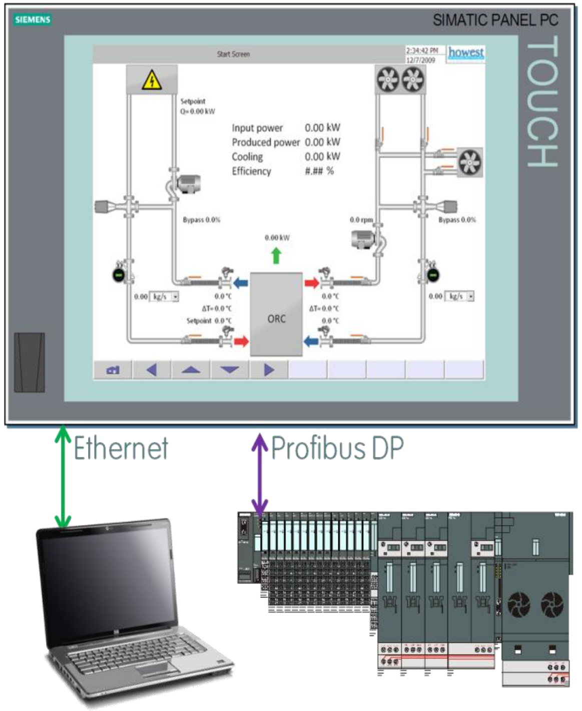
CAMPUS KORTRIJK

Heat source: Thermal oil boiler 250kW, Maxxtec

ORC, 10kWe, BEP-Europe E-Rational



Cooling loop

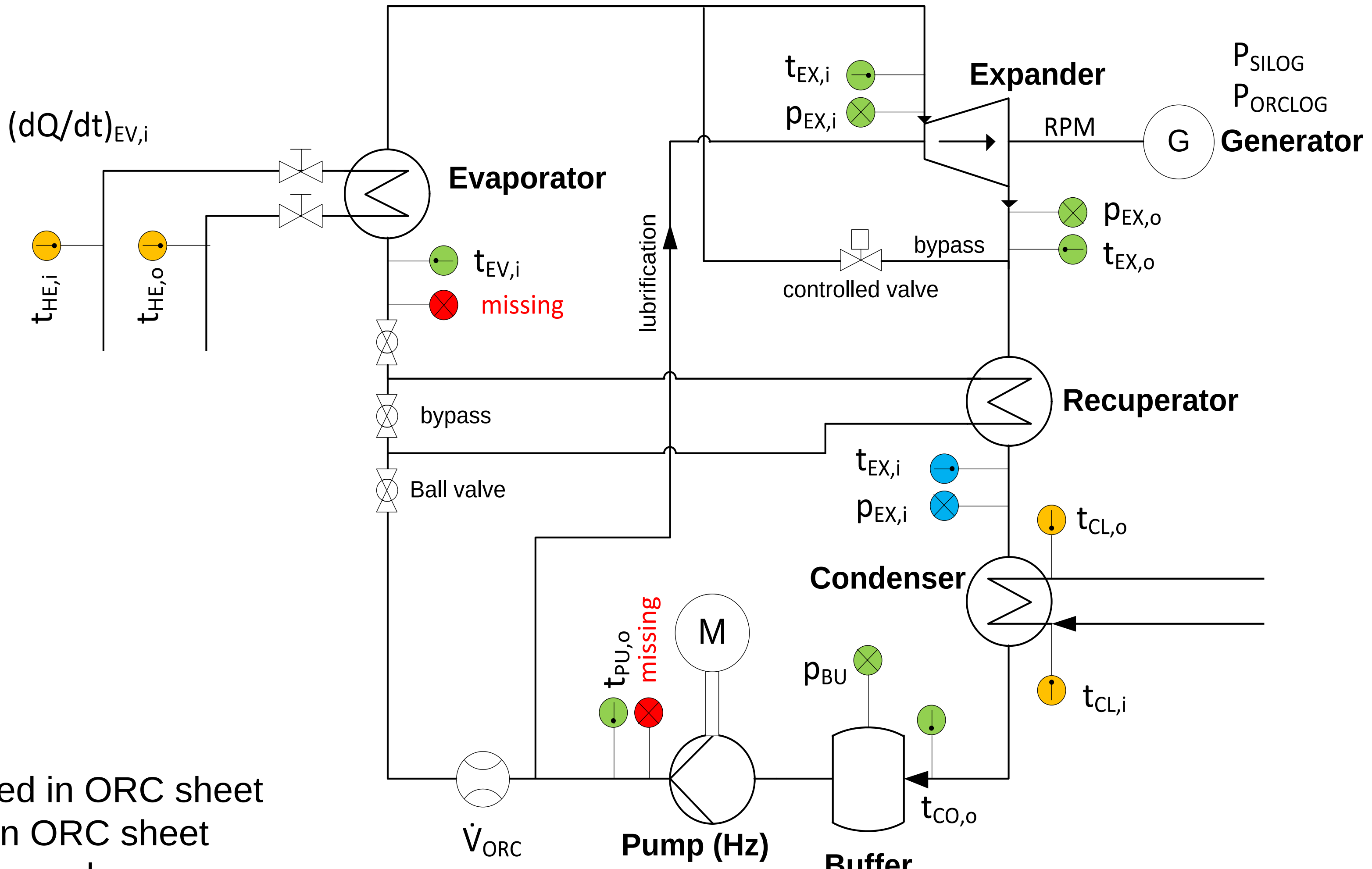


Measurement and acquisition system, Siemens

ORC test and demo facility

UNIVERSITEIT GENT

CAMPUS KORTRIJK



KEY:

- temperature logged in ORC sheet
- pressure logged in ORC sheet
- installed but not logged
- temperature logged in Siemens sheet
- desirable sensors

Thanks for your attention

Time for questions…discussion ?

ing. Bruno Vanslambrouck

Ghent University Campus Kortrijk
Research Group Thermal Energy in Industry
Graaf Karel de Goedelaan 5, B-8500 Kortijk

bruno.vanslambrouck@ugent.be
Tel: +32 56 241211 of +32 56 241227 (dir)

www.orcycle.eu www.wasteheat.eu