THE SZEWALSKI
INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES

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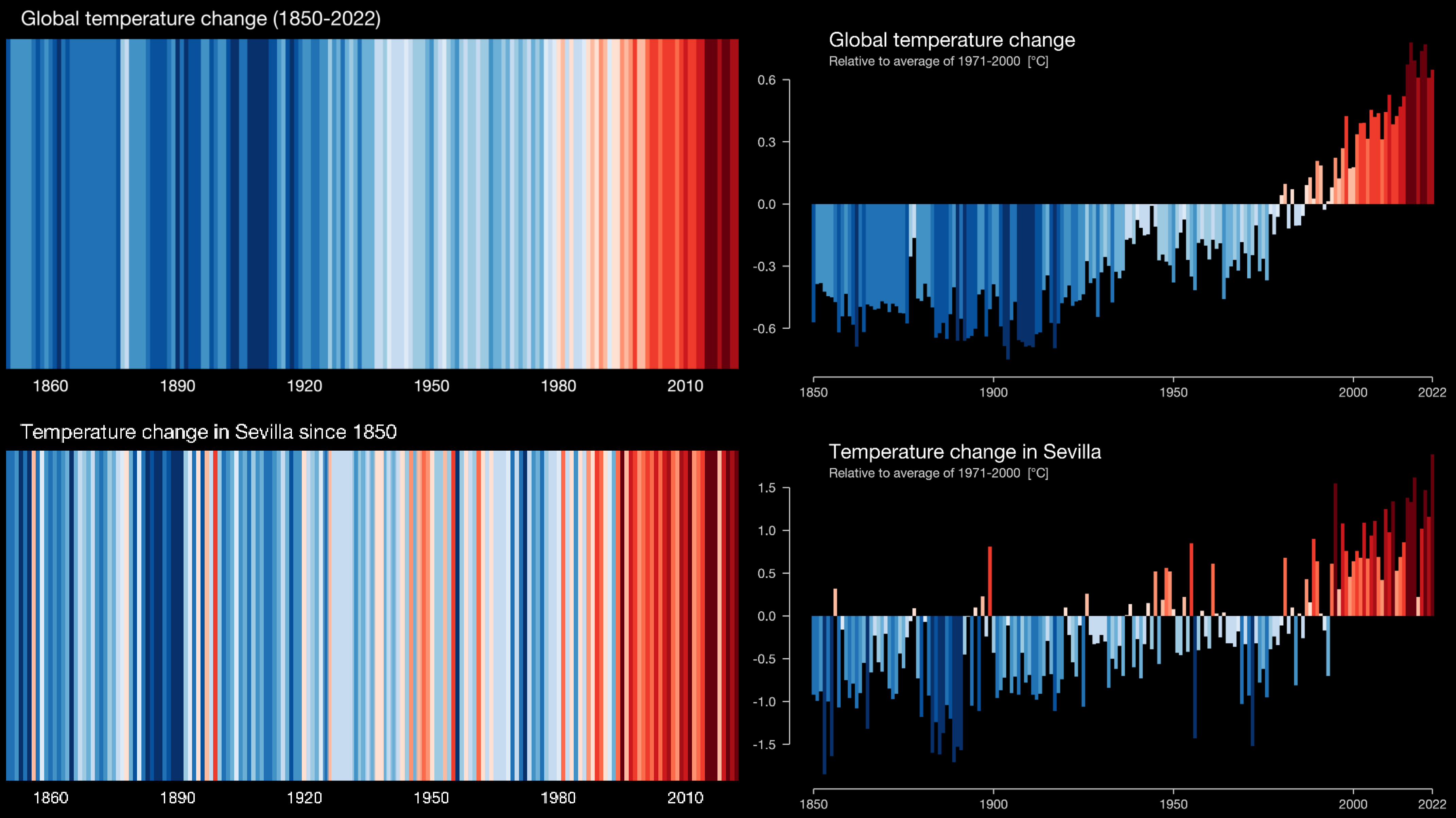
on O.R.C. Power Systems

TURBINE DEPARTMENT
CENTRE FO HEAT AND POWER NGINEERING

COMPREHENSIVE ANALYSIS OF ORC-VCC SYSTEM FOR AIR CONDITIONING FROM LOW-TEMPERATURE WASTE HEAT

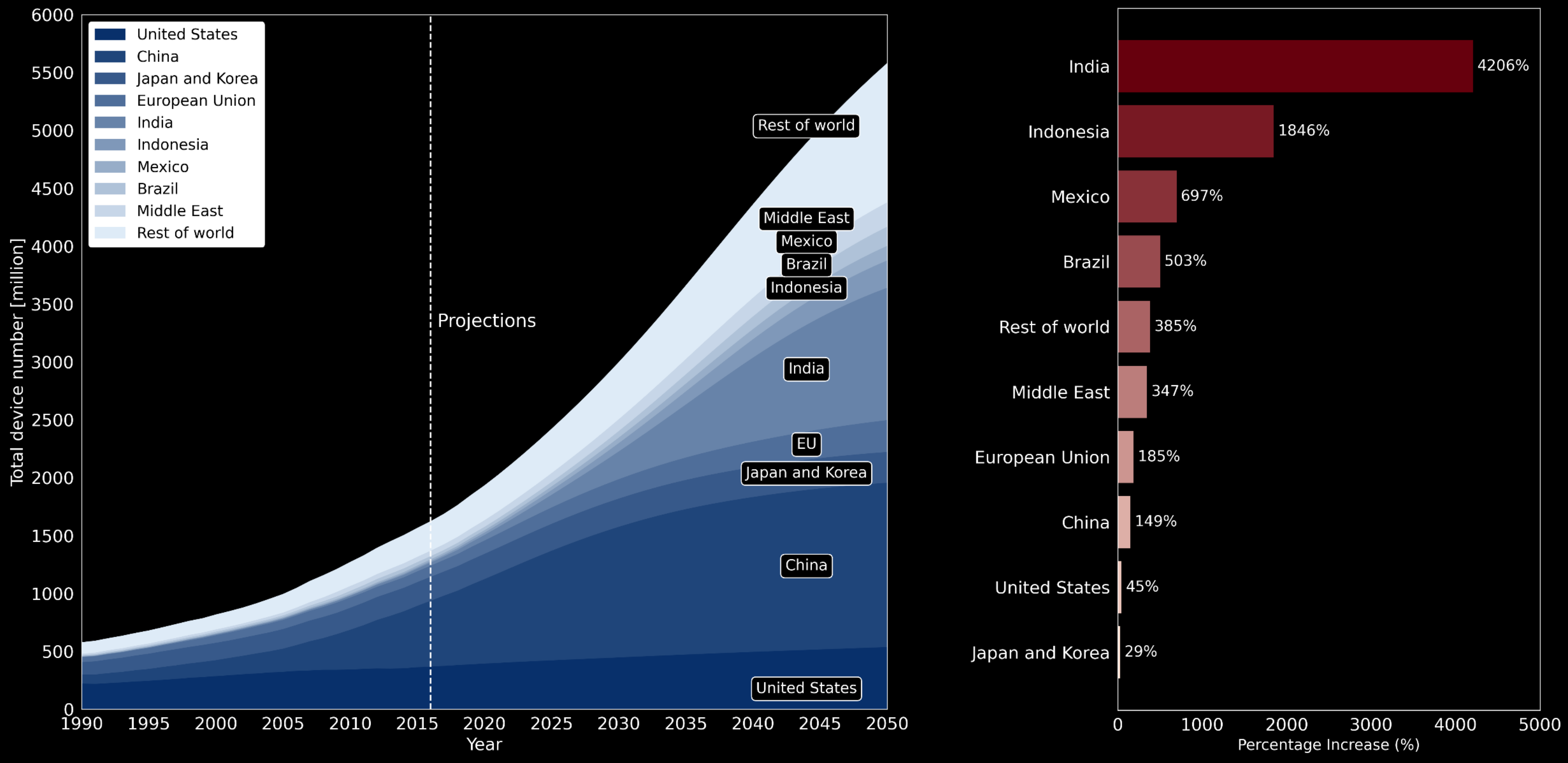
ŁUKASZ WITANOWSKI

Technical session 3B
„Thermodynamics of ORC systems#1"
Chair: Piero Colonna



Graphics and lead scientist: Ed Hawkins, National Centre for Atmospheric Science, University of Reading., National Centre for Atmospheric Science, UoR.
www.showyourstripes.info [1]

Global air conditioner stock (1990-2050)



Source: IEA. This data is subject to the IEA's terms and conditions: **www.iea.org/t_c/termsandconditions [2]**
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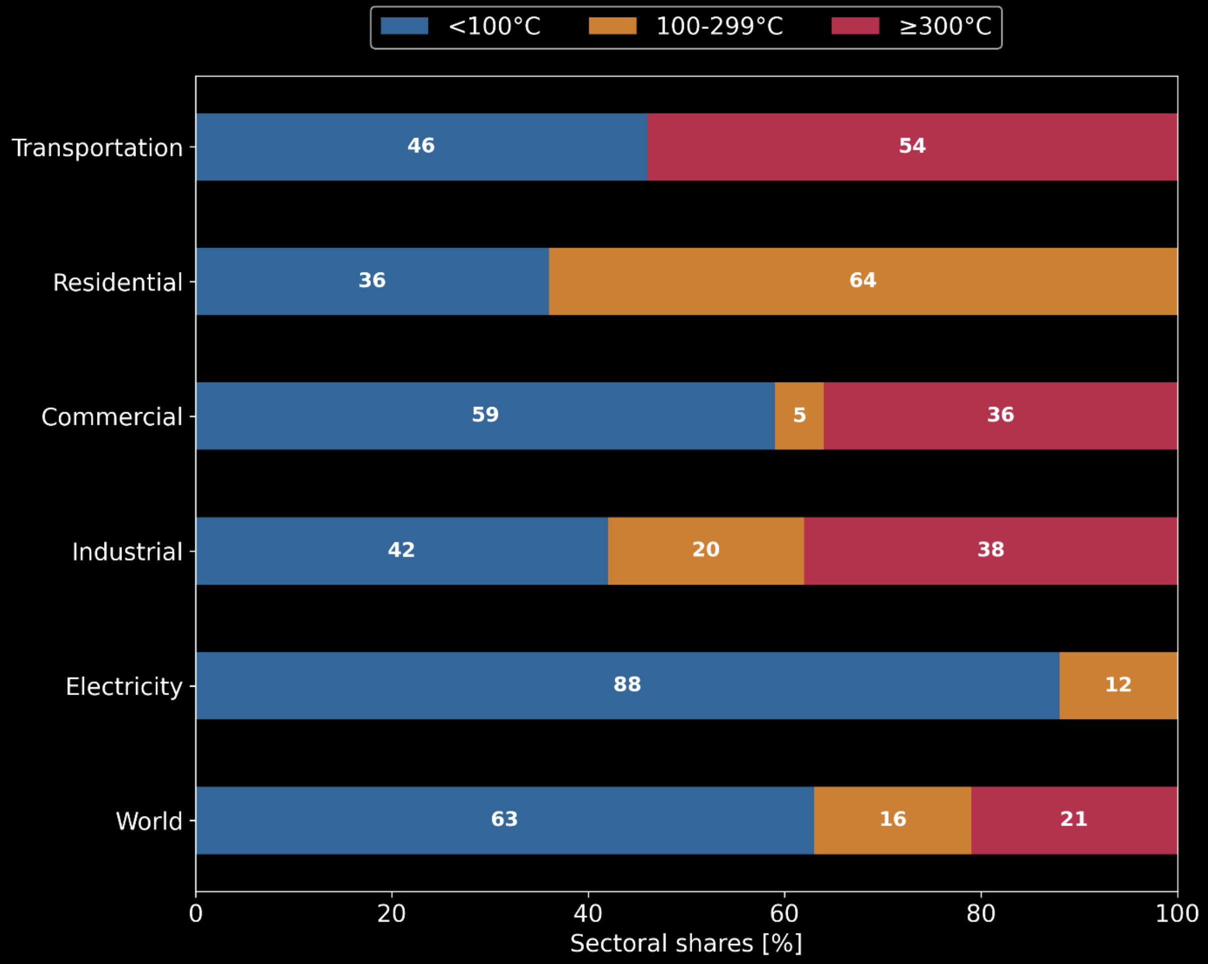
Sectoral shares of waste heat distribution



GLOBAL

- low temperature - 43. 2 TWh
- medium temperature - 11.0 TWh
- high temperature - 14.1 TWh

INDUSTRIAL

- low temperature - 3.8 TWh
- medium temperature - 1.8 TWh
- high temperature - 3.4 TWh

ELECTRICITY GENERATION

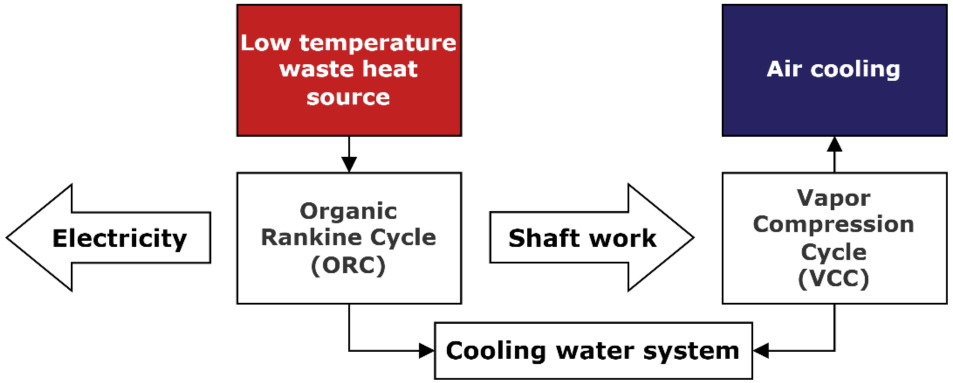
- low temperature - 26.2 TWh
- medium temperature - 3.6 TWh

Source: C. Forman, I.K. Muritala, R. Pardemann, B. Meyer, Estimating the global waste heat potential, Renewable and Sustainable Energy Reviews, 57 (2016) 1568–1579. doi:10.1016/j.rser.2015.12.192. [3] Graphics: Łukasz Witanowski

Cooling Production from Waste Heat Technologies

TYPE	TECHNOLOGY READINESS LEVEL	ADVANTAGES	DISADVANTAGES	Ref.
ABSORPTION SYSTEM	System tests, **TRL9**	• High efficiency. • Versatility of configurations.	• High investment costs. • Frequent maintenance required. • High operational costs. • Limited operating conditions. • Complex installation.	[4]
ADSORPTION SYSTEM	System tests, **TRL9**	• Low noise level.	• High investment costs. • Low efficiency.	[5]
EJECTOR SYSTEM	System tests, **TRL9**	• Simple construction. • Reliability. • Limited maintenance requirements. • Low investment and operational costs.	• Low efficiency. • Narrow operational characteristics. • High working pressure often required.	[6]
THERMOELECTRIC SYSTEM	Technology dvelopment, **TRL4/TRL5**	• Low failure rate. • Compact size and low weight. • Low levels of noise and vibration. • Precise temperature control.	• Low efficiency. • High investment costs. • High operational costs. • Limited applicability. • Legislation restricting the use of HFCs in small cooling devices.	[7]
MAGNETOCALORIC SYSTEM	Technology dvelopment, **TRL4/TRL5**	• Ability to adapt technology to specific needs. Wide operational range.	• Low efficiency. • High investment costs. • High operational costs. • High electrical energy consumption.	[8]
ORC-VCC	Research to prove feasibility, **TRL3/TRL4**	• High efficiency across a wide operational range. • Low electrical energy consumption. • Low failure rate. • Low operational costs.	• Sensitivity to partial efficiencies of compressors and turbines.	[9]

ORC-VCC SYSTEM



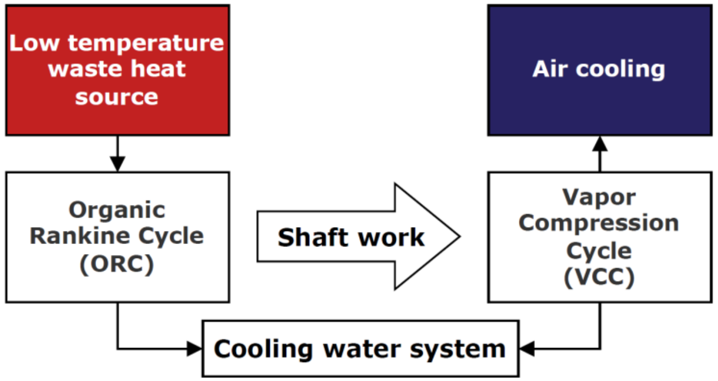


Figure 1: *Conception of the ORC-VCC systems.*

Cooling and electricity generation

- Versatility.
- High efficiency of the system.

Cooling generation

- High efficiency of the expander and compressor.
- High efficiency of the system.
- Wide operating characteristics of the system.
- Simplicity.

METHODOLOGY

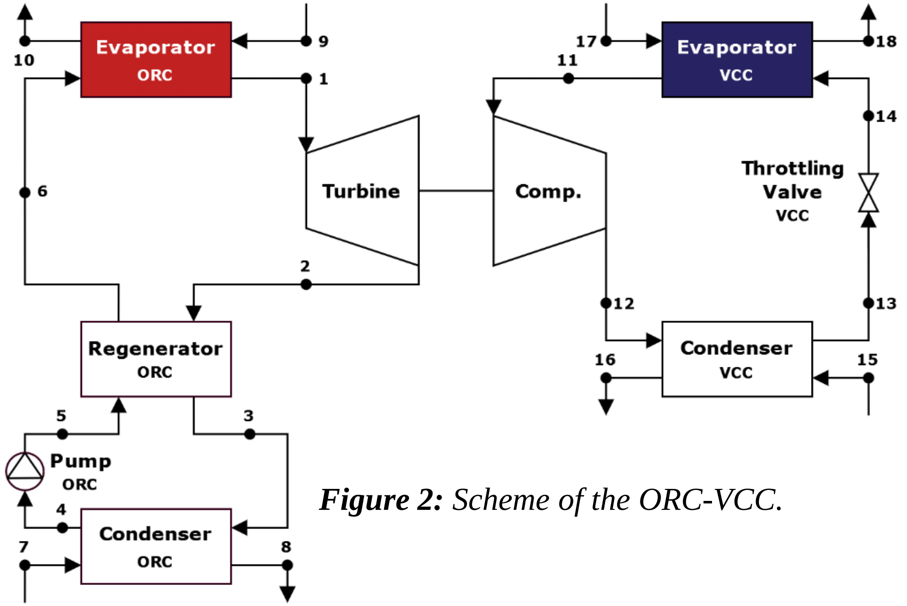


Figure 2: *Scheme of the ORC-VCC.*

EFFICIENCY AND THERMODYNAMIC ASSUMPTIONS

- Chilled water temperature (cold side) – 8ºC
- Chilled water temperature (hot side) – 12ºC
- Cooling water temperature (cold side) – 15ºC
- Heat source mass flow – 1 kg/s
- Heat source temperature (hot side) – 95ºC
- Compressor efficiency – 80%
- Pump efficiency – 50%
- Turbine efficiency – 80%
- Pressure losses not included.
- **$p_2 = p_{12}$!**
- R1224yd(Z), R1233zd(E), R133yd(Z).

ECONOMICAL ASSUMPTIONS

- Electricity prices for non-household consumers [10]:
  - Greece 0.3042 €/kWh
  - Italy 0.2525 €/kWh
  - Poland 0.1555 €/kWh
  - Spain 0.1879 €/kWh
- Cost of ORC-VCC system (up to 35 kWth) – 30 000 €
- Discount rate (NPV analysis) – 5%
- Operation time – 8 years
- Annual operation time – 8000 h

1. $C_i = (P_{comp} - P_{porc} - P_{pcs}) * AOT * C_{ei}$
2. $SPBT = C_s / C_i$
3. $NPV = \sum_{j=1}^{t} \frac{C_{ij}}{(1+d)^j} - C_s$
4. $\sum_{j=1}^{t} \frac{C_{ij}}{(1+IRR)^j} = C_s$

OPTIMIZATION APPROACH

Optimization

„the act of making something as good as possbile" (Cambridge Dictionary)

Figure 3: *Optimization concept.*

OPTIMIZATION APPROACH

OBJECTIVE FUNCTIONS

R1233zd(E)	R1336mzz(Z)	R1224yd(Z)
$f_0 = NPV$	$f_6 = NPV$	$f_9 = NPV$
$f_1 = \mathrm{IRR}$	$f_7 = \mathrm{IRR}$	$f_{10} = \mathrm{IRR}$
$f_2 = \eta_{cyc}$	$f_8 = \eta_{cyc}$	$f_{11} = \eta_{cyc}$

$$f_3 = 0.3 \times \mathrm{NPV} + 0.7 \times \eta_{cyc}$$

$$f_4 = 0.5 \times \mathrm{NPV} + 0.5 \times \eta_{cyc}$$

$$f_5 = 0.7 \times \mathrm{NPV} + 0.3 \times \eta_{cyc}$$

- Optimization algorithm – hybrid algorithm, Genetic Algorithm (GA) + Pattern Search Method (PA).
- MATLAB script.
- 11 parameters (decision variables).
- 8 penalty functions.

PENALTY FUNCTIONS

- Temperature.
- Mass flow rate.
- Turbine power > Compressor power

PARAMETERS

	PARAMETERS	UNIT	LB	UB
x_1	Evaporator pinch temperature difference (VCC)	K	3	10
x_2	Degree of superheating in evaporator (VCC)	K	3	10
x_3	Degree of subcooling in condenser (VCC)	K	3	10
x_4	Regenerator pinch temperature difference (ORC)	K	3	15
x_5	Degree of superheating in evaporator (ORC)	K	3	15
x_6	Degree of subcooling in condenser (ORC)	K	7	15
x_7	Evaporator pinch temperature difference (ORC)	K	3	10
x_8	Condenser pinch temperature difference (ORC)	K	3	10
x_9	Saturation temperature in evaporator (ORC)	ºC	50	85
x_{10}	Saturation temperature in evaporator (ORC)	ºC	25	55
x_{11}	Chilled water mass flow rate	kg/s	0.7	2

RESULTS

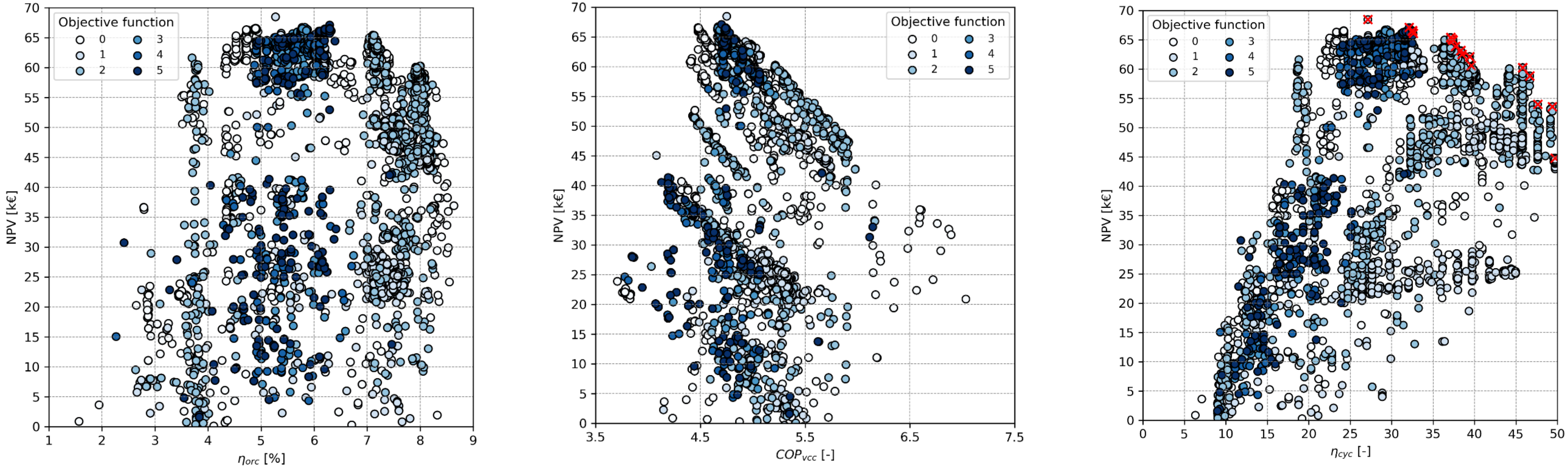
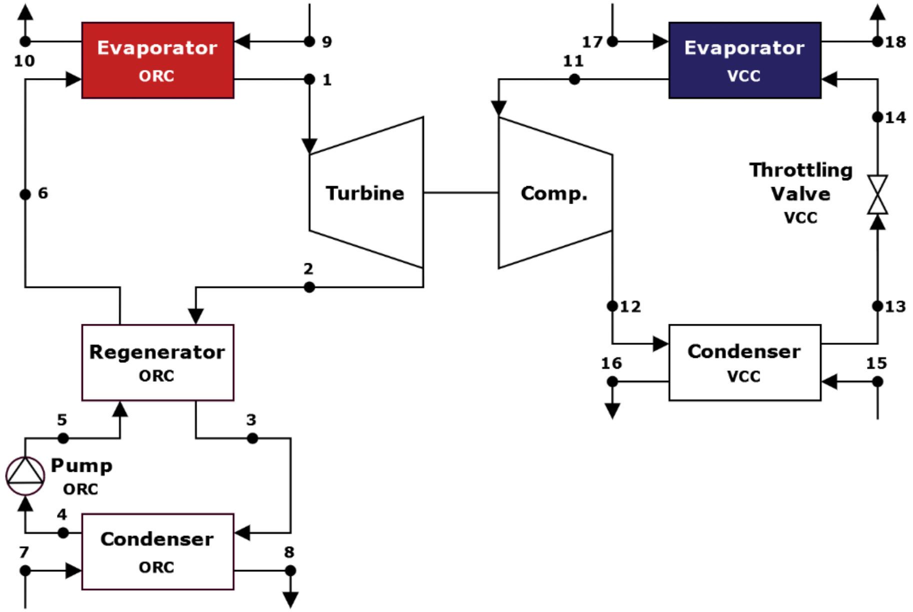


***Figure 4:** of NPV with ηorc (left), COPvcc (center) and η_{cyc} (right).*

RESULTS



PARAMETERS		UNIT	LB	O	UB
x_1	Evaporator pinch temperature difference (VCC)	K	3	9.82	10
x_2	Degree of superheating in evaporator (VCC)	K	3	5.24	10
x_3	Degree of subcooling in condenser (VCC)	K	3	9.28	10
x_4	Regenerator pinch temperature difference (ORC)	K	3	13.97	15
x_5	Degree of superheating in evaporator (ORC)	K	3	4.65	15
x_6	Degree of subcooling in condenser (ORC)	K	7	8.38	15
x_7	Evaporator pinch temperature difference (ORC)	K	3	5.81	10
x_8	Condenser pinch temperature difference (ORC)	K	3	4.17	10
x_9	Saturation temperature in evaporator (ORC)	ºC	50	64.9	85
x_{10}	Saturation temperature in evaporator (ORC)	ºC	25	41.26	55
x_{11}	Chilled water mass flow rate	kg/s	0.7	1.99	2

ORC

t_1 = 73.73ºC, p_1= 447 kPa
t_2 = 55.06ºC, p_2= 210 kPa
t_3 = 48.82ºC, p_3= 210 kPa
t_4 = 34.61ºC, p_4= 210 kPa
t_5 = 34.85ºC, p_5= 447 kPa
t_6 = 79.19ºC, p_6= 447 kPa
t_8 = 31.11ºC, t_{10} = 65.62ºC

VCC

t_{11} = 3.41ºC, p_{11}= 44 kPa
t_{12} = 51.21ºC, p_{12}= 210 kPa
t_{13} = 29.97ºC, p_{13}= 210 kPa
t_{14} = -1.83ºC, p_{14}= 44 kPa
t_{16} = 31.11ºC

P_{tur} = 6.97 kW
P_{comp} = 6.93 kW
P_{p_orc} = 0.23 kW
P_{p_cs} = 0.46 kW

IRR = 48.65%
NPV = 68.47%
SPBT = 1.97

η_{cyc} = 27.1%
η_{orc} = 5.27%
COP_{vcc} = 4.75

RESULTS

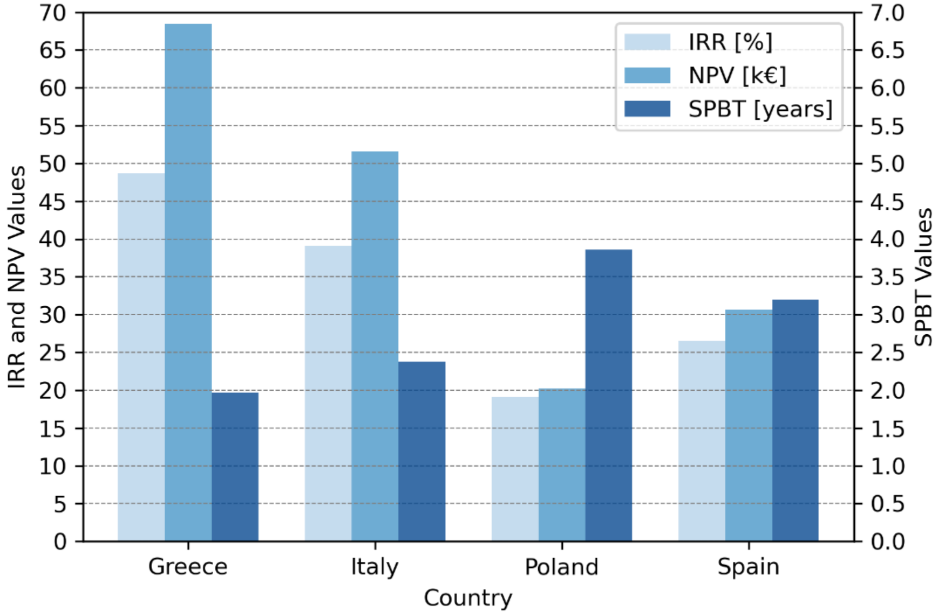
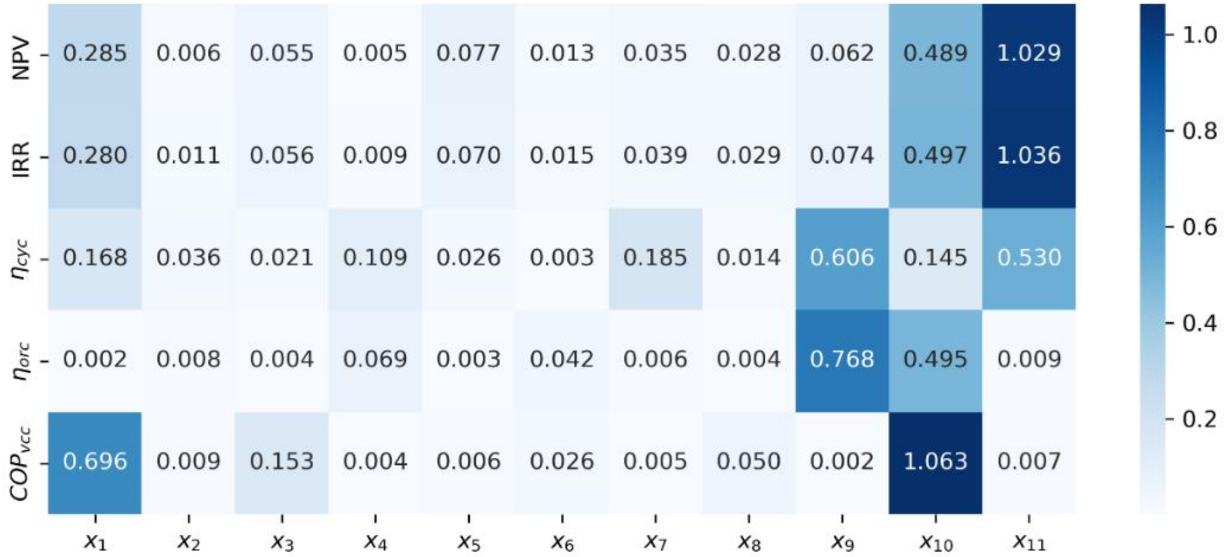


Figure 5: *Comparison of economic indicators in selected UE countries.*

PARAMETERS SIGNIFICANCE

PARAMETERS

- x_1 Evaporator pinch temperature difference (VCC)
- x_2 Degree of superheating in evaporator (VCC)
- x_3 Degree of subcooling in condenser (VCC)
- x_4 Regenerator pinch temperature difference (ORC)
- x_5 Degree of superheating in evaporator (ORC)
- x_6 Degree of subcooling in condenser (ORC)
- x_7 Evaporator pinch temperature difference (ORC)
- x_8 Condenser pinch temperature difference (ORC)
- x_9 Saturation temperature in evaporator (ORC)
- x_{10} Saturation temperature in evaporator (ORC)
- x_{11} Chilled water mass flow rate



ORC-VCC SYSTEM FOR AIR CONDITIONING

- Due to the need to reduce electricity consumption, methods of increasing the efficiency are being sought.
- One of the possibilities is the use of low-temperature waste heat for electricity or/and cooling.
- Simplified version of the system was investigated.
- An in-house code was developed for cycle calculation.
- Various novel working fluids are considered.
- Single and multi-objective optimization was conducted.
- The obtained cycle efficiency was 27.1%.
- Simple pay back time was received less than 2 years.

Literature

[1] www.showyourstripes.info, Ed Hawkins, National Centre for Atmospheric Science, University of Reading., National Centre for Atmospheric Science, UoR.

[2] www.iea.org/t_c/termsandconditions, The International Energy Agency.

[3] C. Forman, I.K. Muritala, R. Pardemann, B. Meyer, Estimating the global waste heat potential, Renewable and Sustainable Energy Reviews, 57 (2016) 1568–1579. doi:10.1016/j.rser.2015.12.192.

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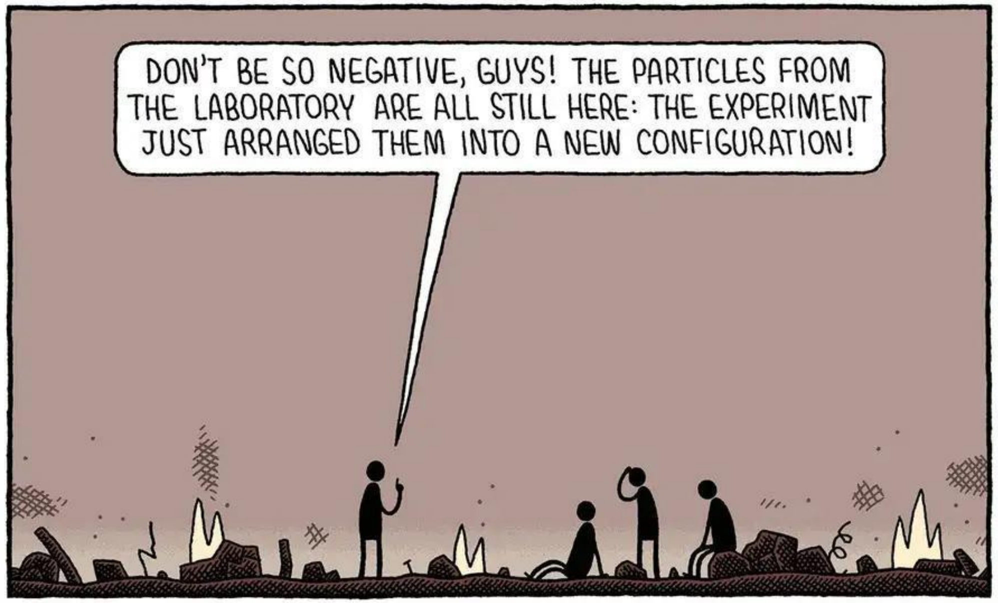

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