Thermo-economic Optimization of Subcritical and Transcritical ORC Systems

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WHO ?

Startup company, created in 2008

Headquarters in Paris, France.15 employees

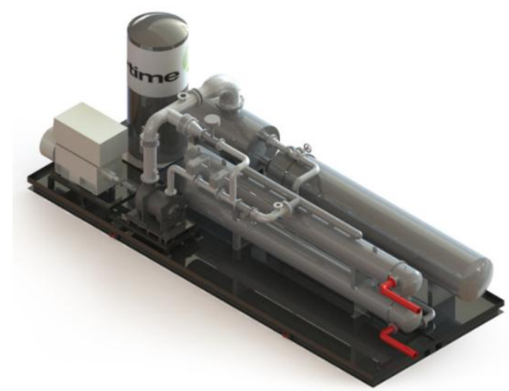
Profile

Design and construction of turnkey ORC systems and axial turbines

Engineering and consulting in renewable energy

References

ORCHID©, Chateaubriand, France
WHR 1 MWe
November 2012



ORCHID© Cogen, Montpellier, France
CHP 600 kWe + 4 MWth 90°C
Summer 2014

PROBLEM STATEMENT

Application :

Low-temperature heat source (100°C – 150°C), medium power (200-1000 kWe)

Question :

Do transcritical cycles result in a better profitability?

Based on the SURORC Project (2012), funded by the French Energy Agency (ADEME), realized with partners:

METHODOLOGY

Heat source : Water, inlet 100°C < T < 150°C, 15 kg/s

Cold sink : Water, inlet 15°C, outlet 25°C

Fluid selection : focus on non flammable/mildly flammable fluids

	HFC				HFO		
Fluid	**R134a**	**R227ea**	**R125**	**R245fa**	**R1234yf**	**R1234ze(e)**	**R1233zd(e)**
Tc [°C]	101,1	101,75	66,023	154,01	94,7	109,36	165,6
Pc [bar]	40,6	29,25	36,17	36,51	33,82	36,34	35,7
GWP	1430	3220	3500	1030	4	6	7
ASHRAE 34	A1	A1	A1	B1	A2	A2L	A1 (?)

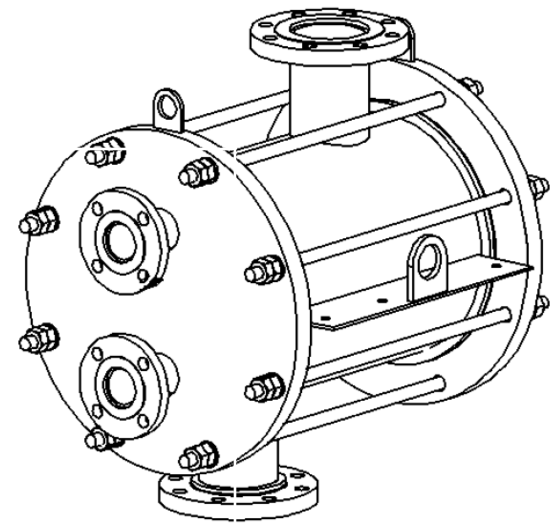
Modeling

- ORC cycle calculation EES® + REFPROP® 9.1
- Heat exchanger and axial turbine preliminary design
- Realistic cost functions based on offers from suppliers

HEAT EXCHANGERS

Plate heat exchangers

- High heat transfer efficiency
- Low refrigerant charge
- Small temperature approach
- Lower cost
- Compact size



Evaporator

Welded plate heat exchanger (suitable for pressure up to 200 bar)

Condenser

Semi-welded plate heat exchanger (suitable for pressure<40 bars, temperature<150°C)

Cost

Linear with respect to heat transfer area

$$Cost_{evaporator} = 0.2604 \cdot A + 0.0423\ [k€]$$

$$Cost_{condenser} = 0.2284 \cdot A - 6.3434\ [k€]$$

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HEAT EXCHANGERS

Model (inspired from Quoilin 2011)

Enthalpy discretization of the heat exchanger. Iterate on geometry until total ΔP=30 kPa.

Outputs: total heat transfer area A + refrigerant charge

Condensation heat transfer correlation from Yan (1998)

Evaporation heat transfer correlation from Hsieh (2002)

Supercritical heat transfer correlation from Jackson (1979)

$$Nu_b = 0.0183 \cdot Re_b^{0.82} \cdot Pr^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \cdot \left(\frac{\bar{C}_p}{C_{p_b}}\right)^{n}$$

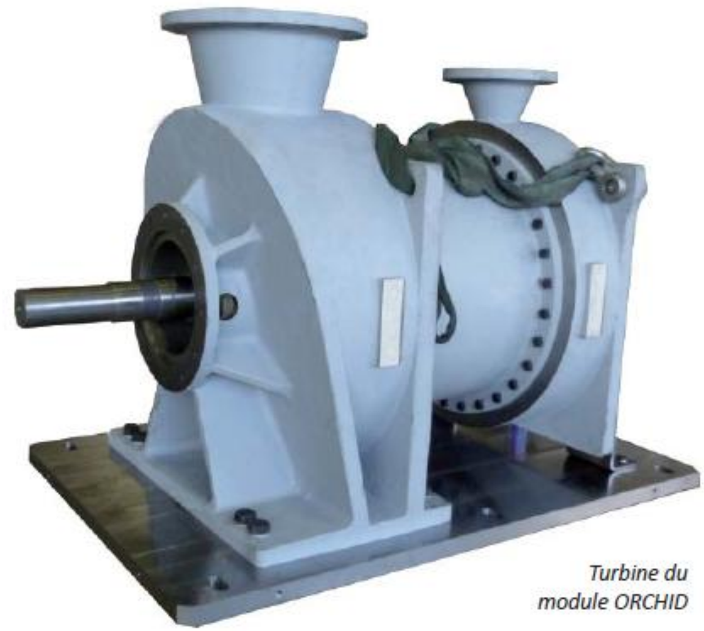
Limits

- Few experimental results on heat transfer and pressure drops with refrigerants at supercritical pressures
- High uncertainty of subcritical heat transfer and pressure drop correlations at high pressures

Axial Turbine Preliminary Design

Hypothesis

- Fixed rotation speed : 3000 rpm
- Half reaction turbine
- Repeated velocity triangles
- Subsonic flow for higher efficiency
- Simple geometry and manufacturing



Turbine du module ORCHID

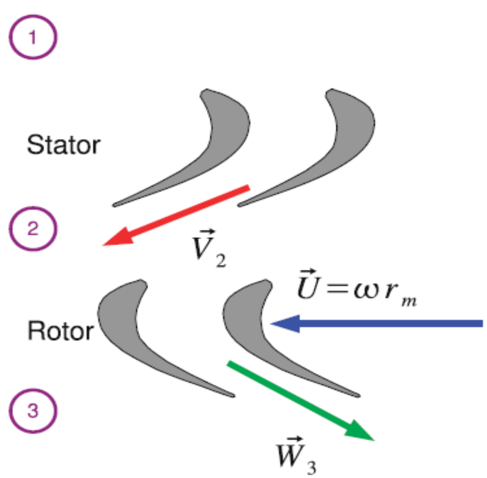
Goal

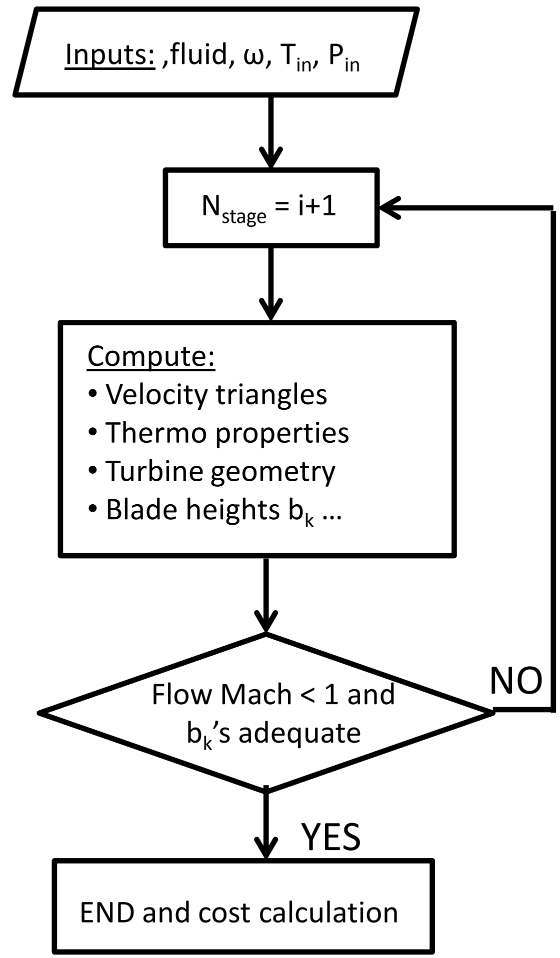
$$number\ of\ stages \approx \frac{\Delta H}{(R \cdot \omega)^2}$$

Axial Turbine Preliminary Design

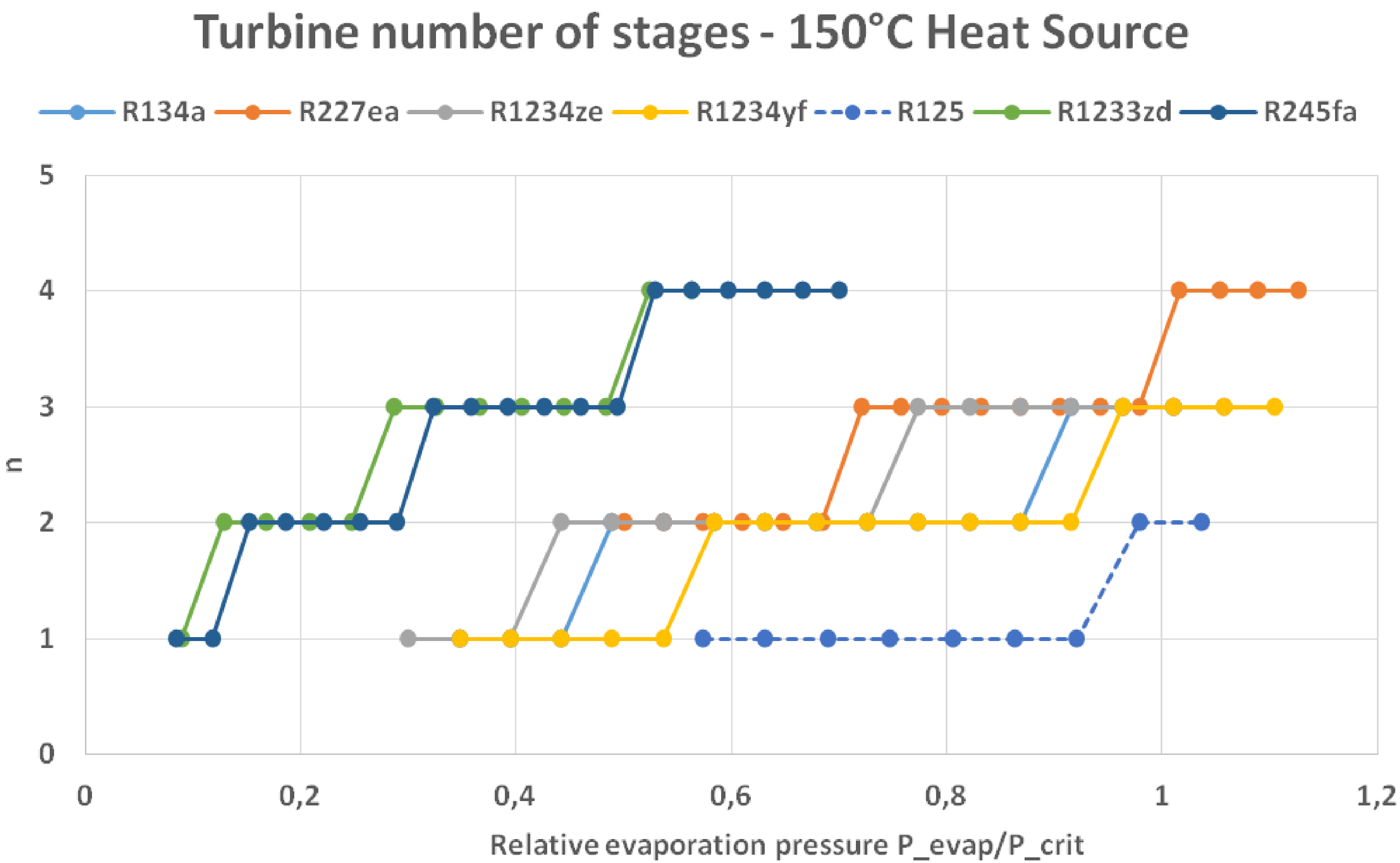
Outputs

- Number of stages
- Geometry of the turbine wheels
- Height and number of the turbine blades





Axial Turbine Preliminary Design



Axial Turbine cost

$$Cost_{turbine} = fixed\ costs + \sum Cost_{stage}(i)$$

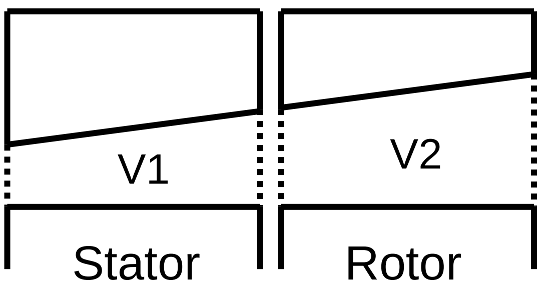
Fixed cost (valid only in a limited range of power and rotation speed)

- Bearings
- Mechanical seals
- Lubrication system
- Other…

Variable cost

Manufacturing time for the weel and casing

$$Cost_{stage} = \alpha \cdot V^3 + \beta \cdot V^2 + \gamma \cdot V + \delta$$



Other cost functions

Refrigerant : from 6.5€/kg to 27€/kg

Generator : $Cost_{generator} = 0.50863 \cdot Power^{0.7326}\ [k€]$

Pump : $Cost_{pump} = 0.5681 \cdot Power^{0.6548}\ [k€]$

Mechanical parts:

- Piping (purchase + welding): $Cost_{piping} = 129.23 \cdot D^2 - 25.808 \cdot D + 7.546\ [k€]$
- Other (skid, insulation, installation…) : fixed cost

Electrical equipments, instrumentation and controls : fixed cost

Other fixed cost :

Engineering, transportation, installation, insurance…

Genetic Algorithm Optimization

Heat source : 15 kg/s of water at T=100…150°C

Optimization parameters

- Relative evaporation pressure P_evap/P_crit : 0,1 … 1,3
- Superheating : 3 … 30°C
- Evaporator pinch temperature difference : 3 … 15°C

Objective function

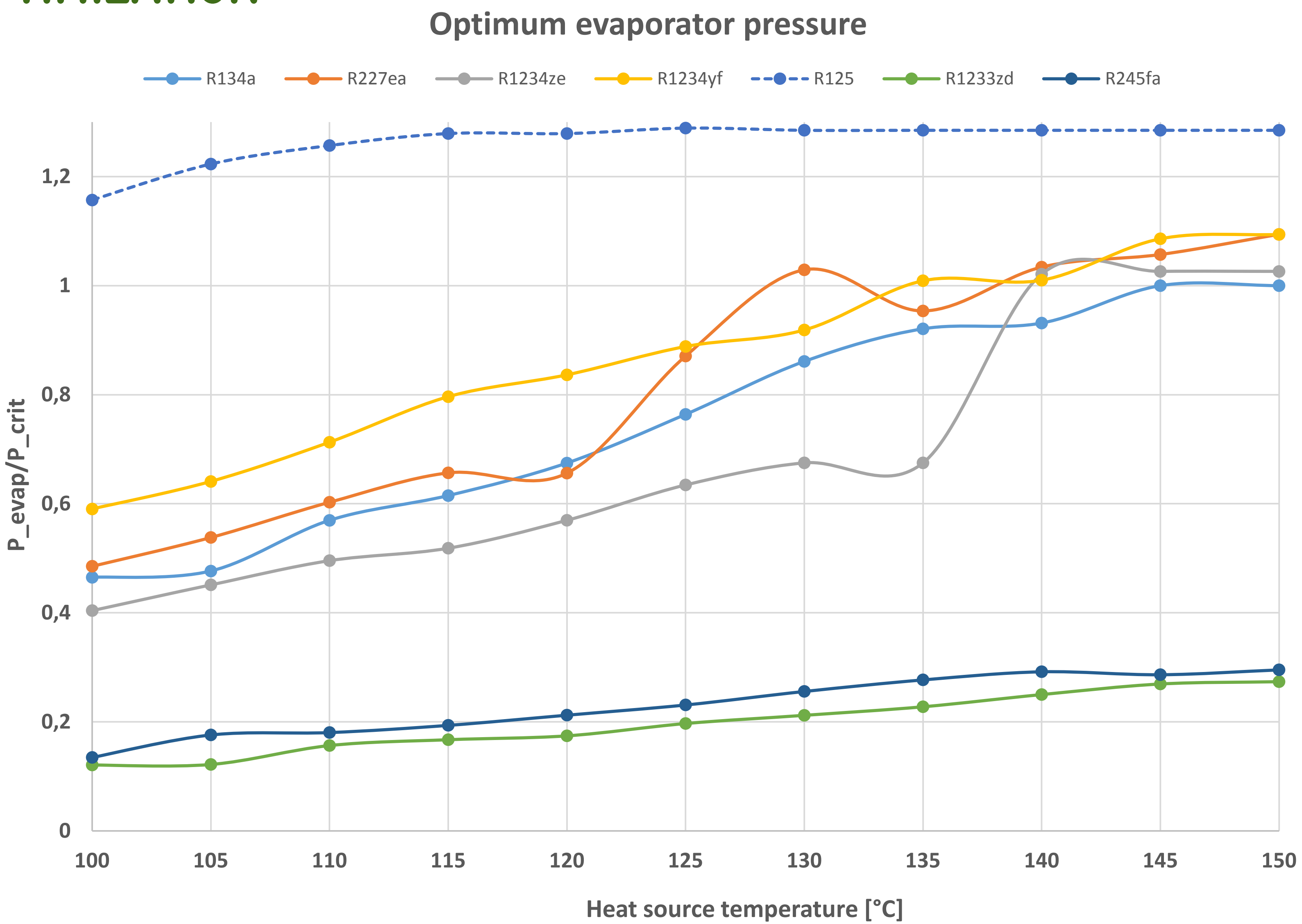
Minimize SIC (Specific Investment Cost) = Total Investment Cost/Net output Power

Other parameters

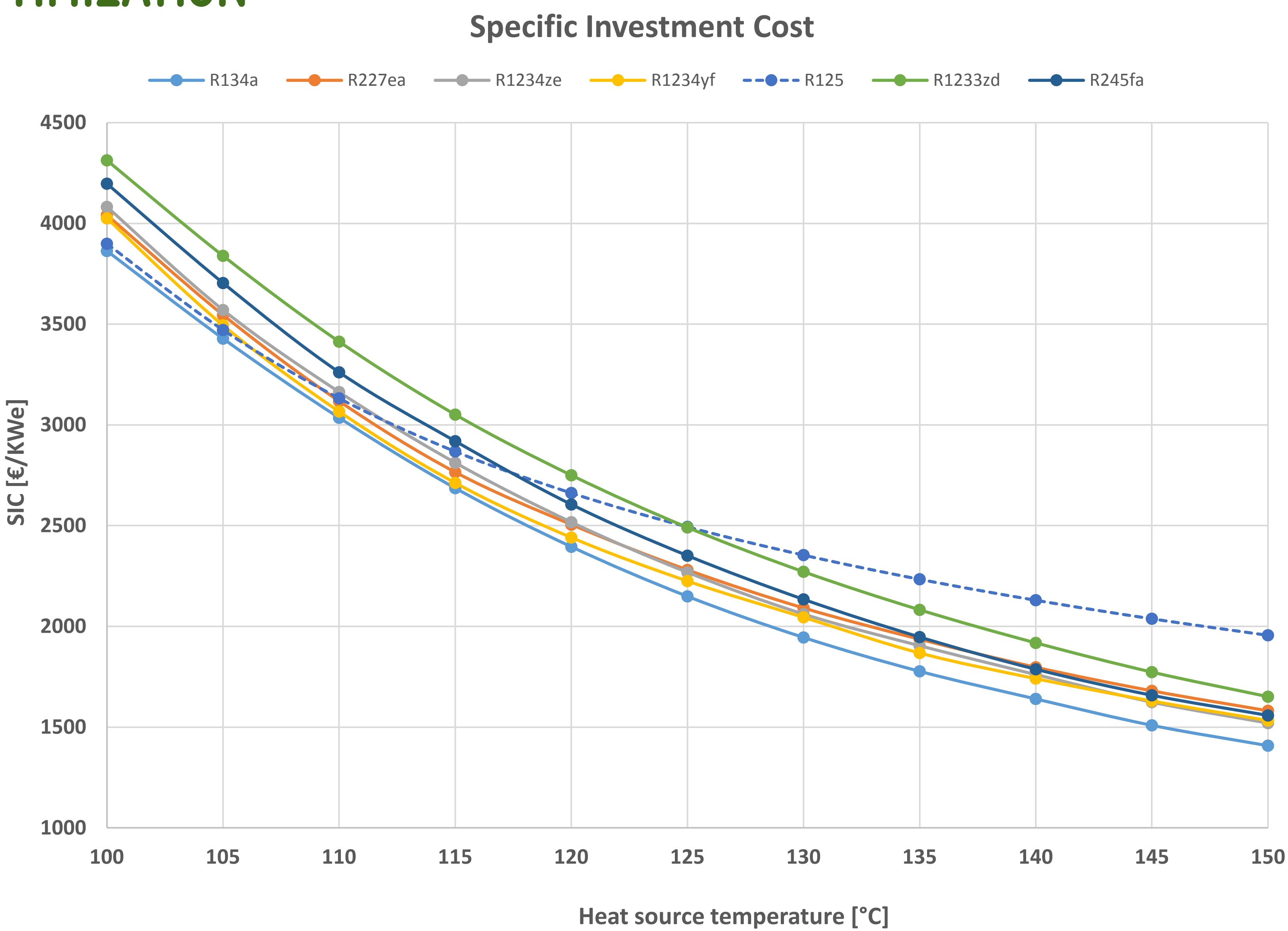
Condensation temperature : 30°C
Condenser subcooling : 3°C
Water cooling inlet : 15°C
Water cooling outlet : 25°C

Turbine efficiency : 85 %
Generator efficiency : 95%
Pump efficiency : 70%

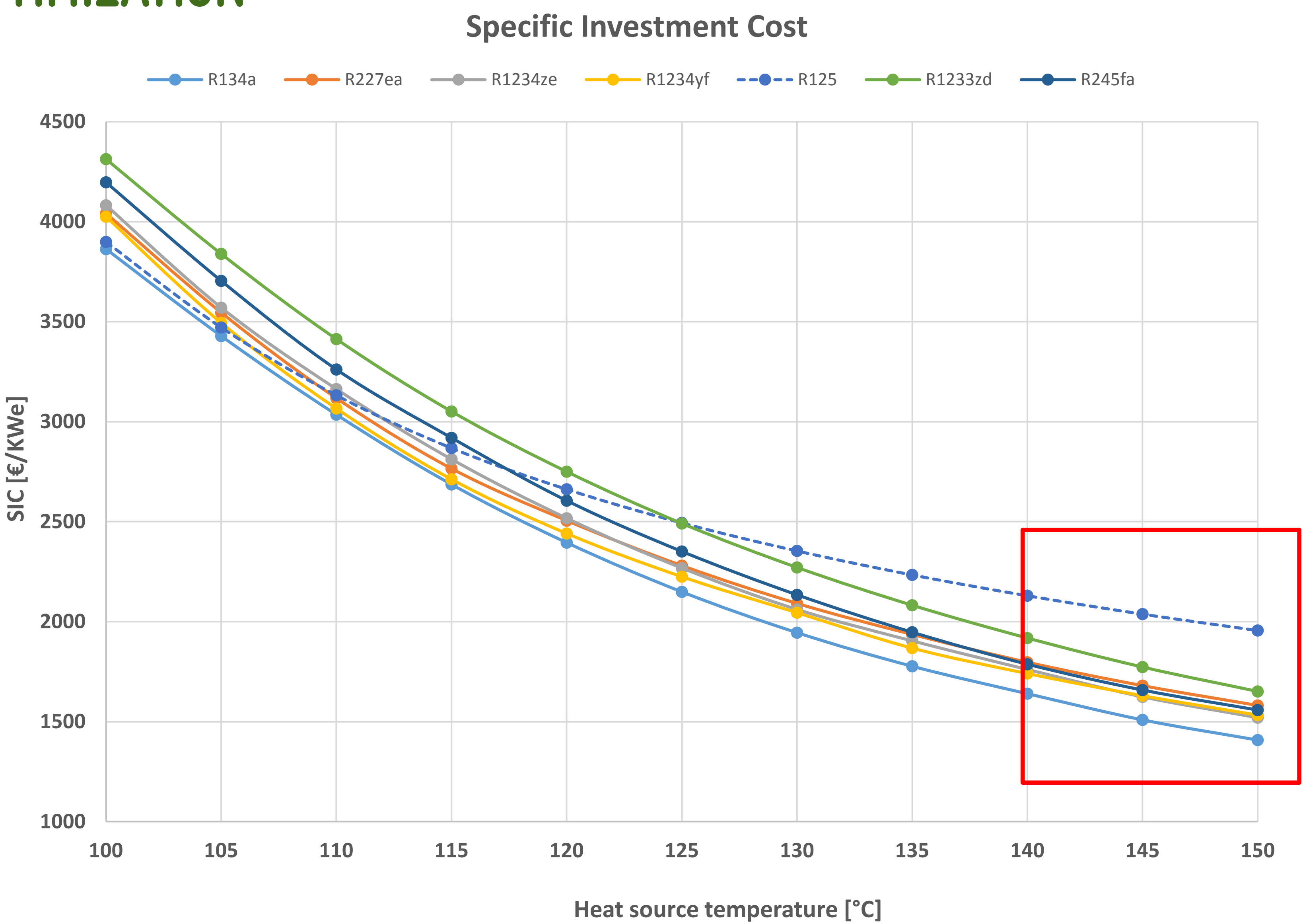
Optimization



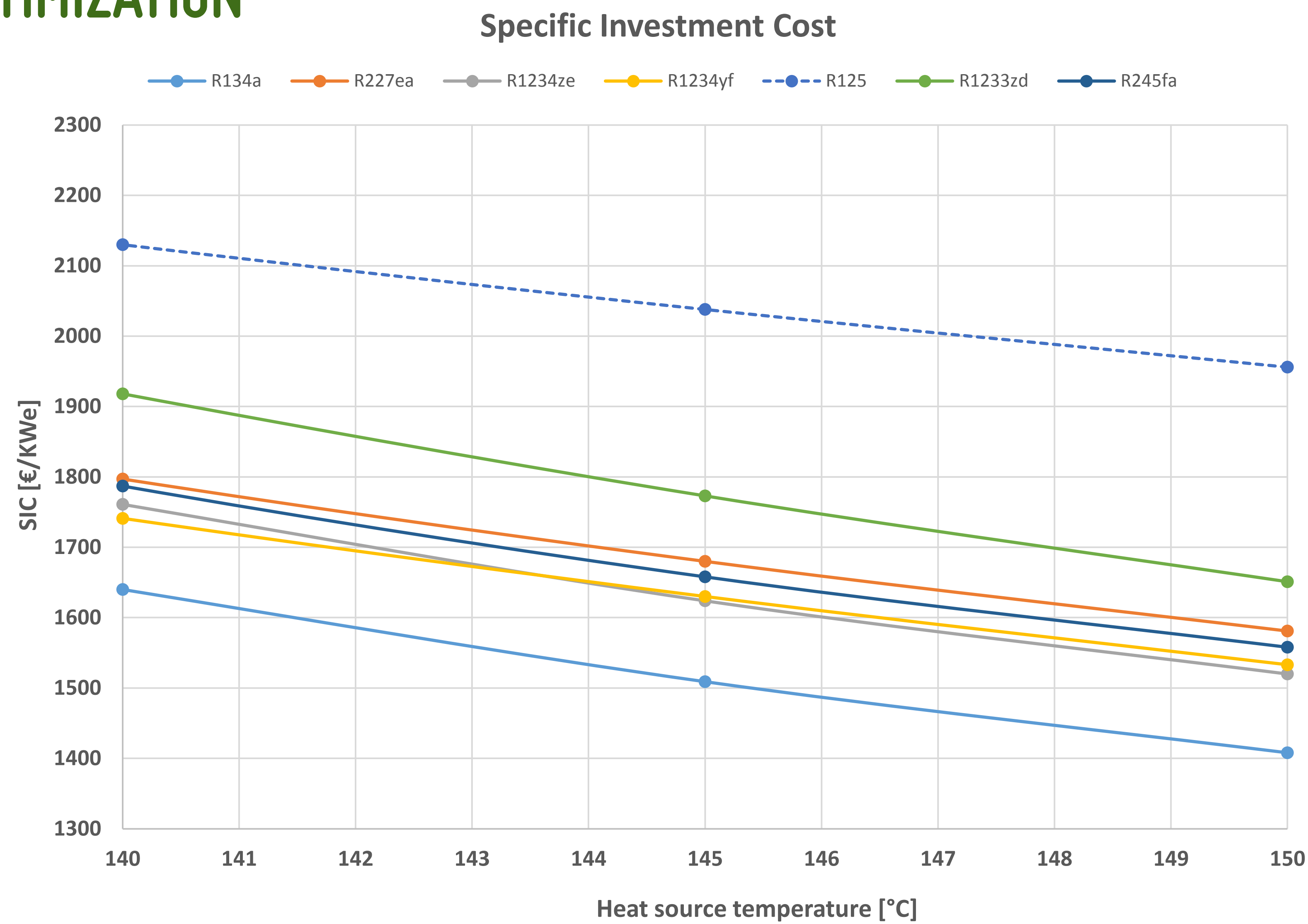
Optimization



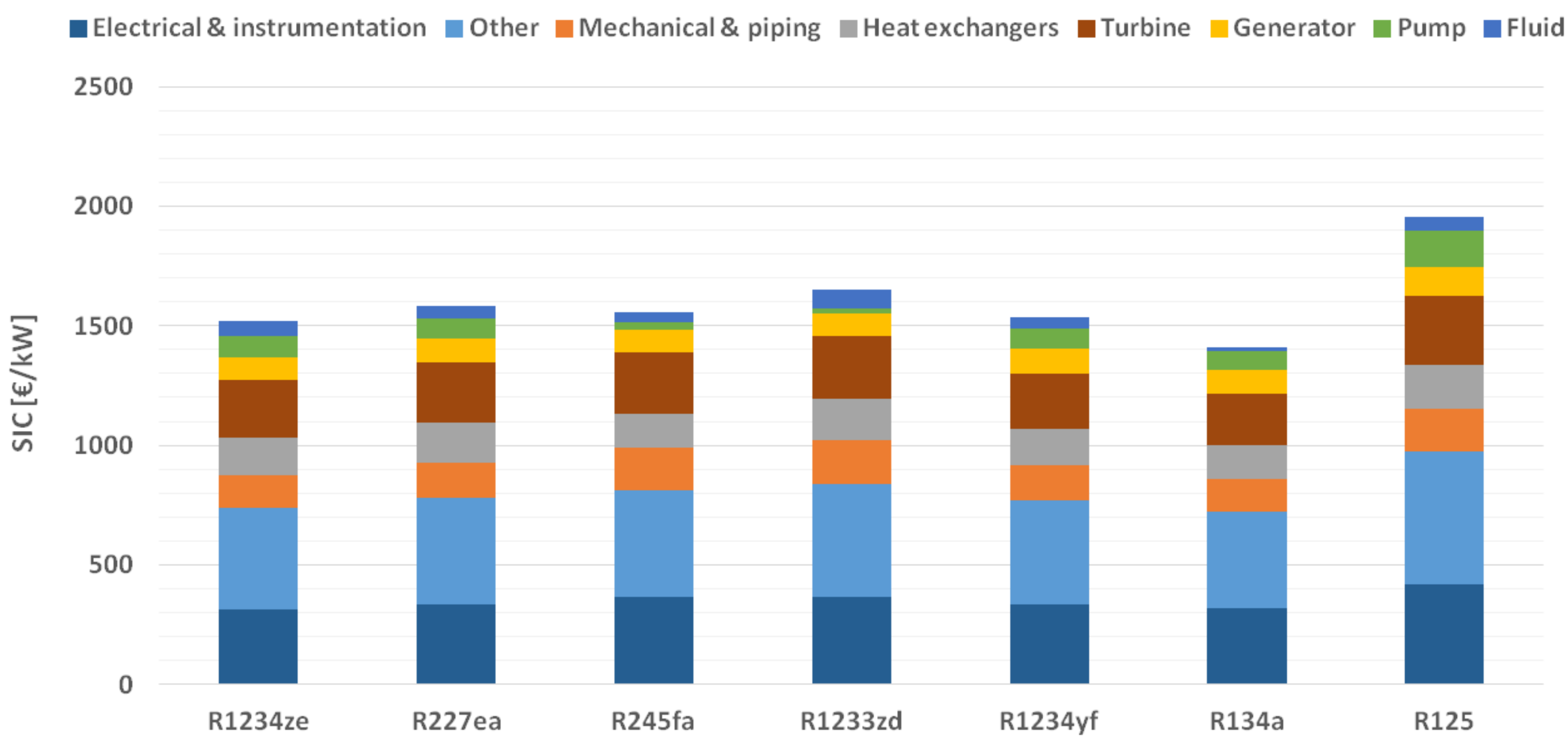
Optimization



Optimization



Specific Investement Cost Breakdown – 150°C



	R1234ze	R227ea	R245fa	R1233zd	R1234yf	R134a	R125
Net power	706 kW	659 kW	604 kW	601 kW	654 kW	687 kW	523 kW
Total Investment	1072 k€	1042 k€	941 k€	991 k€	1003 k€	968 k€	1024 k€

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THANK YOU

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