4th International Seminar on ORGANIC RANKINE CYCLE POWER SYSTEMS

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Design and Off-Design Analysis of an ORC Coupled with a Micro-Gas Turbine

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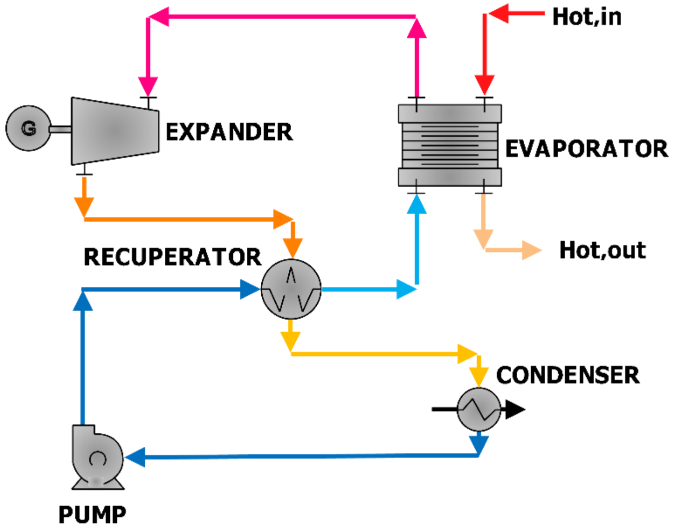

AGENDA

1. Introduction
2. Methodology
3. Case Study
4. Results
5. Conclusions

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INTRODUCTION

- Energy → Essential → Development → Nations
- Total Primary Energy Consumption → Based → Non-Renewable Sources
- Recent Years → Increasing Concern → Energy Systems Environmental Impact
- New Energy Policies
  - *Renewable Energy Sources*
  - *Energy Efficiency*
  - *Waste Heat Recovery*
- Waste Heat Recovery → Sources → Medium/Low Temperature Heat Sources → Converted → Electricity

INTRODUCTION

- Organic Rankine Cycle → Valid Alternative → Conventional Steam Rankine Cycle → Fails
  - *Technical Problems*
  - *Economic Reasons*
- ORC → Operates → SRC → But → ORC Design
  - *Select → Working Fluid*
  - *Select → Plant Arrangement*
- Design Point Analysis → Fluid and Plant Configuration → But
  - *Are the Fluid and the Plant Arrangement Able to Guarantee Good Performance During Part-load Conditions??*

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METHODOLOGY

1. Design Point Analysis → ORC-PD tool → Optimisation Code
   - *Fluid Selection*
   - *Plant Configuration Optimisation*

2. Off-Design Analysis → ASPEN Tools

   I. *Aspen EDR → Heat Exchangers Design*
   II. *Aspen Plus → Plant Off-Design Behaviour*

- Analyses Results → Fluid, Plant Layout and Control Strategy → Fit → Heat Source Profile

METHODOLOGY: DESIGN POINT OPTIMIZATION

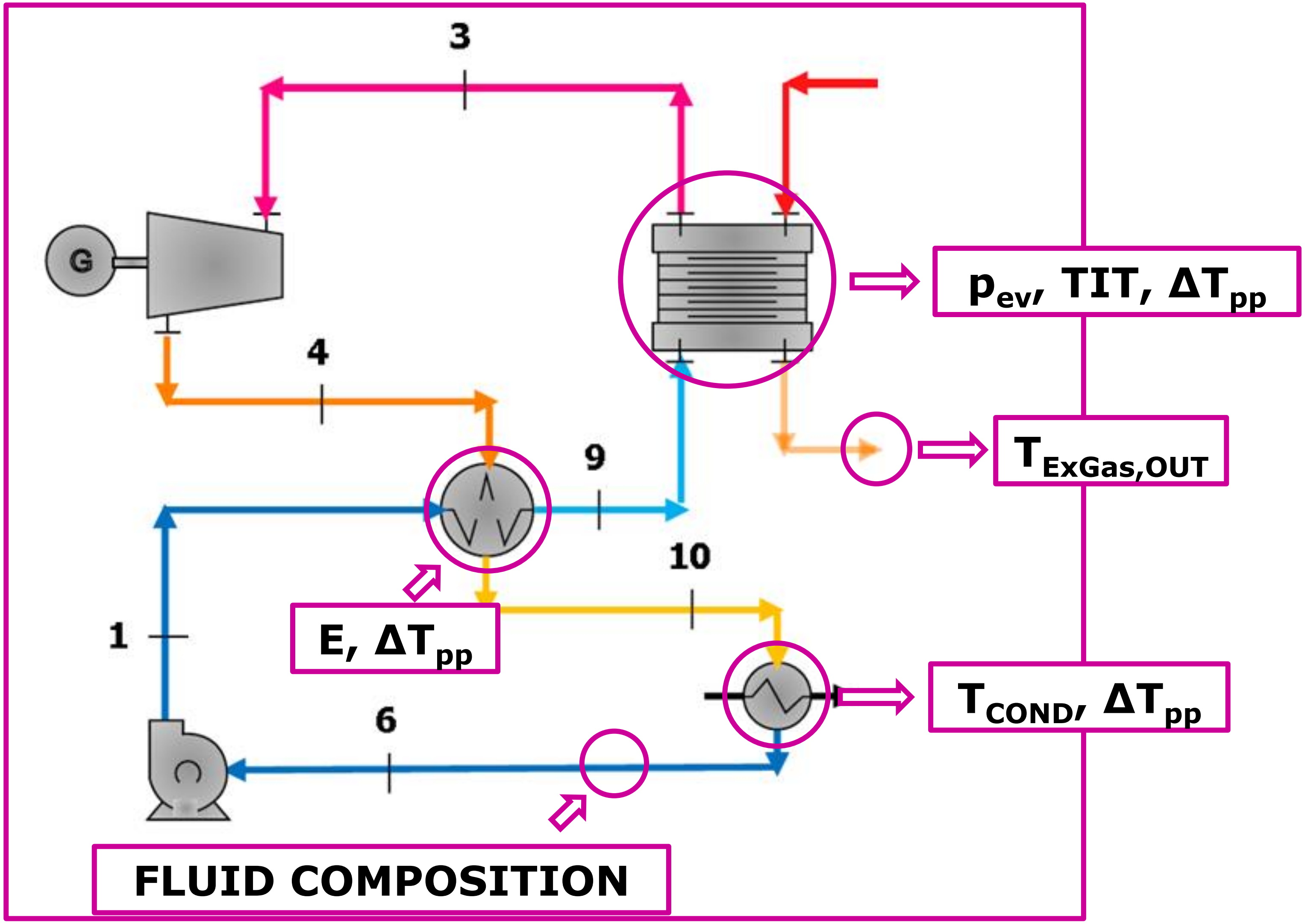
- ORC-PD tool → MATLAB Environment → CoolProp and REFPROP Databases
  - *Different Heat Sources*
  - *115 Pure Fluids and Their Mixtures*
  - *8 Plant Configurations*
  - *Axial and Radial Turbines Efficiency Charts*
  - *Sub- and Trans-critical Cycles*
- Possible Objective Functions
  - *Net Electric Power*
  - *Thermal Efficiency*
  - *Exergetic Efficiency*
  - *Profitability Index*
  - *Levelized Cost of Energy*

METHODOLOGY: DESIGN POINT OPTIMIZATION

- Tool Input Parameters
  - *Heat Sources Medium*
  - *Inlet Temperature and Pressure and Mass Flow of the Heat Source*
  - *Pump Isentropic and Mechanical Efficiency*
  - *Expander Mechanical Efficiency*
  - *Electric Generator Efficiency*
  - *Electric Motor Efficiency*
  - *Sink Type*

METHODOLOGY: DESIGN POINT OPTIMIZATION

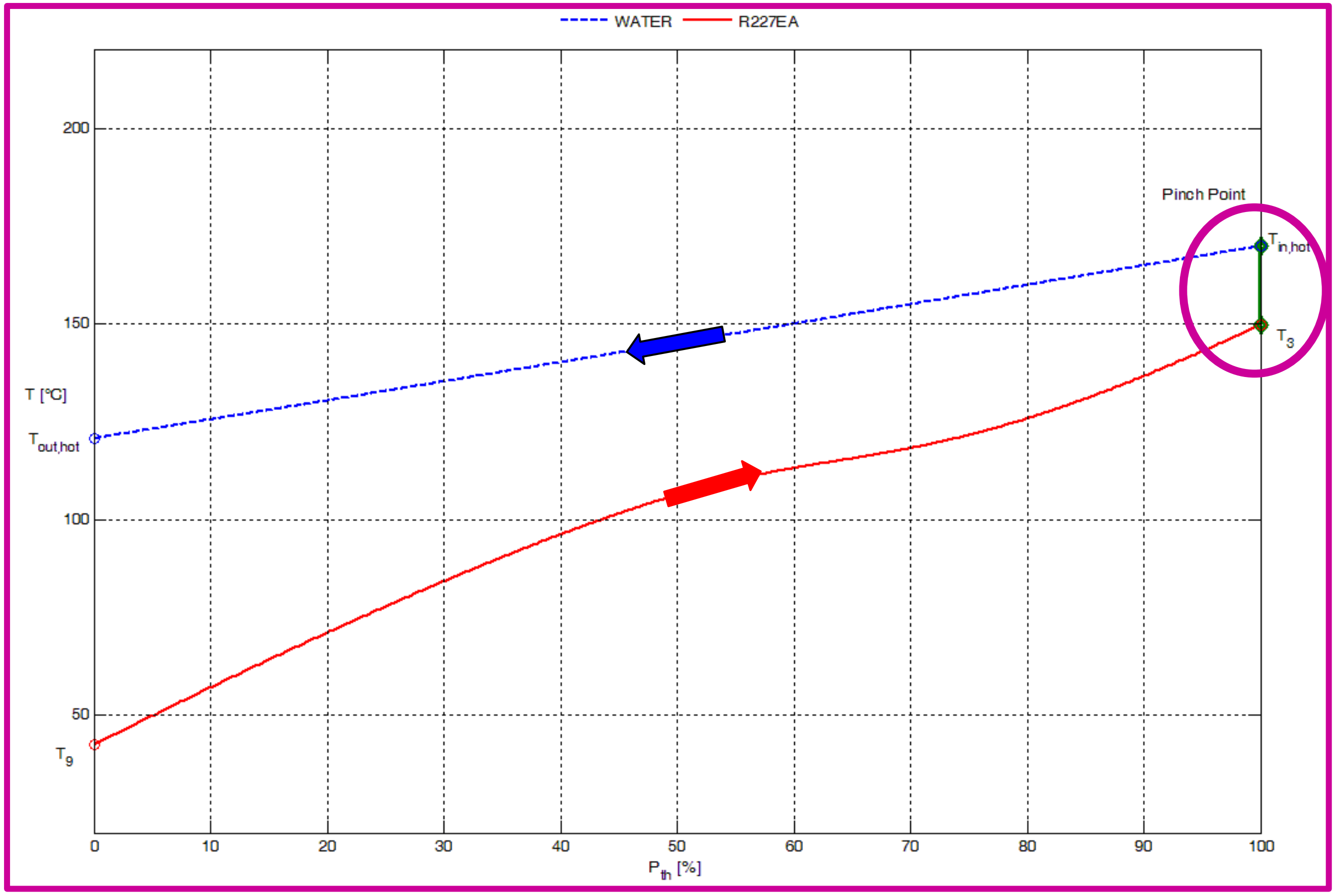
◇ Optimized Variables



METHODOLOGY: DESIGN POINT OPTIMIZATION

- Several Checks
  - *Evaporation in the Recuperator*
  - *Liquid at the Turbine Inlet*
  - *Steam Quality at the Turbine Outlet*
  - *Pinch Point Violation in the Heat Exchangers*
- Each Heat Exchanger → “n” Elements
- Not Fixed Pinch-Point Position

METHODOLOGY: DESIGN POINT OPTIMIZATION



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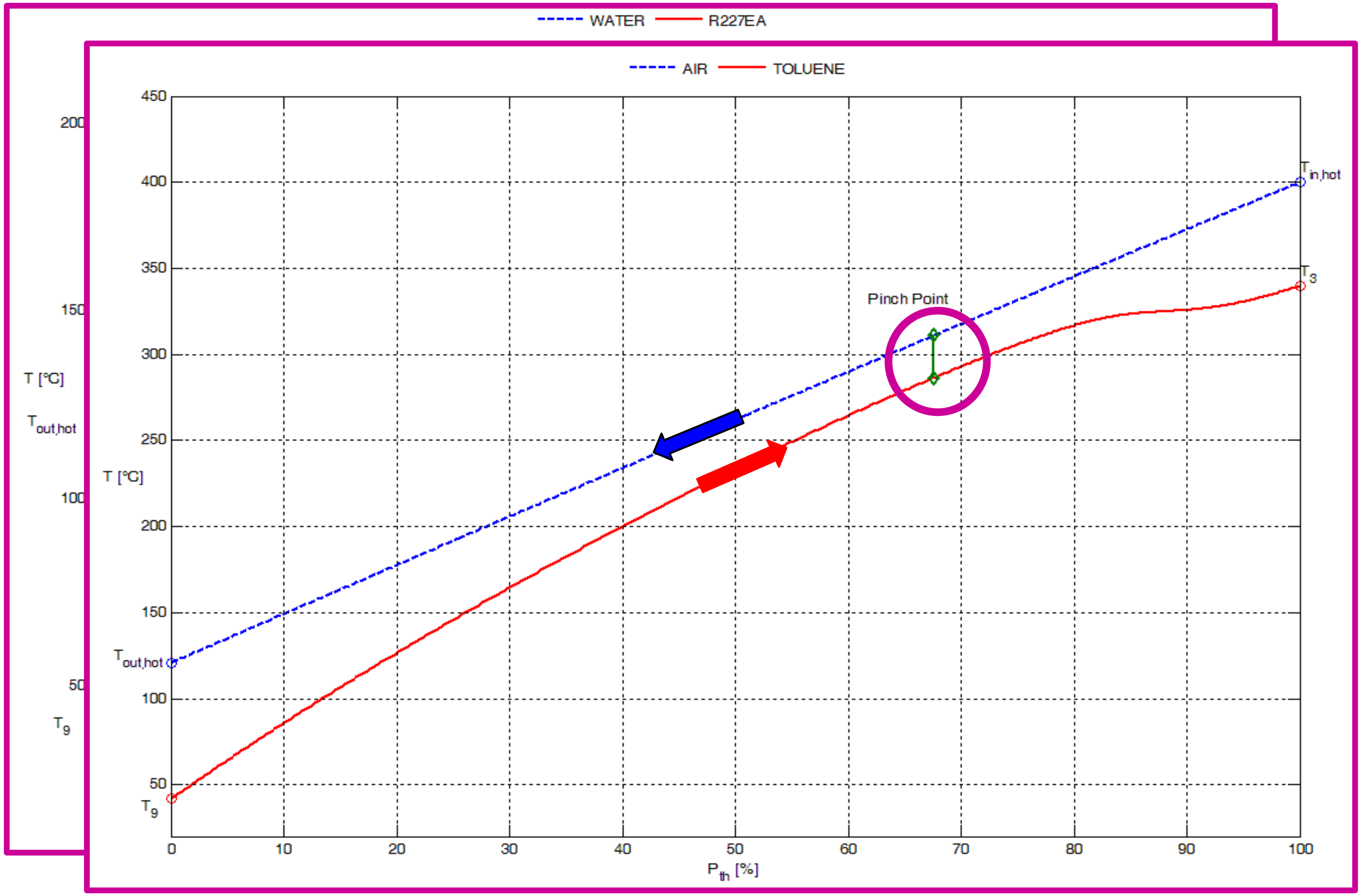

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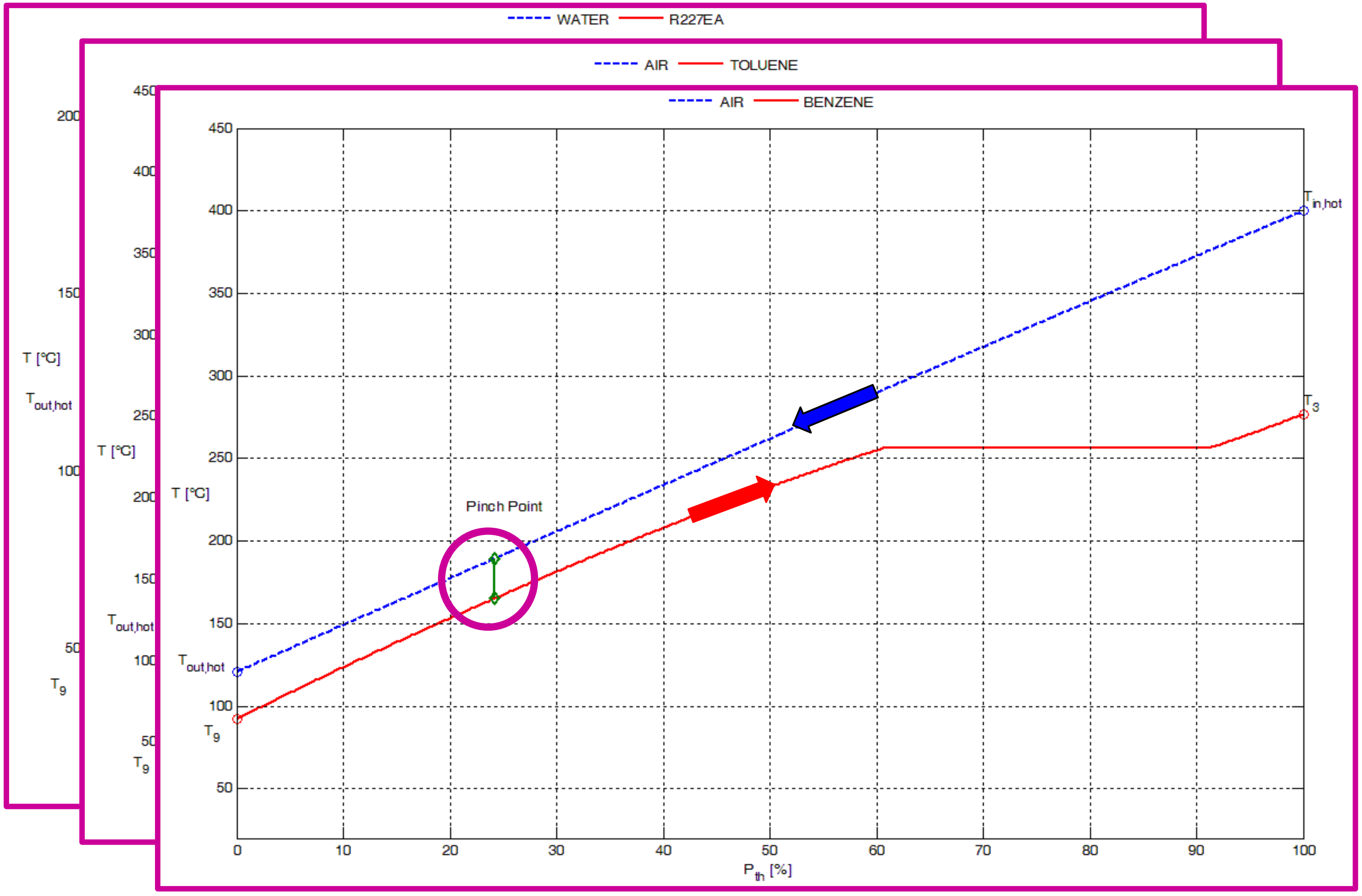

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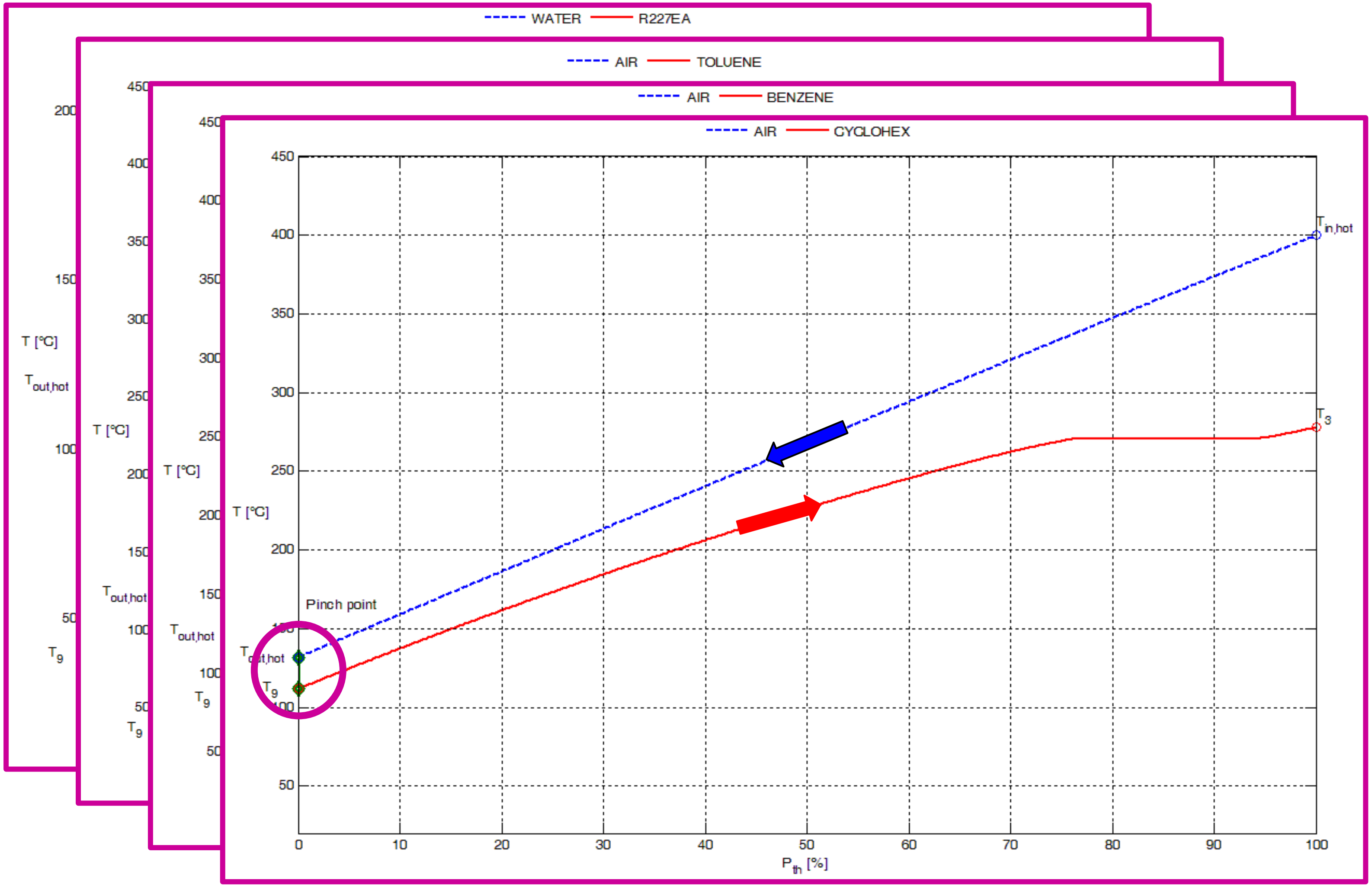

METHODOLOGY: DESIGN POINT OPTIMIZATION

- For Each Plant Configuration → ORC-PD tool → Performs → Energy, Exergy and Economic Analysis

- End → Design Point Optimisation Process
  - *One or More → Good → Working Fluids*
  - *One or More → Good → Plant Layouts*

- Are They Also Good → Off-Design???

METHODOLOGY: OFF-DESIGN ANALYSIS

- Aspen Exchanger Design and Rating (EDR) → Heat Exchangers → Detailed → Geometry Design
- Aspen Plus → ORC Off-Design Model → Predicts → Part-Load Behaviour
  - *Heat Exchangers Geometry*
  - *Turbine → Stodola's Equation*
  - *Pump → Real Centrifugal Pump Efficiency Maps*
  - *Dedicated Control System*

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CASE STUDY

- Small Manufacturing Industry
  - *Boiler → Process Heat & Space Heating → 250 kW_{th}*
  - *Photovoltaic Plant → 50 kW_{el}*
- Add → 65 kW_{el} m-GT → Exhaust Gases → Electricity Self Production → Non-cogenerative m-GT → Capstone C65
- Explore → Possibility → Recovers → 65 kW_{el} m-GT Exhaust Gases → Waste Heat Recovery Unit → Organic Rankine Cycle Turbogenerator

CASE STUDY

- m-GT Main Characteristics
  - *Fluid* → Exhaust Gases
  - *Exhaust Temperature* → 309 °C
  - *Exhaust Mass Flow* → 0.49 kg/s

- Goal of the Analysis
  - *Best Working Fluid* → *Pure Fluids or Mixtures*
  - *Best Configuration* → *Simple or Recuperative*
  - *Objective Function* → *Maximization of the Net Electric Power*
  - *Design* + *Off-Design* → *Approach*

AGENDA

RESULTS: DESIGN POINT ANALYSIS

Fluid	P_{el} (kW)	**E** (-)	p_{ev} (bar)	**TIT** (°C)	$T_{Hot,out}$ (°C)	p_{cond} (bar)	η_{ORC} (%)	**NPV** (M$)	**IP** (-)	**SPB** (y)
Cyclopen	*12.58*	*0*	*23.2*	*201.8*	*101.8*	*1.85*	*11.5*	*0.033*	*0.168*	*8.9*
R141b	*12.42*	*0*	*34.4*	*206.8*	*98.8*	*3.15*	*11.2*	*0.016*	*0.117*	*9.3*
Cyclohex	*12.40*	*0*	*10.3*	*183.9*	*102.9*	*0.68*	*11.4*	*0.032*	*0.166*	*8.9*

- Cyclopentane → Best Working Fluid in Design
- Best Configuration → Basic ORC Layout
- But → Among → Three Fluids → Difference → Produced Power → Really Small

RESULTS: OFF-DESIGN ANALYSIS

- Off-Design Behaviour → Three Cycles
- Aspen EDR → Heat Exchangers Design → Geometry → e.g. Cyclopentane

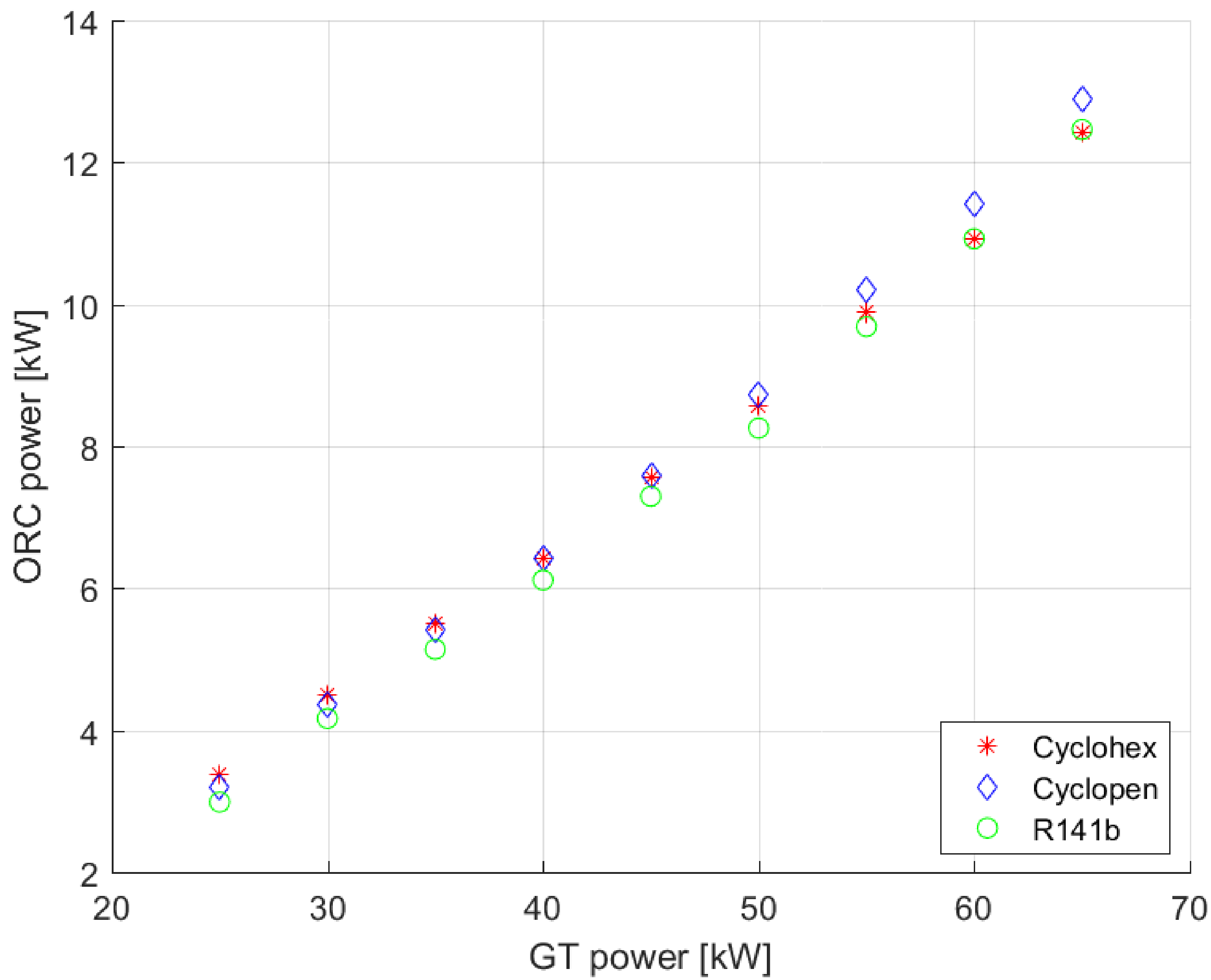
RESULTS: OFF-DESIGN ANALYSIS

	Evaporator	Condenser
Thermal power (kW)	106.6	94.8
Hot fluid mass flow rate (kg/s)	0.49	0.21
Cold fluid mass flow rate (kg/s)	0.21	2.23
Heat transfer area (m^2)	35.3	4.9
Tube external diameter (mm)	8	10
Tube thickness (mm)	1	1
Tube length (mm)	2410	1830
Shell inner diameter (mm)	316	163
Number of tubes	594	88
Number of passes - shell size	1	1
Number of passes - tube side	1	2
Tube pitch (mm)	10	12.5
Pressure drop - tube side (bar)	0.03	0.12
Pressure drop - shell size (bar)	0.09	0.05

RESULTS: OFF-DESIGN ANALYSIS

- Off-design Behaviour → Three Working Fluids
- Aspen EDR → Heat Exchangers Design → Geometry → e.g. Cyclopentane
- Aspen Plus → Plants Models → Control Strategy → Controlled Variable → Pump Rotational Speed → $TIT = TIT_{design}$

RESULTS: OFF-DESIGN ANALYSIS



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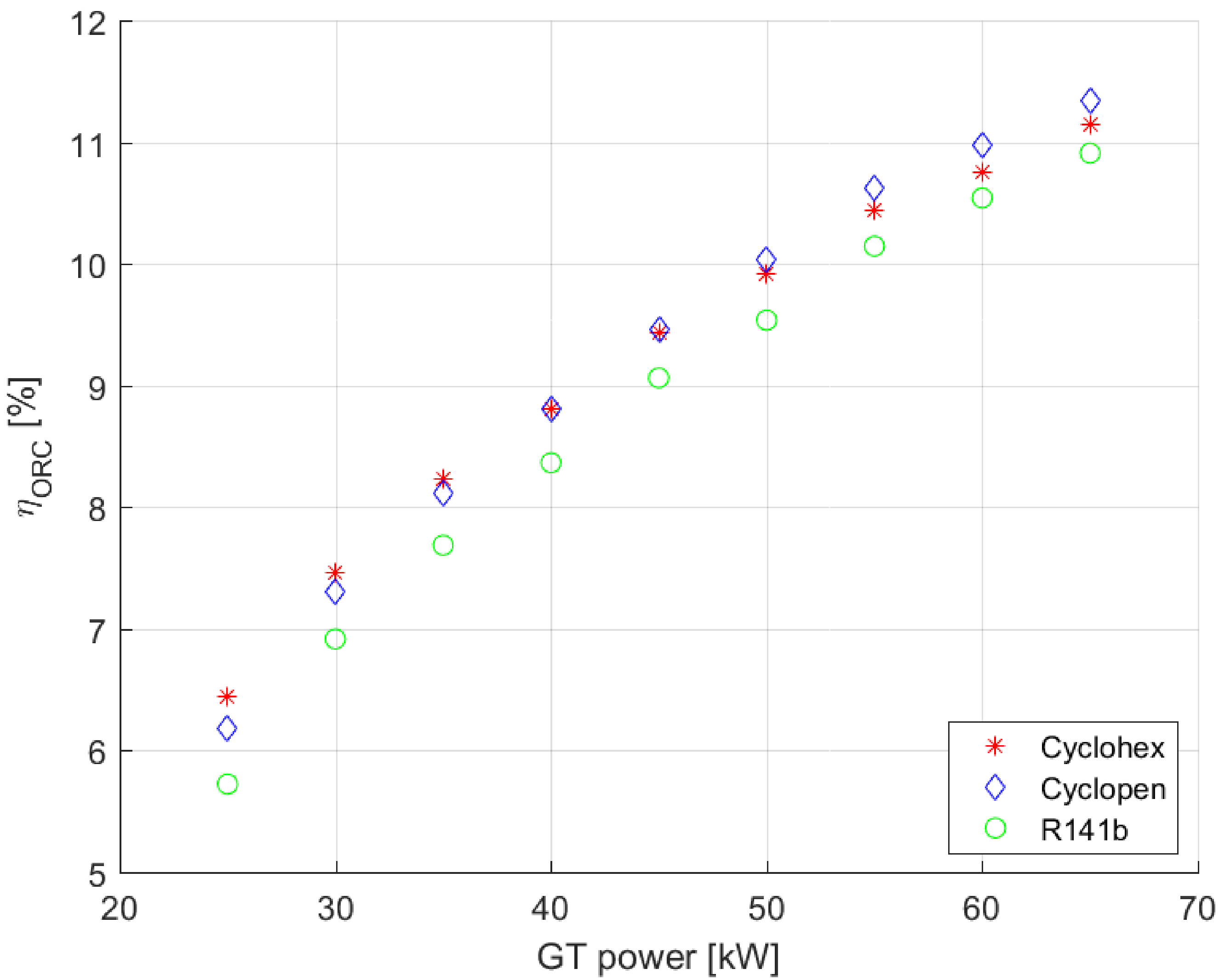
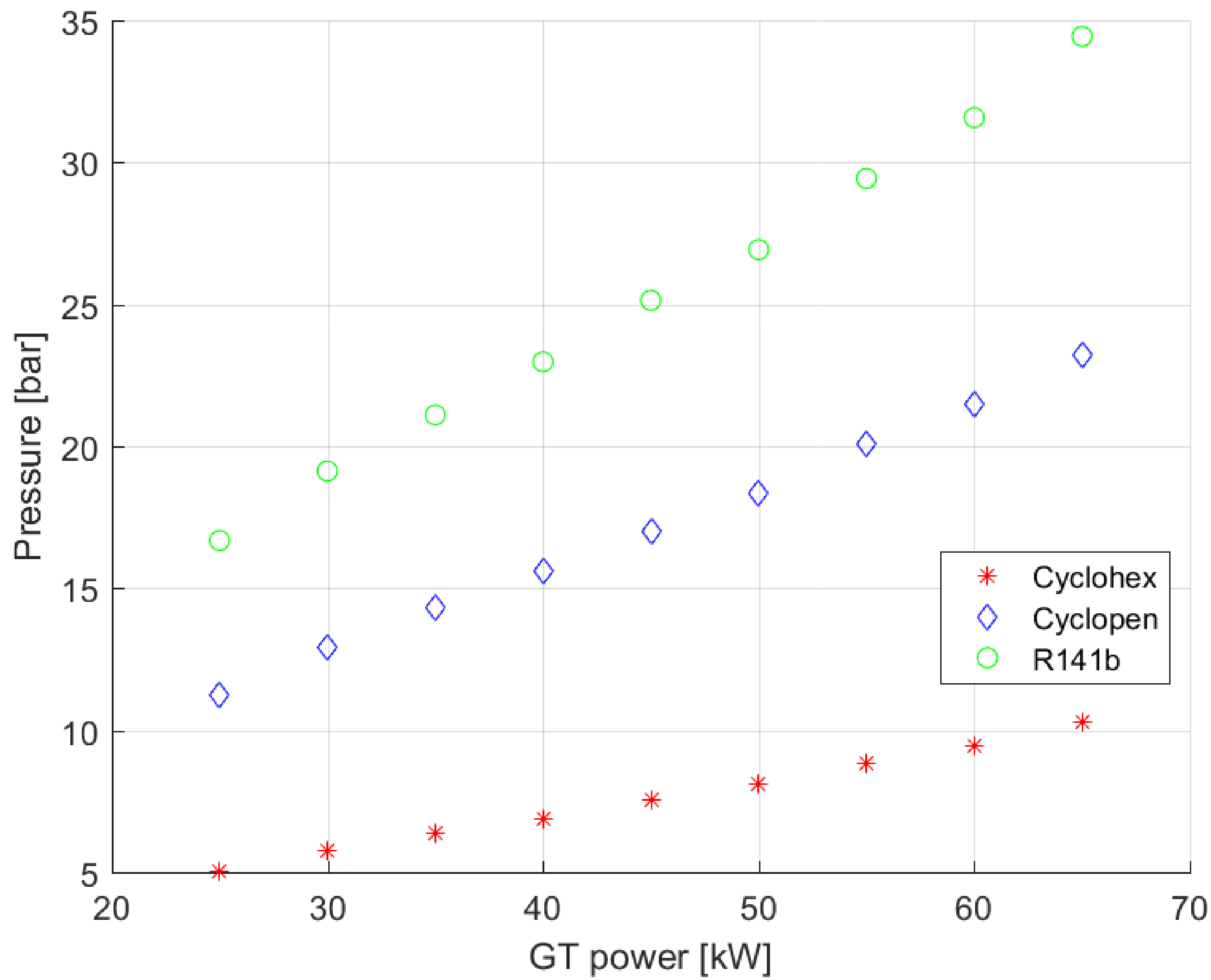


RESULTS: OFF-DESIGN ANALYSIS



RESULTS

- Cyclopentane → Highest P_{el} → $50 < P_{el,GT} < 65$ kW
- Cyclohexane & Cyclopentane → Highest P_{el} → $40 < P_{el,GT} < 50$ kW
- Cyclohexane → Highest P_{el} → $25 < P_{el,GT} < 40$ kW
- Cyclopentane → Can Be Suggested → Working Fluid → Based → Design and Off-design Analyses

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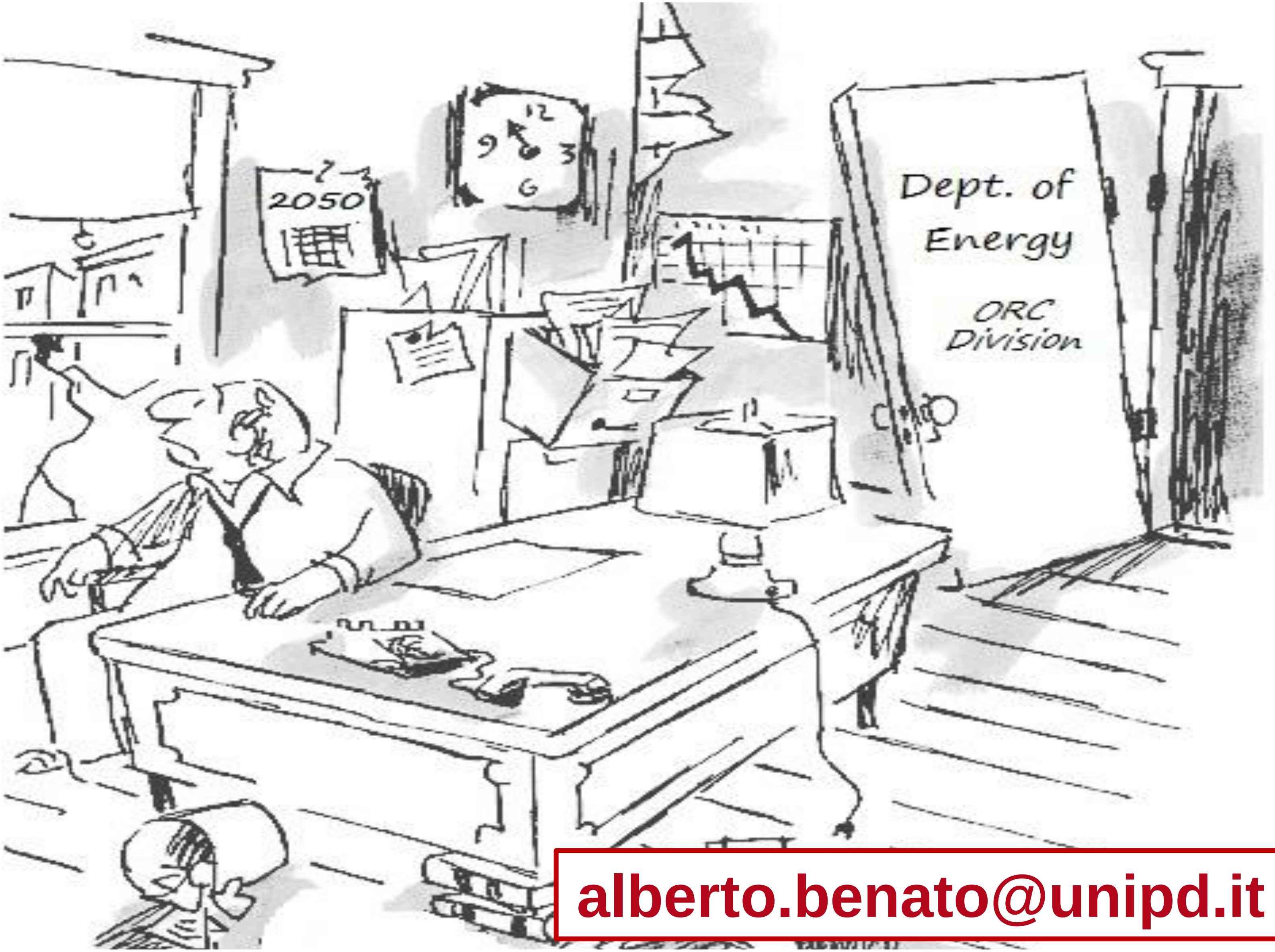
CONCLUSIONS

- Goal → Improve → Efficiency → 65 kW_{el} m-GT → Waste Heat Recovery Unit → ORC
- Methodology → Design point + Off-design Analysis → Select → Best Fluid + Plant Layout → Design Condition
- ORC-PD tool → Design Point Analysis
- Aspen EDR+Plus → HXs and Off-design Model
- Cyclopentane + Basic Layout → Suggested
- Future Works → Different Control Strategy
- Future Works → Dynamic Analysis Integration

THANK YOU FOR YOUR ATTENTION!!!!



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