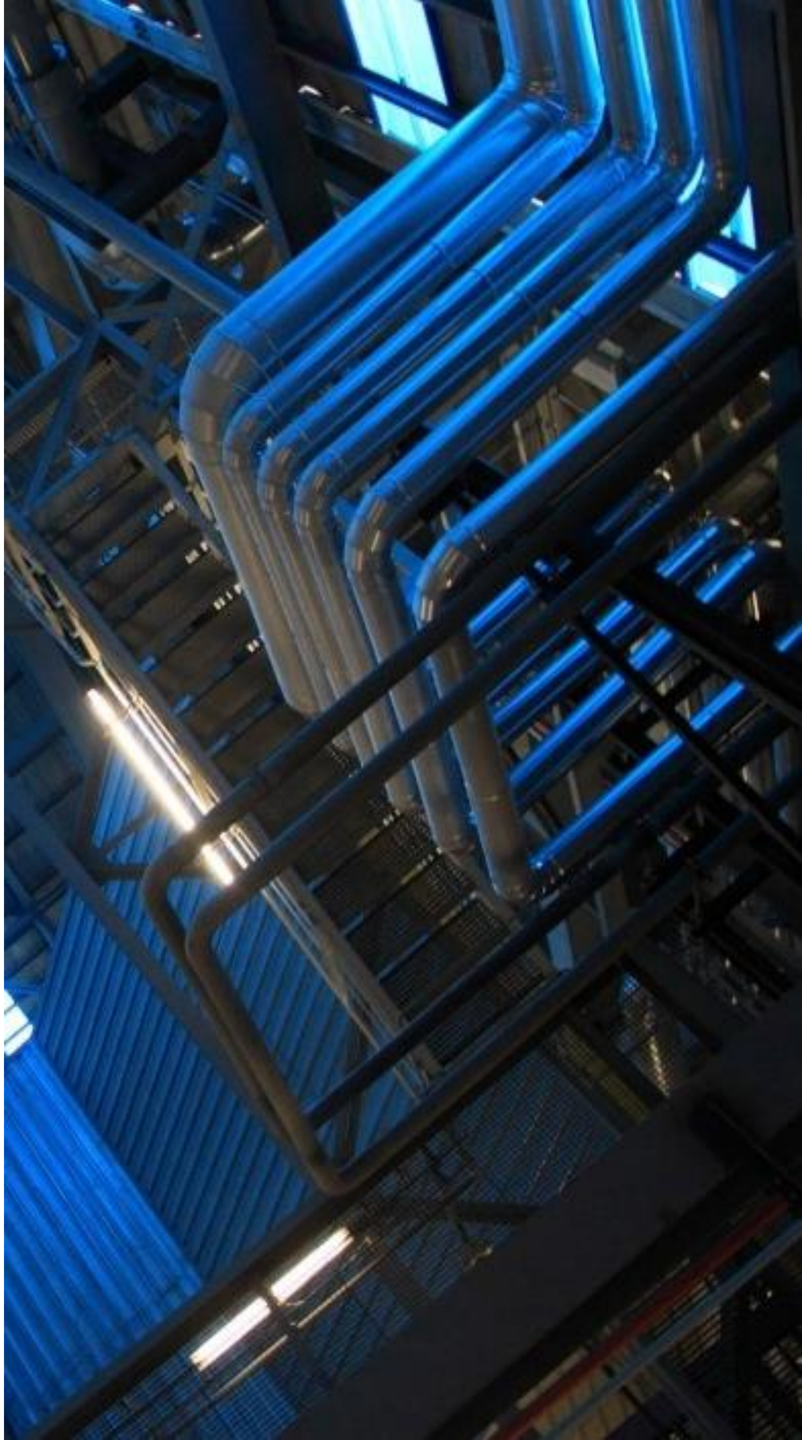
Off-design steady-state performance assessment of supercritical CO_2 Brayton cycle for coal-fired power plants

1st European Seminar on Supercritical CO_2 Power Systems

Vienna – Austria

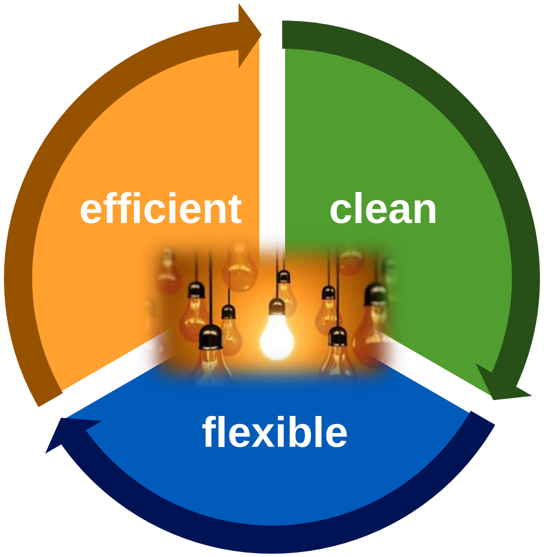
Mounir MECHERI – EDF R&D France

2016 September 30th



OUTLINE

POSITION



- **The sCO_2 cycle is an opportunity to:**
  - Improve power plant efficiency
  - Reduce the fossil plant impact
  - Enhance renewable heat sources
- **Main goals about sCO_2 cycles are to:**
  - Scale-up the sCO_2 Brayton cycle maturity level
  - Prove the sustainability of this technology
  - Optimize processes at any load

2010 – Review of nuclear power cycles for GenIV

2012 – Preliminary studies, performances assessment with CCS, start of internal CO_2 project

[Le Moullec ; 2012]

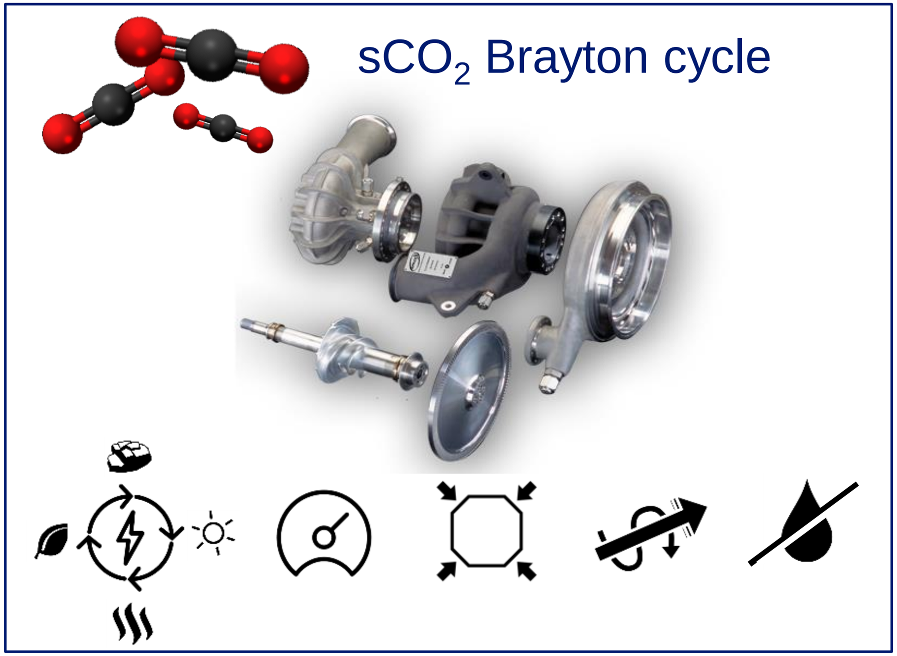
2014

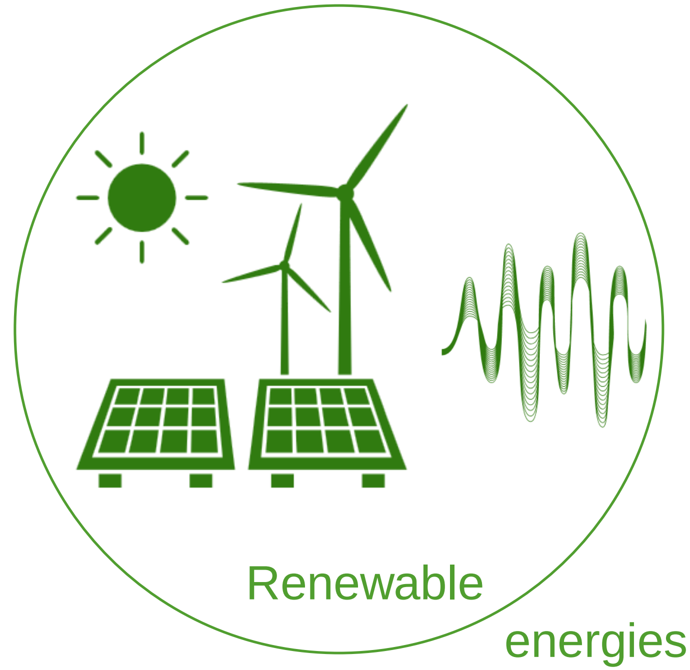
sCO2 performance assessment for coal-fired power plants

[Mecheri, Le Moullec ; 2016]

2016 – EU project constitution, Cycle flexibility assessment

CONTEXT & OBJECTIVES



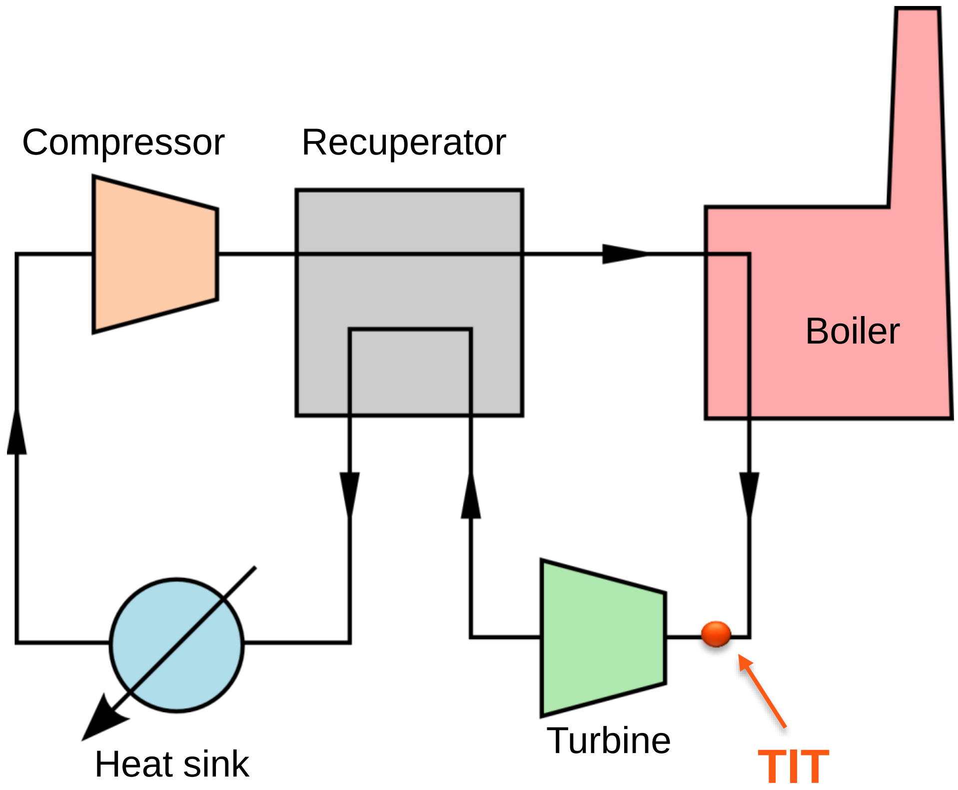


Is the sCO_2 Brayton cycle **flexible?**

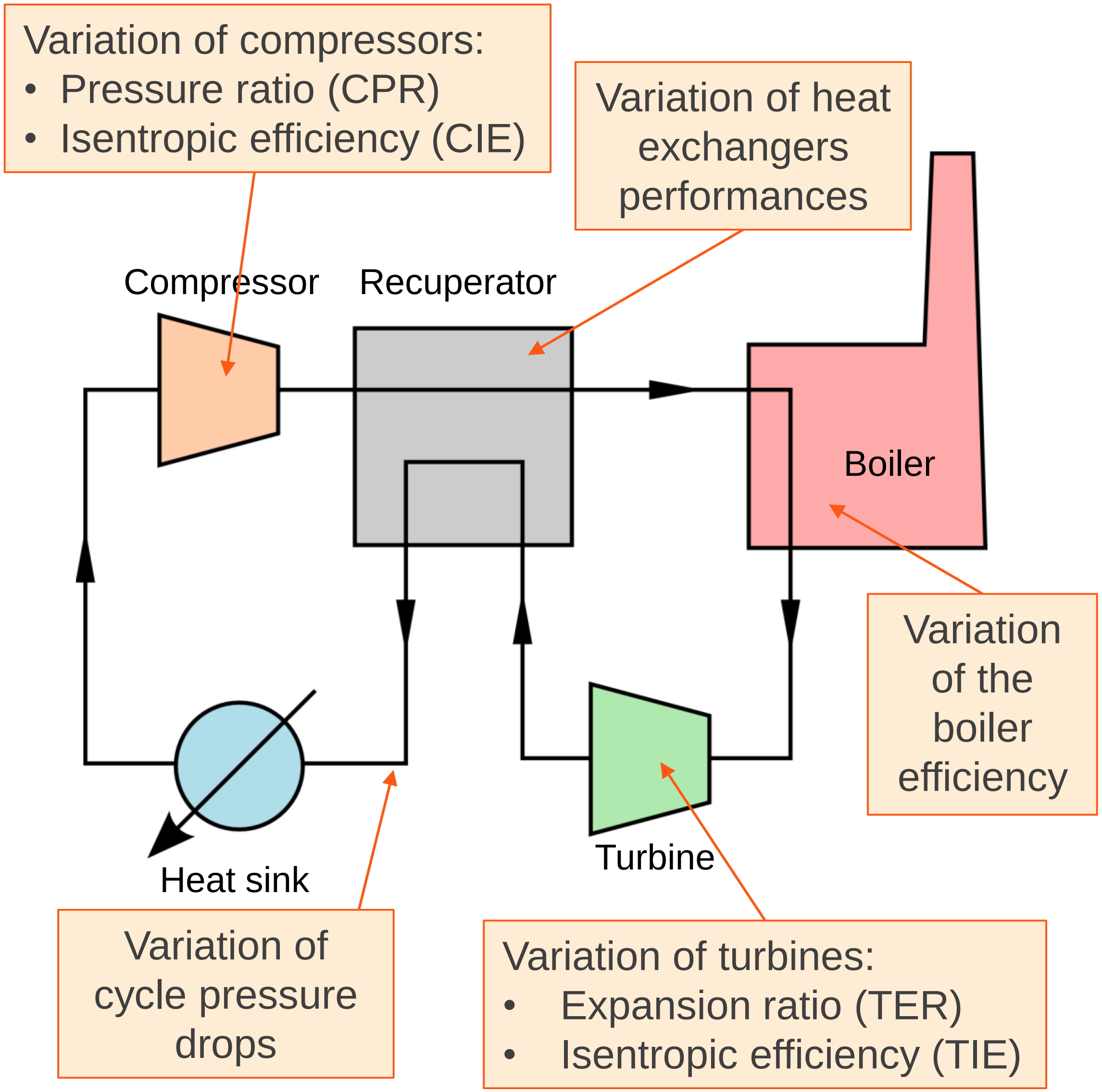
COAL POWER PLANT FLEXIBILITY?

- **Several ways (non-exhaustive list):**
  - Full-load power plant + storage (electro-chemical, hydraulic, energy carriers (H_2)…)
  - Electricity load management (personal consumption, companies…)
  - Smart grids
  - Running at part-load
  - …

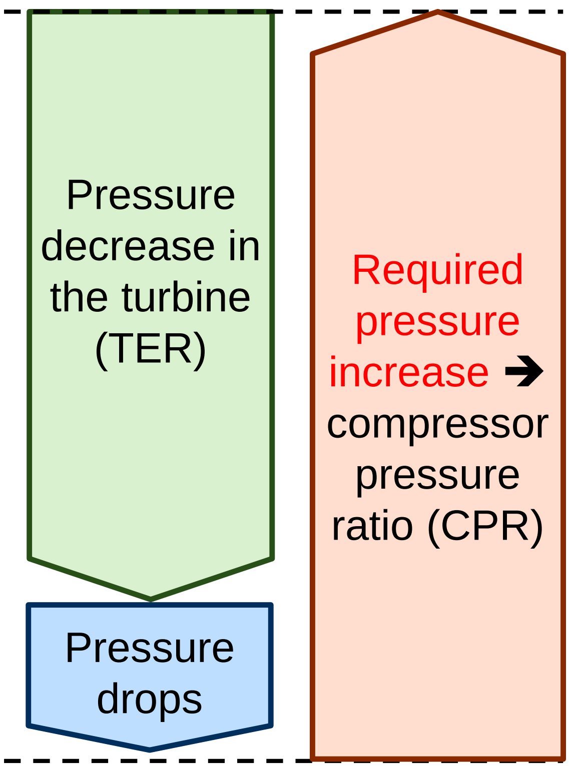
- **Part-load → modifies the boiler heat duty:**
  - CO_2 mass flow = constant → Variation of the Turbine Inlet Temperature (TIT)
  - TIT = constant → variation of the CO_2 mass flow



CO_2 MASS FLOW VARIATION LEADS TO…



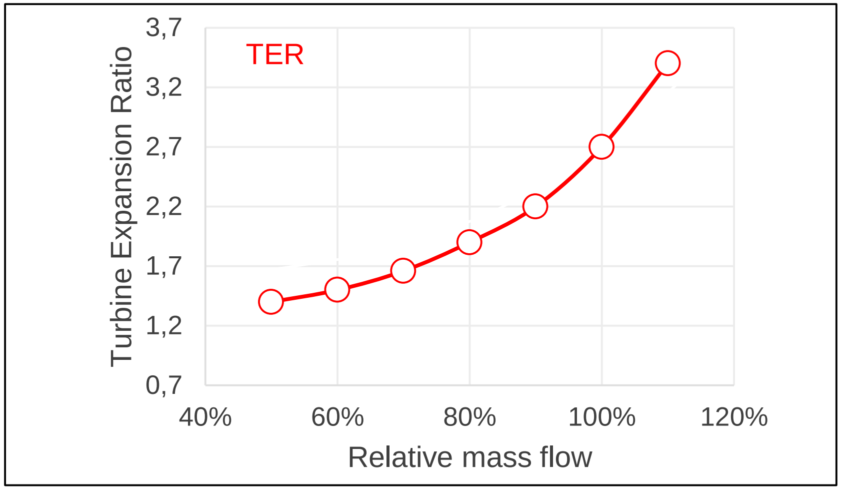
Pressure balance in the cycle.
For <u>each value</u> of the CO_2 mass flow



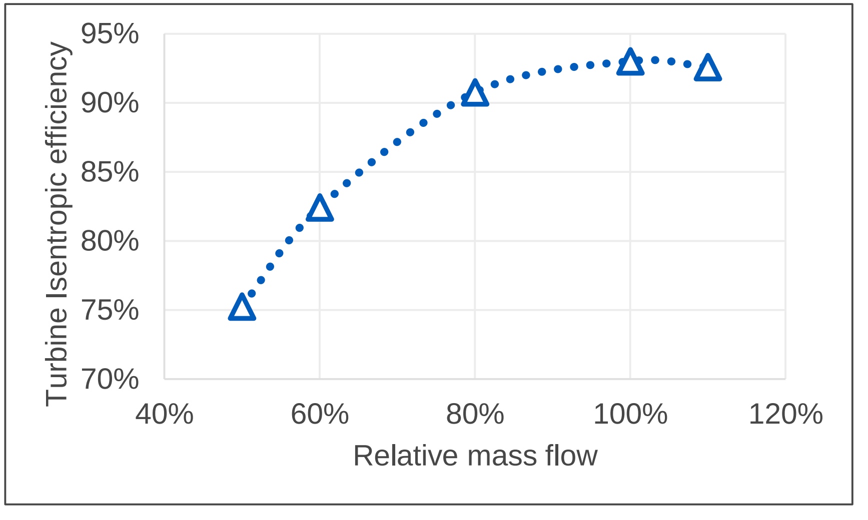
OUTLINE

TURBINE OFF-DESIGN BEHAVIOR

- **The Turbine Expansion Ratio (TER) is expected to follow the Stodola Ellipse Law *[Cooke 1983]*:**



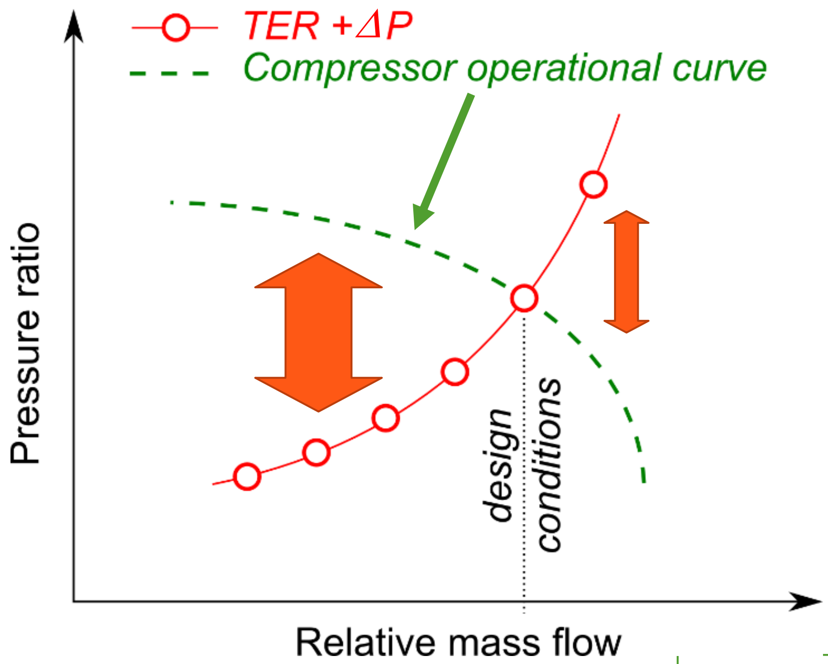
- **The Turbine Isentropic Efficiency (TIE) is expected to follow the Knopf law *[Knopf 2012]*:**

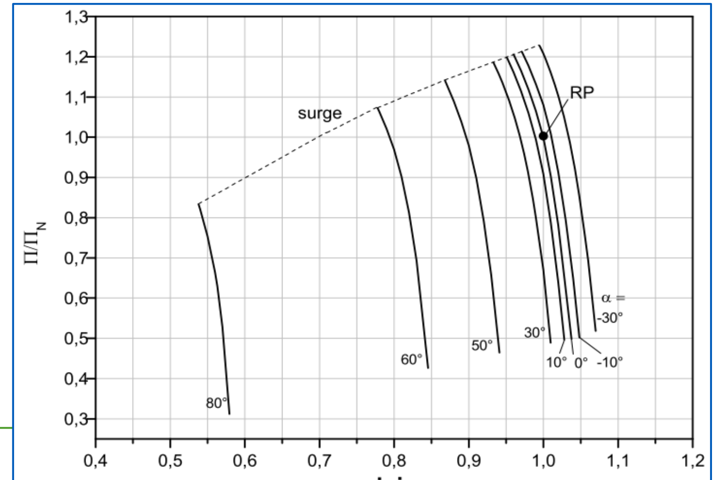


PRESSURE IN THE CYCLE

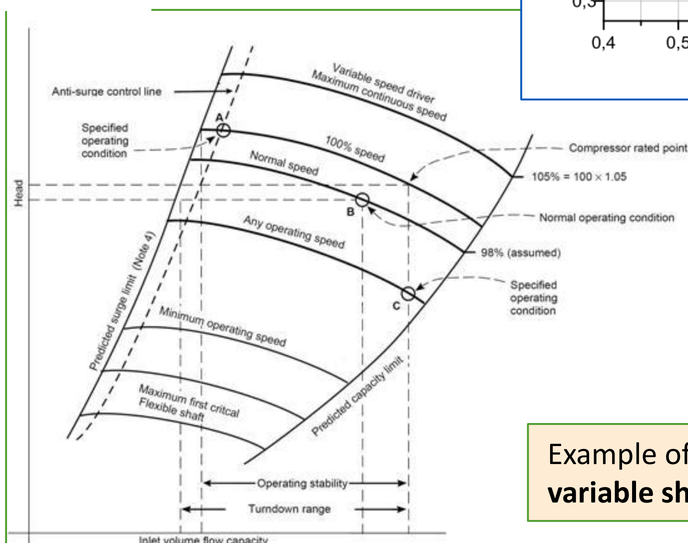
Pressure control

- Throttle
- IGV
- Recycling
- Variable shaft-speed
- …





Example of Compressor **with IGV** [Liebenthal et al. 2011]



Example of Compressor **with variable shaft speed**

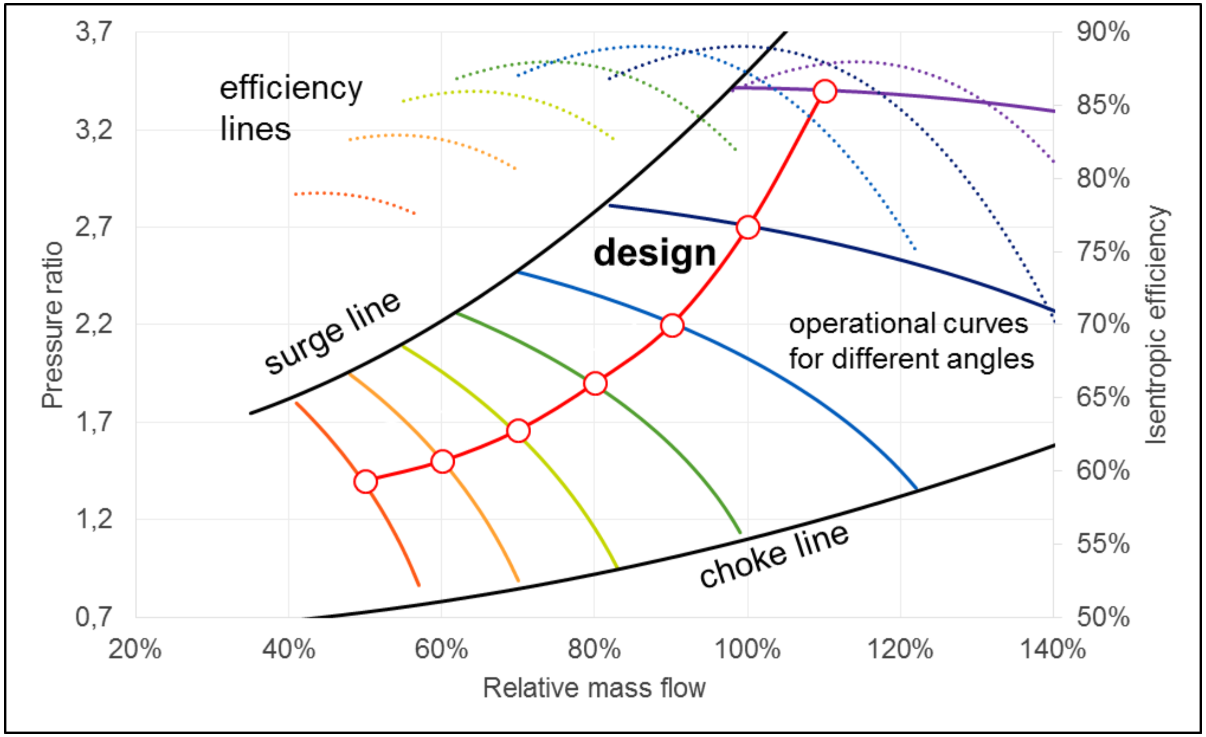
COMPRESSOR OFF-DESIGN BEHAVIOR
(IGV compressor map)

- **Assumptions**
  - Pressure ratio: ellipse laws:

$$Pressure\ Ratio = A_1 * \sqrt{B_1 * (1 - C_1 * (mass\ flow)^2) + D_1} + E_1$$

  - Efficiency lines: polynomial laws

$$Isentropic\ Efficiency = A_2 * (mass\ flow)^3 + B_2 * (mass\ flow)^2 + C_2 * (mass\ flow) + D_2$$



OUTLINE

METHODOLOGY

Reference case (full load)

\+

Assumptions

\+

Scenarios

1

2

3

→

Part-load performances calculation

(**Indicators**:

electrical power production,

&

net cycle efficiency)

METHODOLOGY

Reference case (full load)

Assumptions

Scenarios

1

2

3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Supercritical CO_2 Brayton cycles for coal-fired power plants
Mounir Mecheri [a], Yann Le Moullec [b,*]

7.4 MPa
32 °C

20 MPa

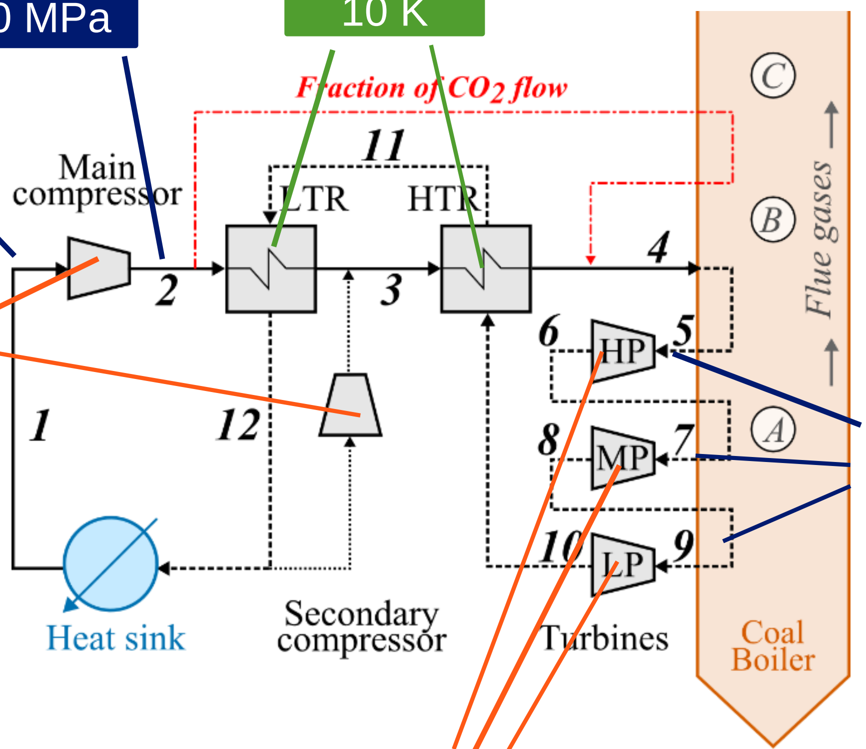
Pinch
10 K

CIE
89 %

TIT
620 °C

TIE
93 %

Pressure drops :
1bar/H.Ex



METHODOLOGY

Reference case (full load)

Assumptions

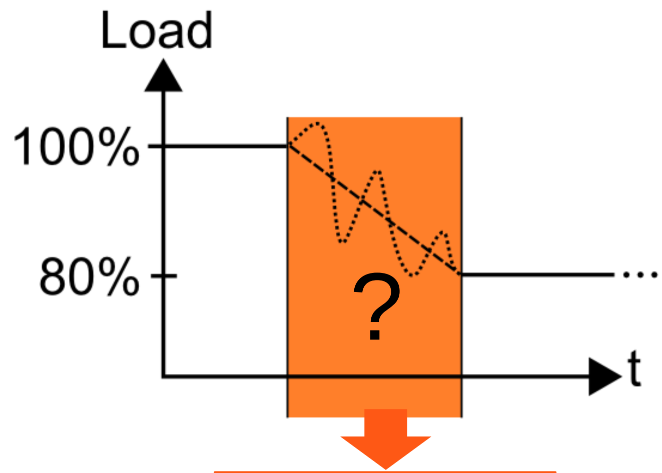
Scenarios

1

2

3

- Steady-state calculations → **no** transient



not considered

- Boiler efficiency variations → not considered
- Pressure drop variations → not considered
- Turbomachines pressure variations = elliptic laws
- Turbomachines efficiency variations = polynomial laws

METHODOLOGY

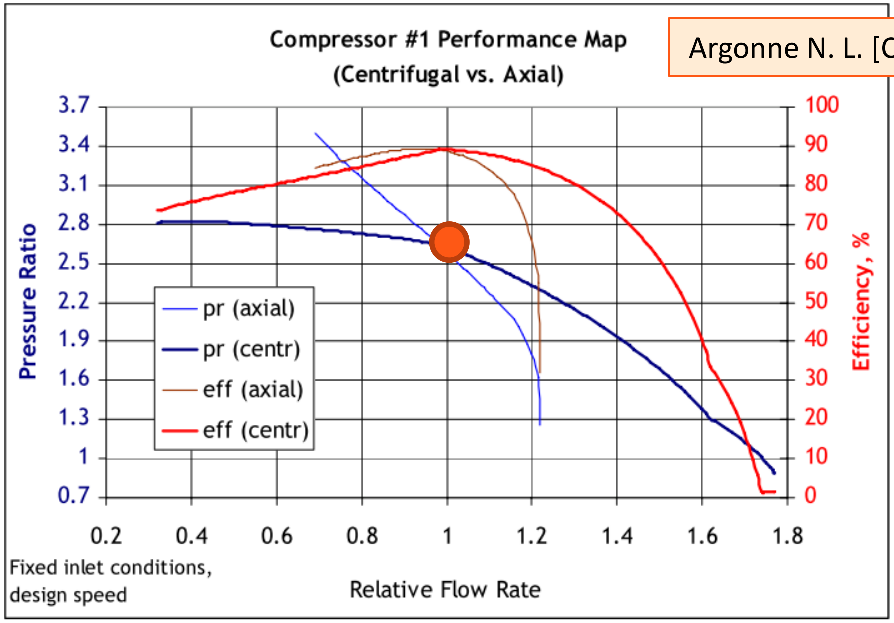
Reference case (full load)

Assumptions

Scenarios
1
2
3

- **Scenario 1 (simplified case):**
  - CPR → ANL law (Chang et al. 2006)
  - TER = CPR

➔ The CO_2 mass flow varies from 60% to 110% of nominal value



Argonne N. L. [Chang et al. 2006]

METHODOLOGY

Reference case (full load)

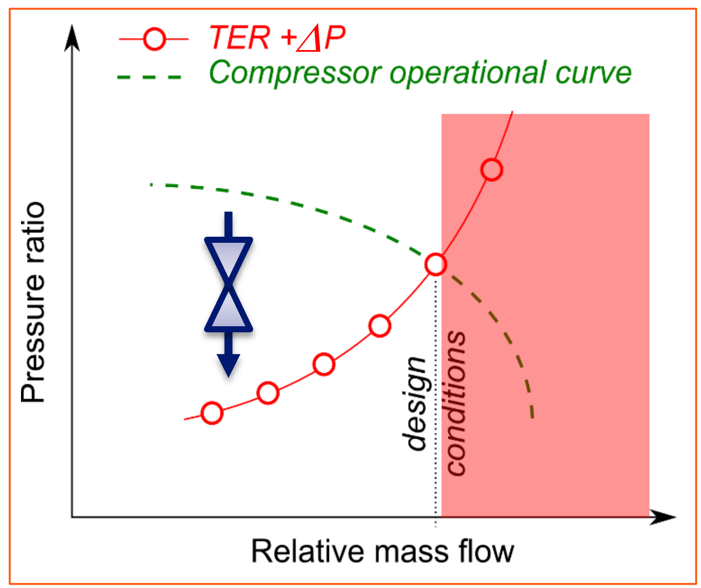
Assumptions

Scenarios 1 **2** 3

- **Scenario 2 (throttle valve):**
  - TER → Stodola ellipse law
  - CPR → ANL law (Chang et al. 2006)

Need to throttle the compressor outlet pressure to fit the TER requirements

➔ The CO_2 mass flow varies from 60% to 100% of nominal value



METHODOLOGY

Reference case (full load)

Assumptions

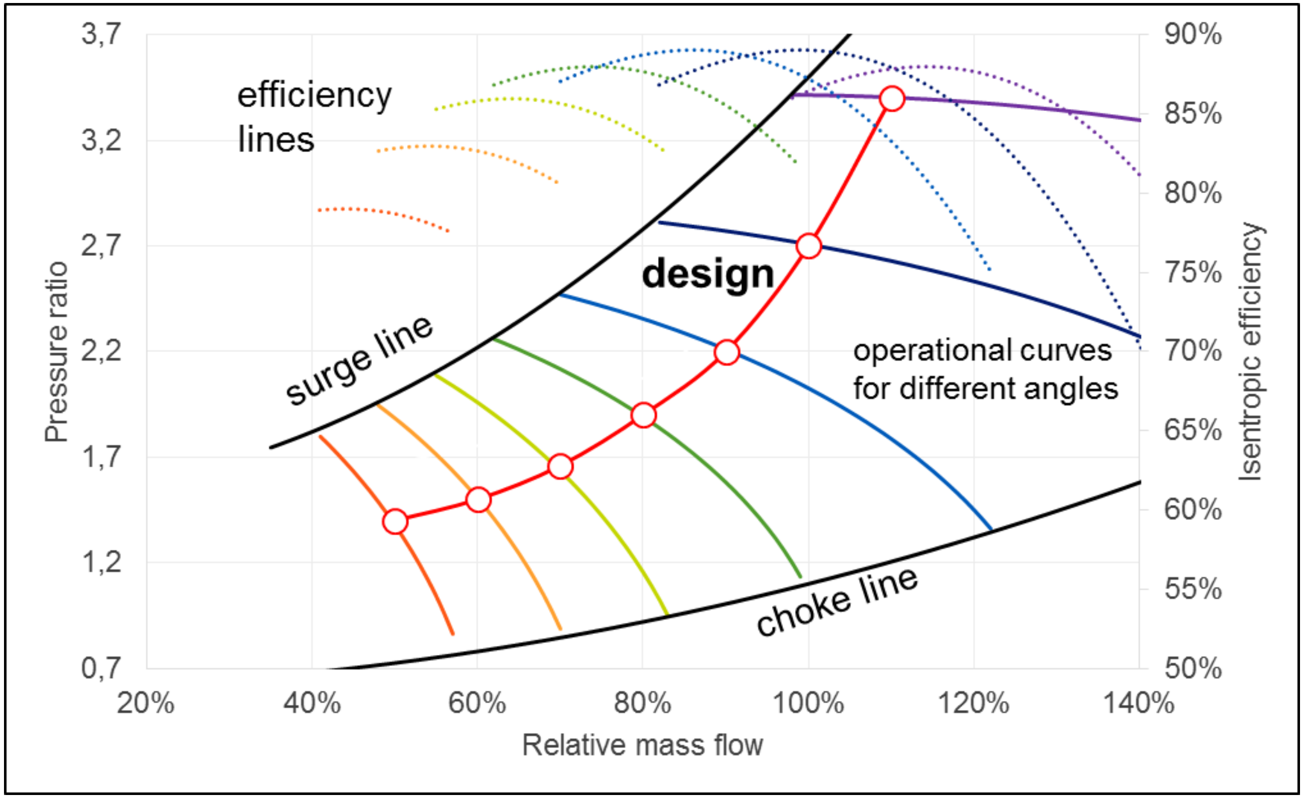
Scenarios

1

2

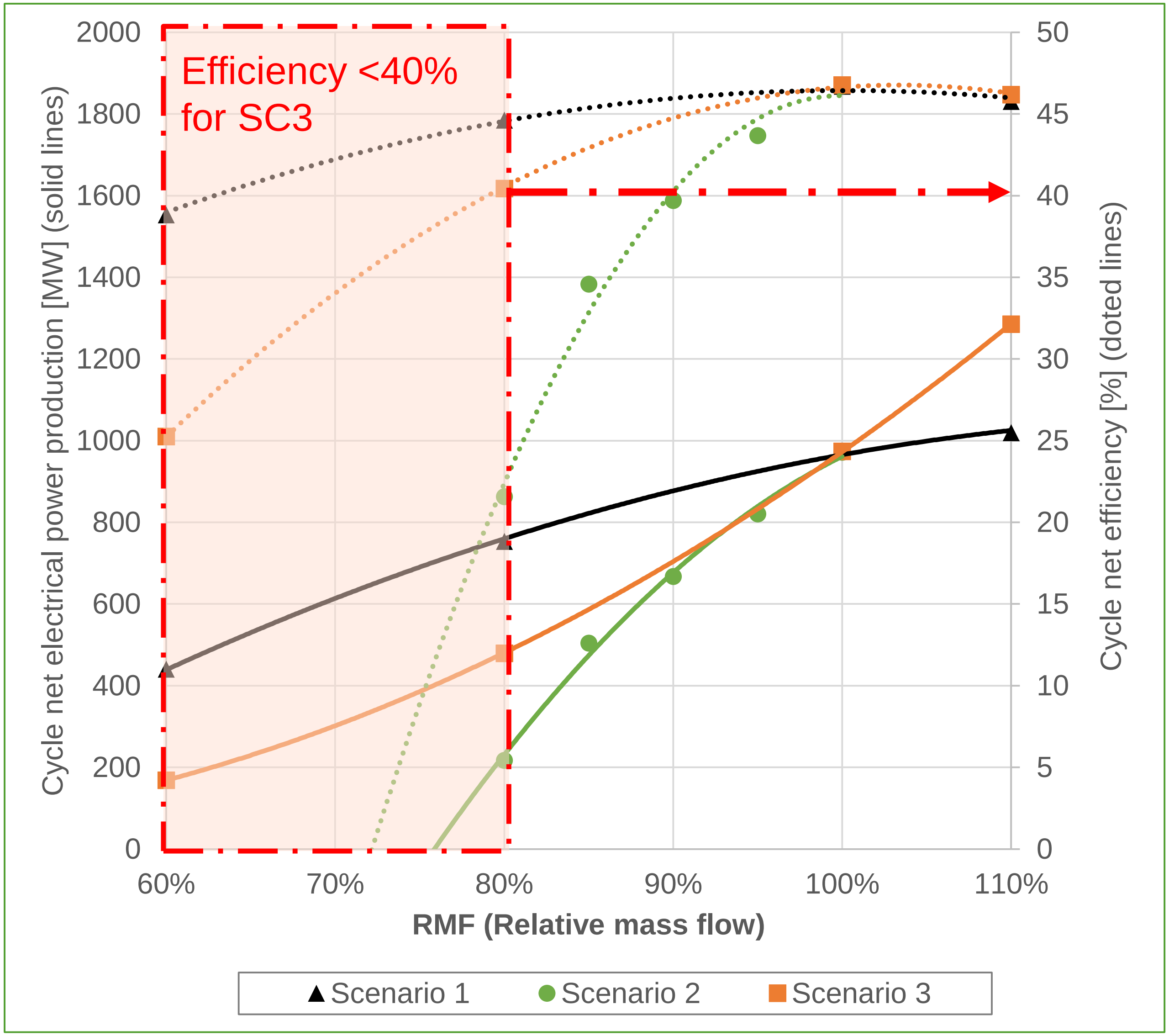
3

- **Scenario 3 (IGV compressors):**
  - TER → Stodola ellipse
  - CPR → **created** IGV compressor map
  - **→ the CO_2 mass flow varies from 60% to 110% of nominal value**



OUTLINE

RESULTS



- **SC 1:**
  CPR = one curve
  TER = CPR
- **SC 2:**
  TER = Stodola
  CPR = one curve
  Pr. Control = throttle
- **SC3:**
  TER = Stodola
  CPR = IGV
- **SC1 = non realistic**
- **SC2 = high losses**
- **SC3 =**
  - better than SC2
  - and more realistic than SC1

OUTLINE

CONCLUSION & DISCUSSIONS

- **Lot of assumptions → must be checked in a more detailed analysis**

- **Lack of information**
  - turbine off-design behavior
  - compressor off-design maps

  ➔ Need for real turbomachinery test and model validations !

- **Conclusions in these modeling conditions:**
  - Single operational curve compressor ➔ unsuitable to follow TER
  - Throttling compressor control ➔ very large losses
  - → IGV compressors = proper operational pressure range + minimal losses at off-design

  - Off-design performances [SC3 - IGV compressors] from 80% to 110% of nominal mass flow:
    * Power production: from ~50% to 120% of nominal value
    * Cycle net efficiency: [40% - 46.8%]

PERSPECTIVES

- **Concerning previous results:**
  - Consolidate the assumptions/hypothesis
  - Improve the current models
  - Compare the off-design performances

- **Ongoing studies: general dynamic model**
  - Dymola modeling of the global power plant
  - Including transient phenomenon
  - Start and stop
  - Instrumentation and control
  - Power plant layout → accurate pressure drops model
  - Turbomachine off-design methods → velocity triangle modification with mass flow

Thank you for your attention

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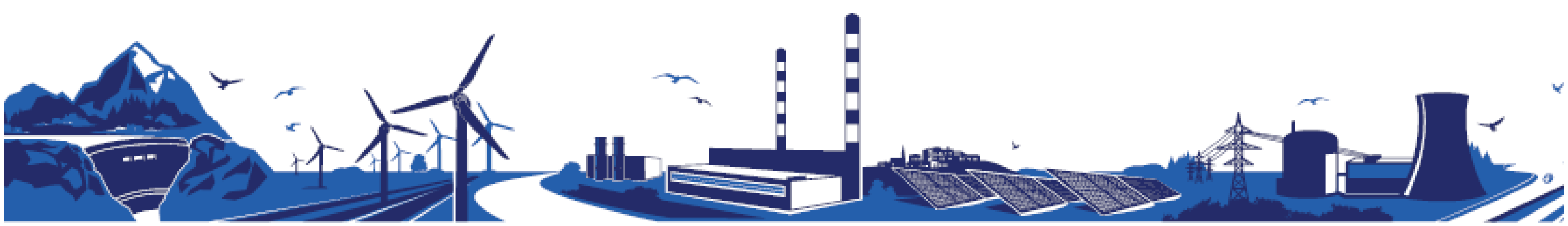

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