Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Energy Conversion

Thermodynamik III

Kältemaschinen, Oxyfuel, Carbon Capture and Storage

HS2021

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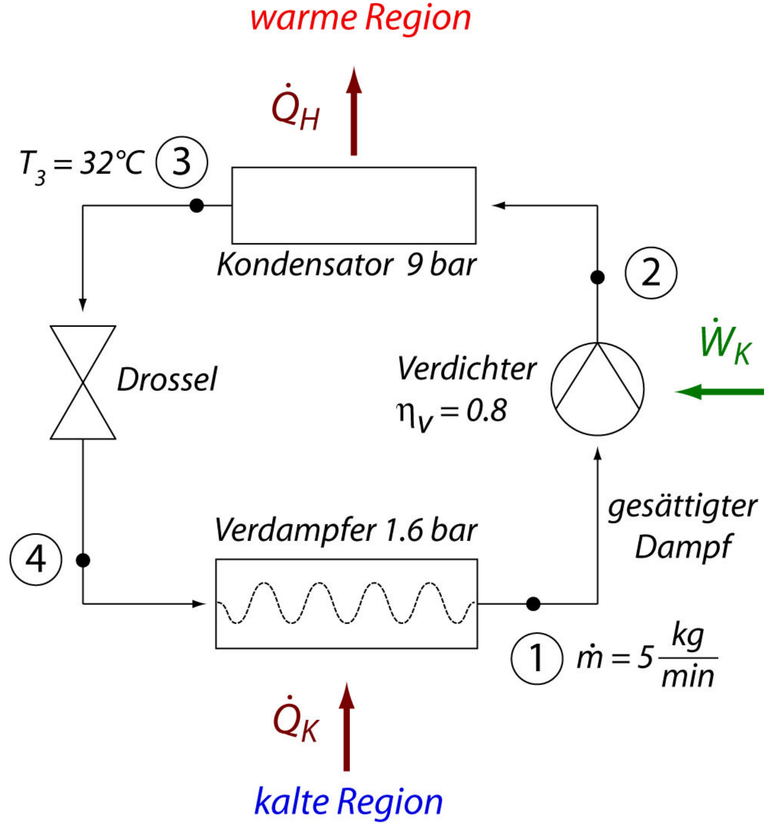
Overview

Vorlesung		Übung/Beispiel	
Datum	**Thema**	**Datum**	**Thema**
09.11	Prozess des Energieaustausches	09.11	Geschwindigkeitsdreiecke
16.11	Dampfkraftprozesse	16.11	Rankine Zyklus
23.11	Gasarbeitsprozesse - Verbrennungsmotoren	23.11	Diesel / Otto Zyklus
30.11	Gasarbeitsprozesse - Gasturbinenprozesse	30.11	Brayton Zyklus
07.12	Gasarbeitsprozesse - Kombinierten Zyklen	07.12	Kombinierter Zyklus
14.12	Kältemaschinen und Wärmepumpen	14.12	Kältemaschine/Wärmepumpe
21.12	Kältemaschinen Oxyfuel, Carbon Capture and Storage	21.12	Wärmepumpe

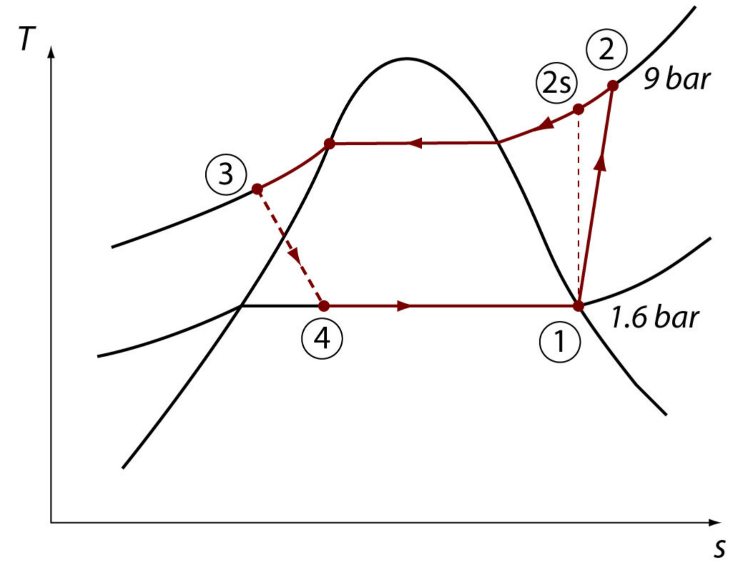
Beispiel

– Kompressionskältemaschine, Arbeitsmittel: R134a (CF_3CH_2F)



– gesucht: $\dot{W}_V, \dot{Q}_K, \varepsilon, T_0\dot{S}_{Erz}, \left(T_0 = 301K\right)$

– Lösung:



– Zustand 1:

  – Gesättigter reiner Dampf
  – p_1 = 1.6 bar, Tabelle: h_1 = 237.97 kJ/kg, s_1 = 0.9295 kJ/kgK

– Zustand 2s:

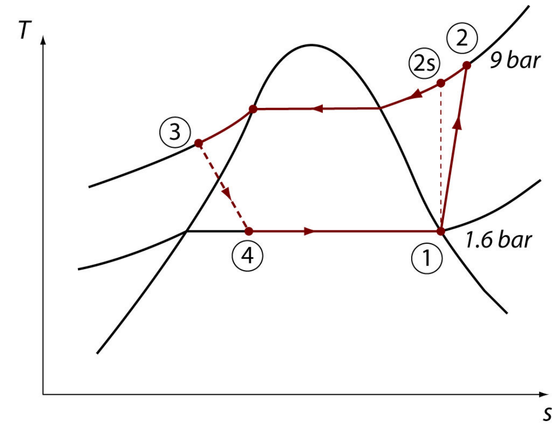
  – s_{2S} = s_1, p_{2S} = 9 bar, Tabelle –> h_{2S} = 273.73 kJ/kg
  – Wirkungsgrad des Verdichters:

$$\eta_{VS} = \frac{h_{2S} - h_1}{h_2 - h_1} = 0.8$$

  - h_2 = 282.67 kJ/kg
  - (p_2 = 9 bar) Tabelle: s_2 = 0.9576 kJ/kgK

- Zustand 3:
  - p_3 = 9 bar, T_3 = 32 °C (unterkühlte Flüssigkeit)
  - Tabelle: h_3 -> h_f(32 °C) = 94.39 kJ/kg
  - Tabelle: s_3 -> s_{3f}(32 °C) = 0.349 kJ/kgK

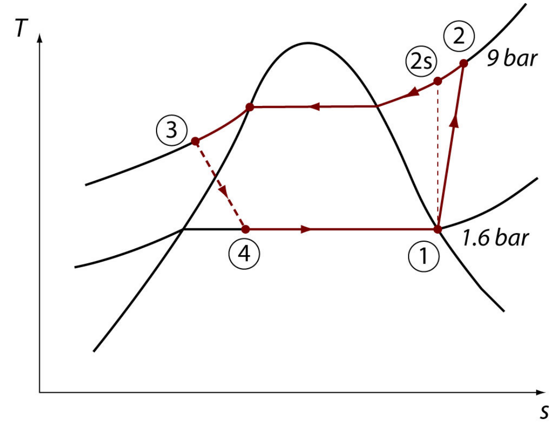
- Zustand 4:
  - $h_4 = h_3$, p_4 = 1.6 bar
  - x_4 = 0.3104, s_4 = 0.37198 kJ/kgK



- $\dot{W}_V = \dot{m}(h_2 - h_1) = 3.725\ kW$

- $\dot{Q}_K = \dot{m}(h_1 - h_4) = 5\ \frac{\text{kg}}{\text{min}}(237.97 - 94.39)\frac{kJ}{kg} = 11.965\ kW$

– Leistungsziffer: $\varepsilon = \dfrac{h_1 - h_4}{h_2 - h_1} = 3.212$



– Entropiebilanz für den Verdichter:

$$0 = \sum_j \left(\frac{\dot{Q}}{T} \right)_j + \dot{m}(s_1 - s_2) + \dot{S}_{ErzVerd}$$

$$T_0 \dot{S}_{ErzVerd} = T_0 \dot{m}(s_1 - s_2) = 0.705\ kW$$

– Entropiebilanz für die Drossel:

$$T_0 \dot{S}_{ErzDrossel} = T_0 \dot{m}(s_4 - s_3) = 0.576 kW$$

Carbon Capture and Storage (CCS)

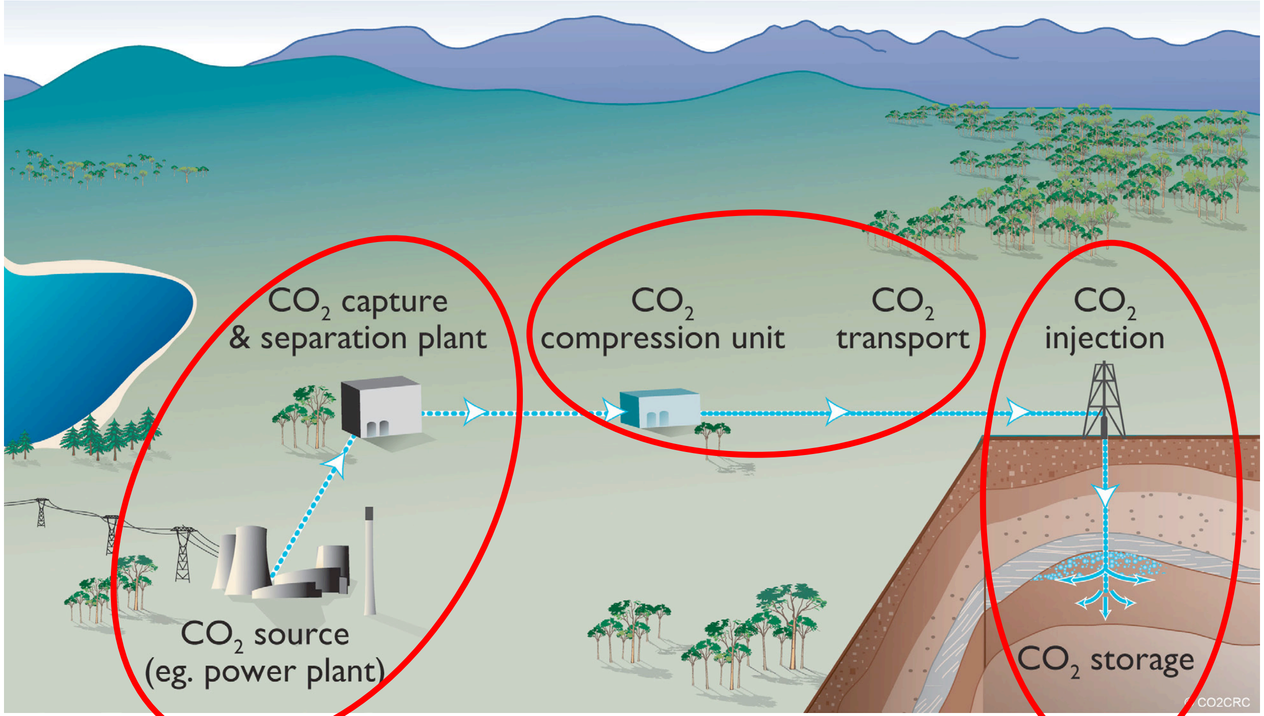


Image courtesy of CO2CRC.

Capture Transport Storage

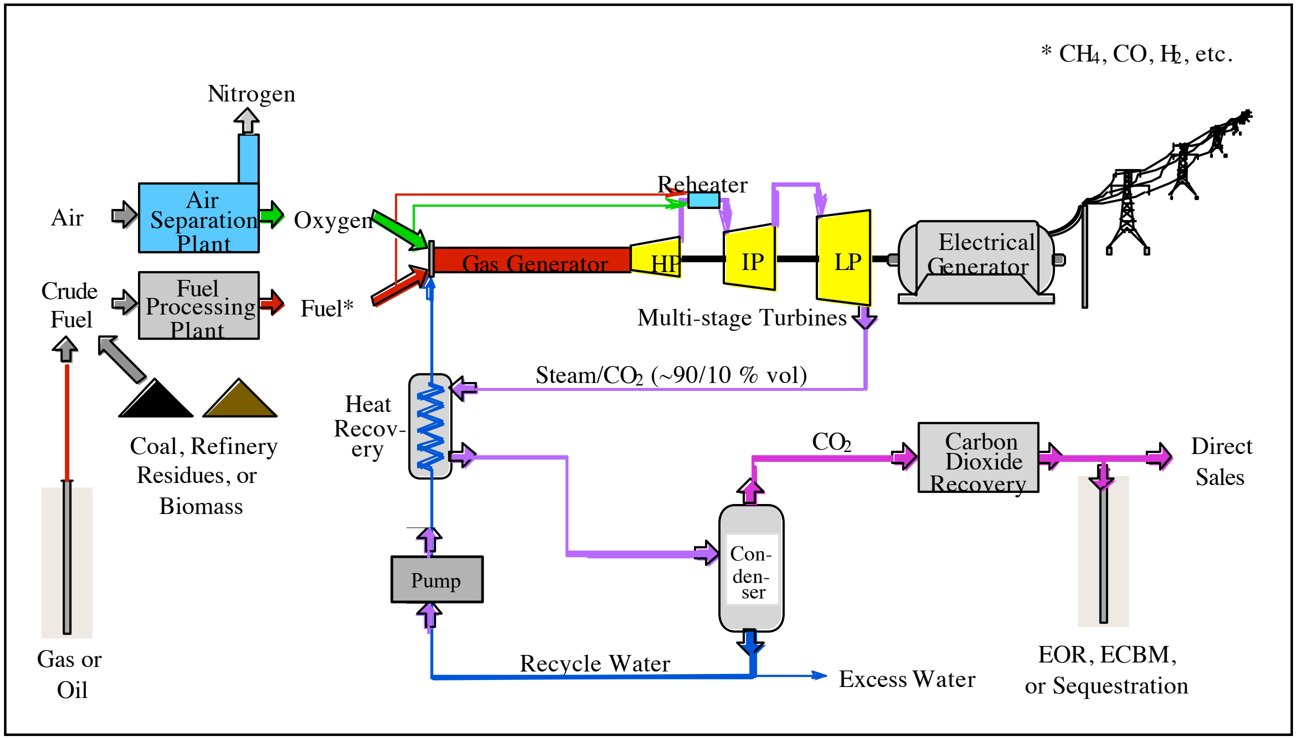
Carbon capture

CO_2 can be separated from a carbon emission source either before or after it has been combusted to produce energy or other products (cement, steel, etc.). There are three ways to capture CO_2 from these combustion processes:

- Pre-combustion technology
- Post-combustion technology
- Oxyfuel combustion

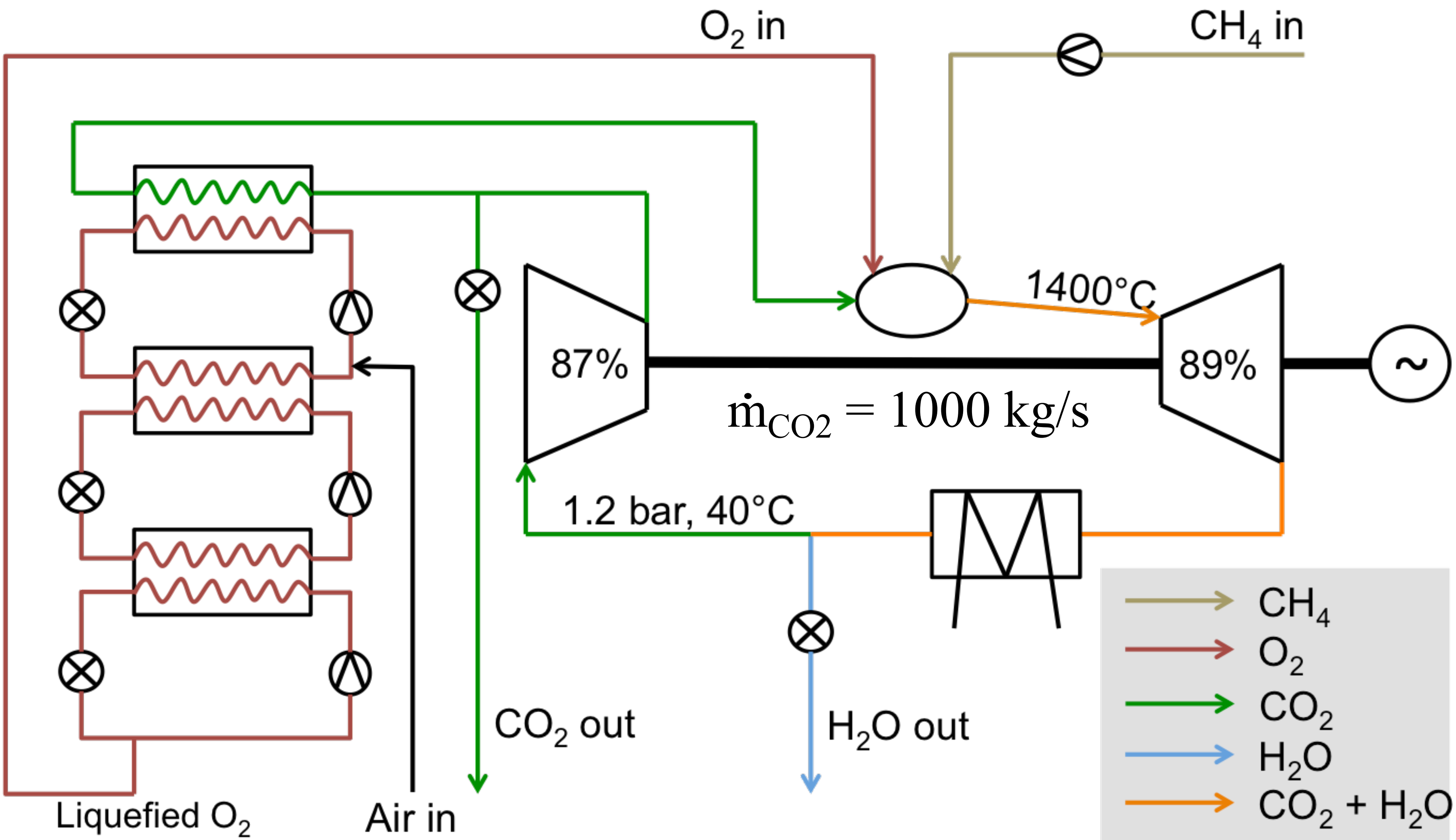
Innovative thermodynamic cycle

Oxyfuel power plant



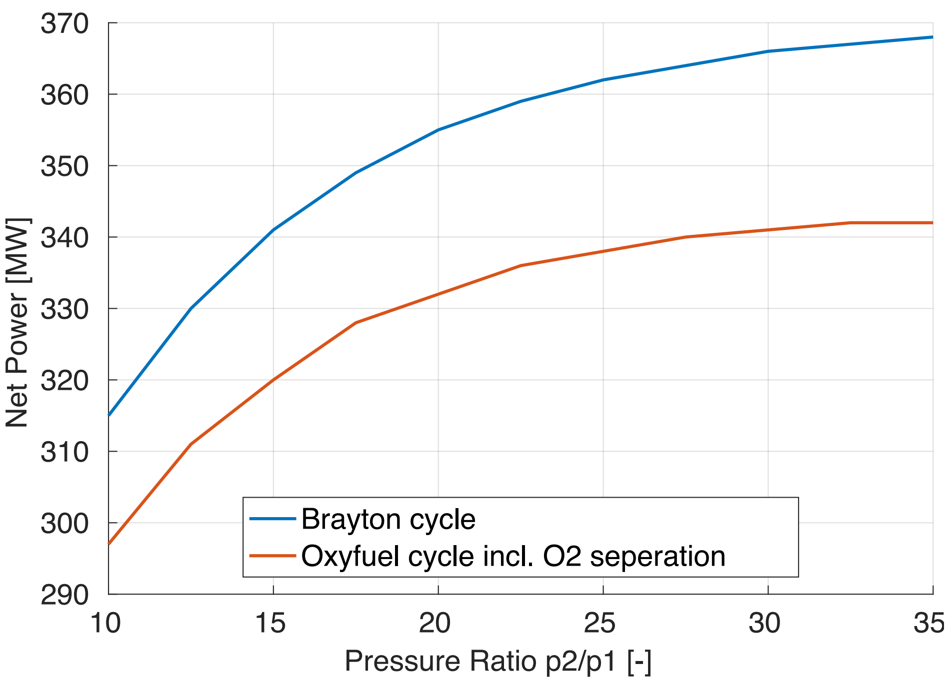
- Burn carbon based fuels with oxygen
- Combustion main products: CO_2, H_2O
- Different cycles have been developed: Water cycle, Graz cycle, and Matiant cycle

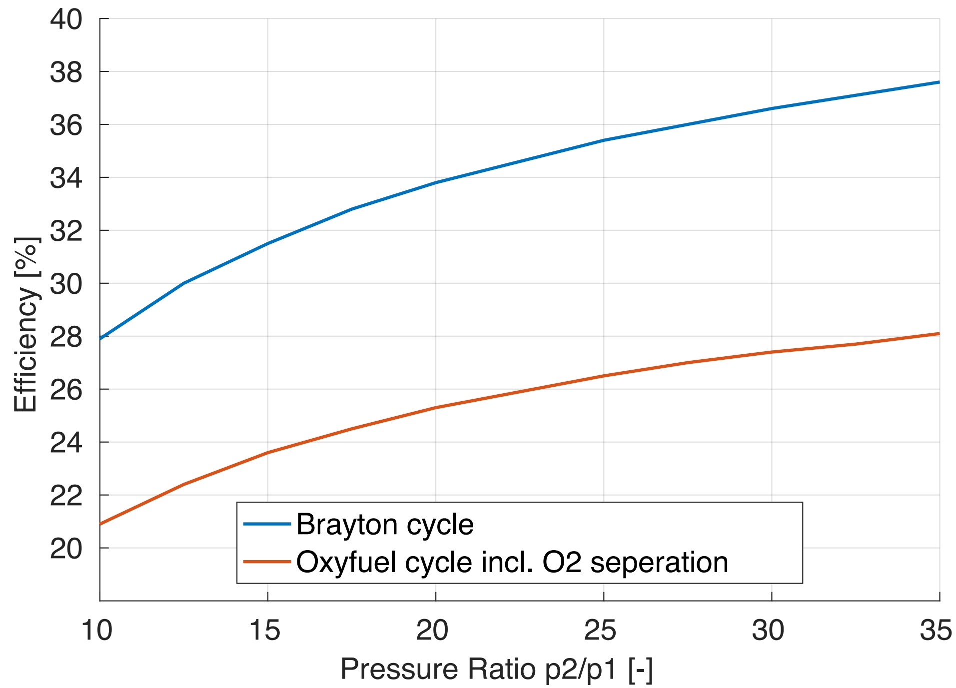
Oxyfuel power plant schematic



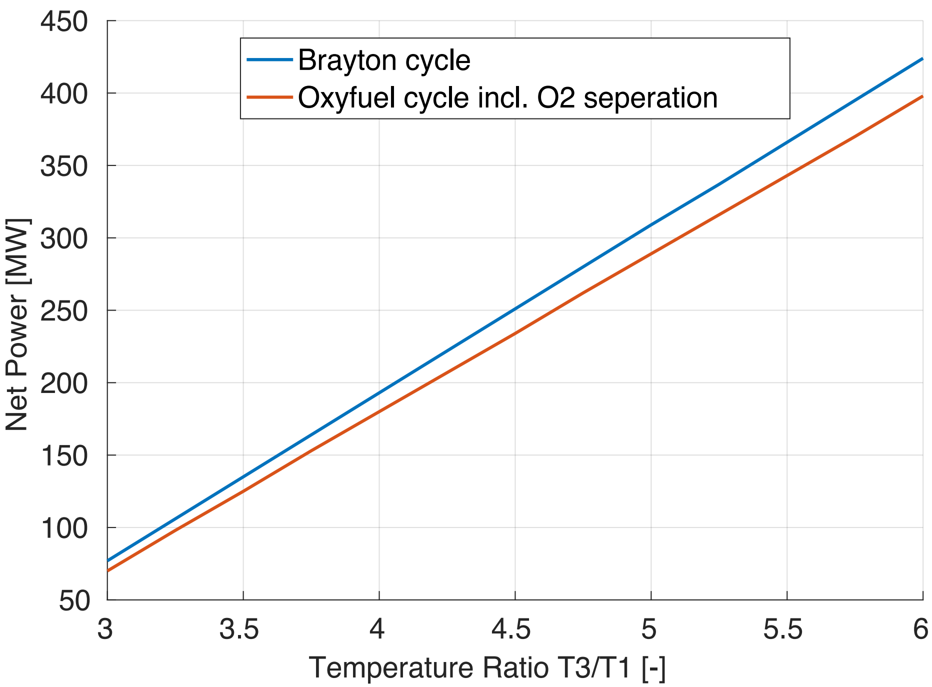
Performance over pressure ratio

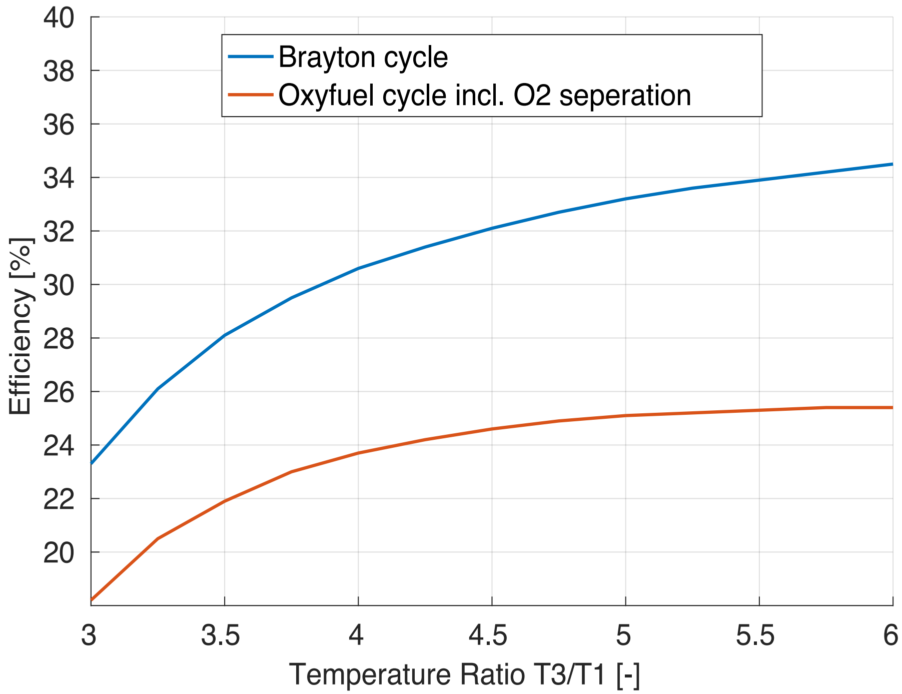
- Power required to liquefy and separate oxygen reduces efficiency of cycle
- Compared to normal Brayton cycle, Oxyfuel cycle has 7-10% lower efficiency and 15-25 MW lower power output





Performance over temperature ratio

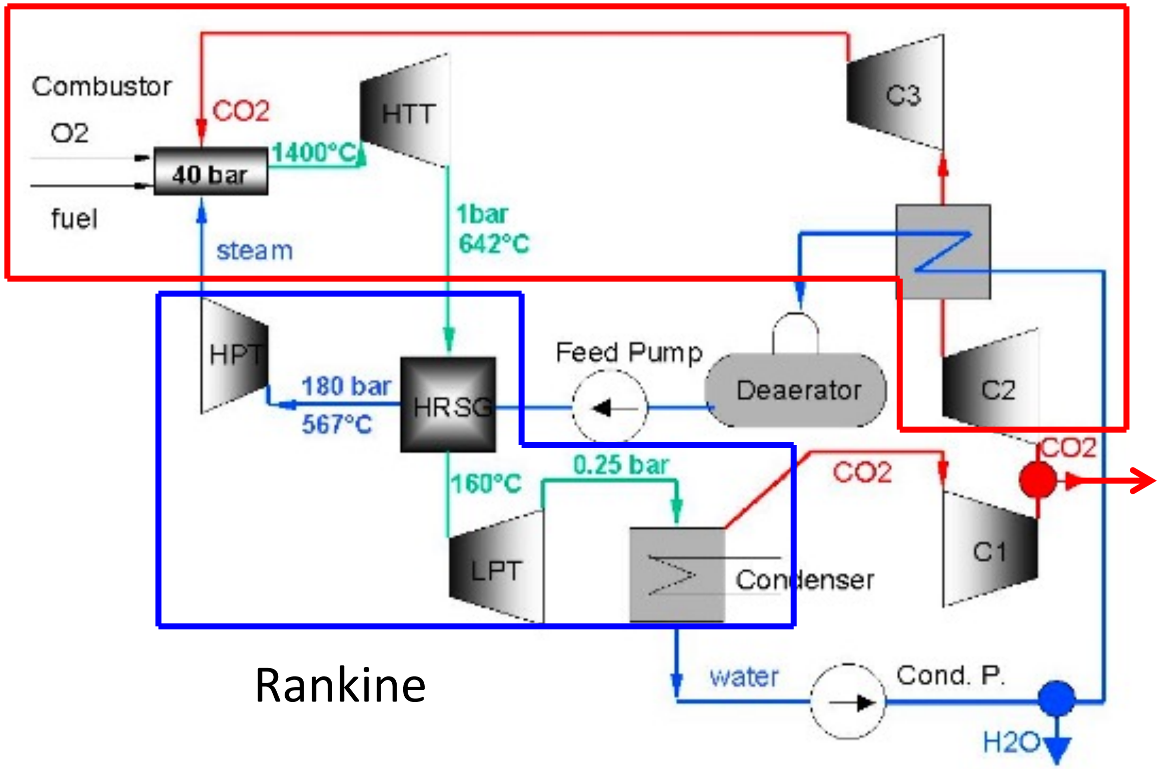




Graz cycle

Combination of a high temperature Brayton cycle, and a low temperature Rankine cycle

Brayton



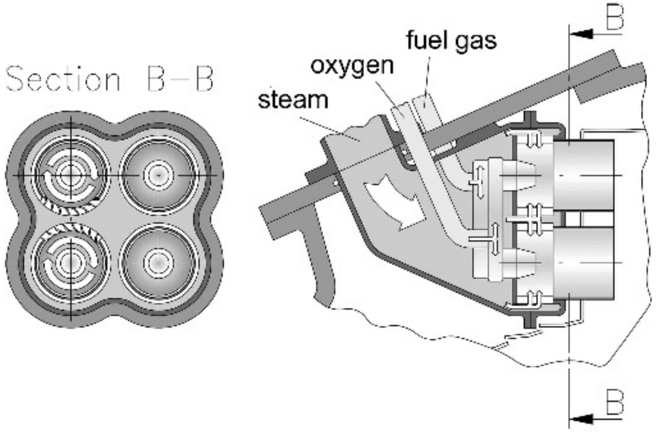
To CO_2 storage

Rankine

[H. Jericha, et al., ASME paper GT2003-38120]

Combustion:

- Fuel with high hydrogen content (e.g.: CH_4) is mixed in stochiometric ratio with O_2
- Negligible N_2 content → no NO_x production
- Danger of too high flame temperature (in normal combustion 70% of the gas is just getting heated, but here 100% is reacting), danger of dissociation of the products
- Need of cooling medium: CO_2 from C3, H_2O from HPT
- Combustion at 40bar, exit temperature 1400° C, heat released: 1.62MJ/kg
- Mixture leaving the combustor of about 74% steam, 25.3% CO_2, 0.5% O_2, 0.2% N_2



Expansion:

- 3 turbines, 2 for H_2O+CO_2, 1 for H_2O, total turbine power: 1.25MJ/kg

Compressors and pumps:

- 3 compressors for CO_2, 2 pumps for H_2O, total power consumption: 0.21MJ/kg

Heat recovery steam generator (HRSG):

- HSRG brings the steam to 180bar and 567° C, cooling the mixture 482° C

Further components:

O_2 generator: needs 1.08MJ/(kg of O_2) or 50.9kJ/(kg of mixture)

O_2 compressor: brings the O_2 from atmosphere to burner pressure level, needs 0.87MJ/(kg of O_2) or 41kJ/(kg of mixture)

Overall maximum theoretical efficiency:

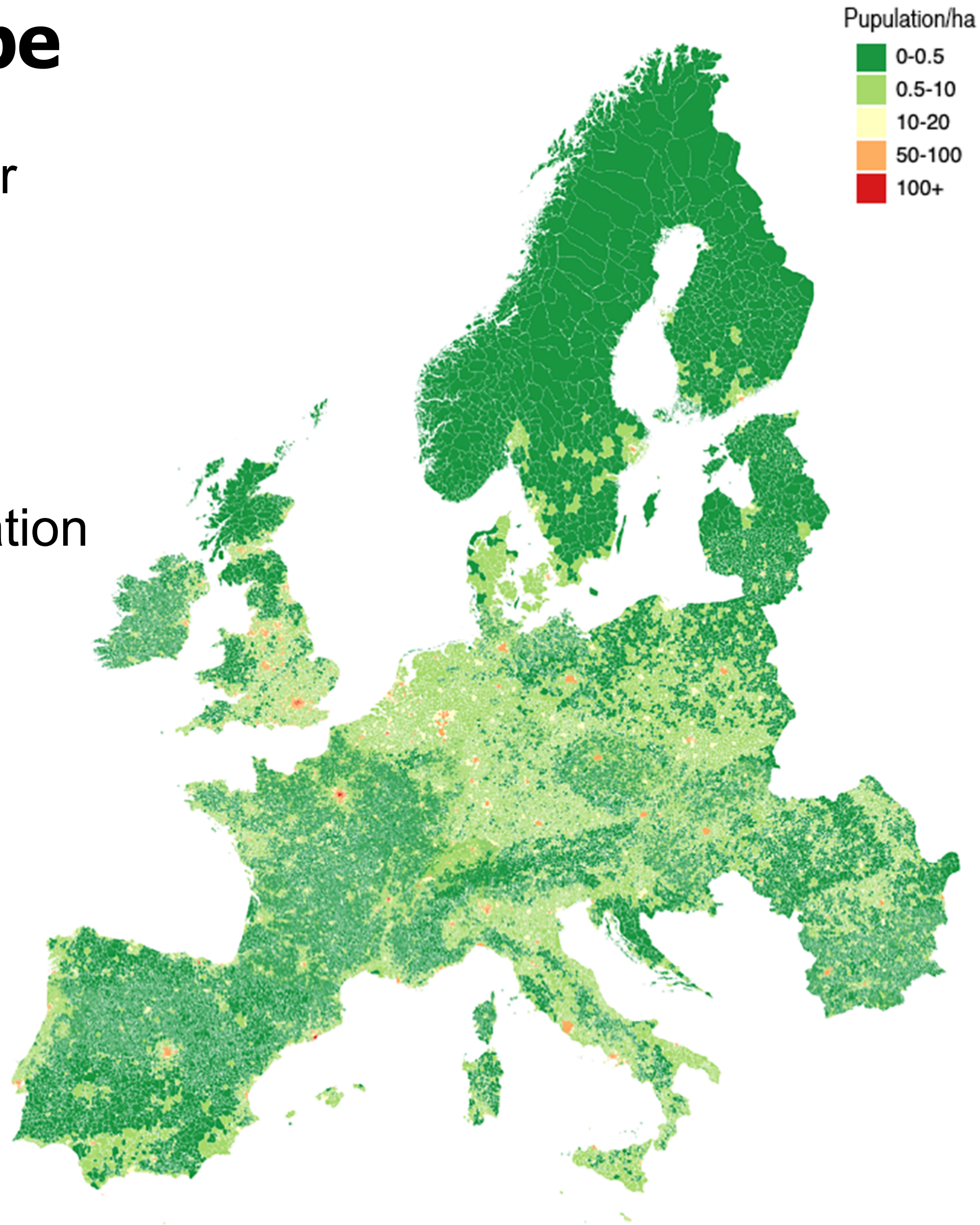
$$\eta_{th}=\eta_{gen}(W_{HTT}+W_{HPT}+W_{LPT}-W_{C1}-W_{C2}-W_{C3}-W_{pump1}-W_{pump2}-W_{O2gen}-W_{O2compr})/Q_{comb}$$
$$= 57.5\%$$

Comments:

- CO_2 storage has to be safe
- Pilot power plants in Texas and Berlin
- The power plant has to be close to the storage point to avoid CO_2 transportation costs

Population in Europe

- Difficult to find safe spot for carbon dioxide storage in Europe, due to population density
- One option is in the ocean while another is mineralization



Scenario analysis: How can EU achieve 45% renewable electricity by 2030?

- EU targets 45% renewable electricity by 2030

- Unlike for 2020 targets, no targets for individual countries are derived for 2030

➢ Which combination of wind and solar, being installed in which locations, will achieve EU target with lowest detrimental effects on cost and security of supply?

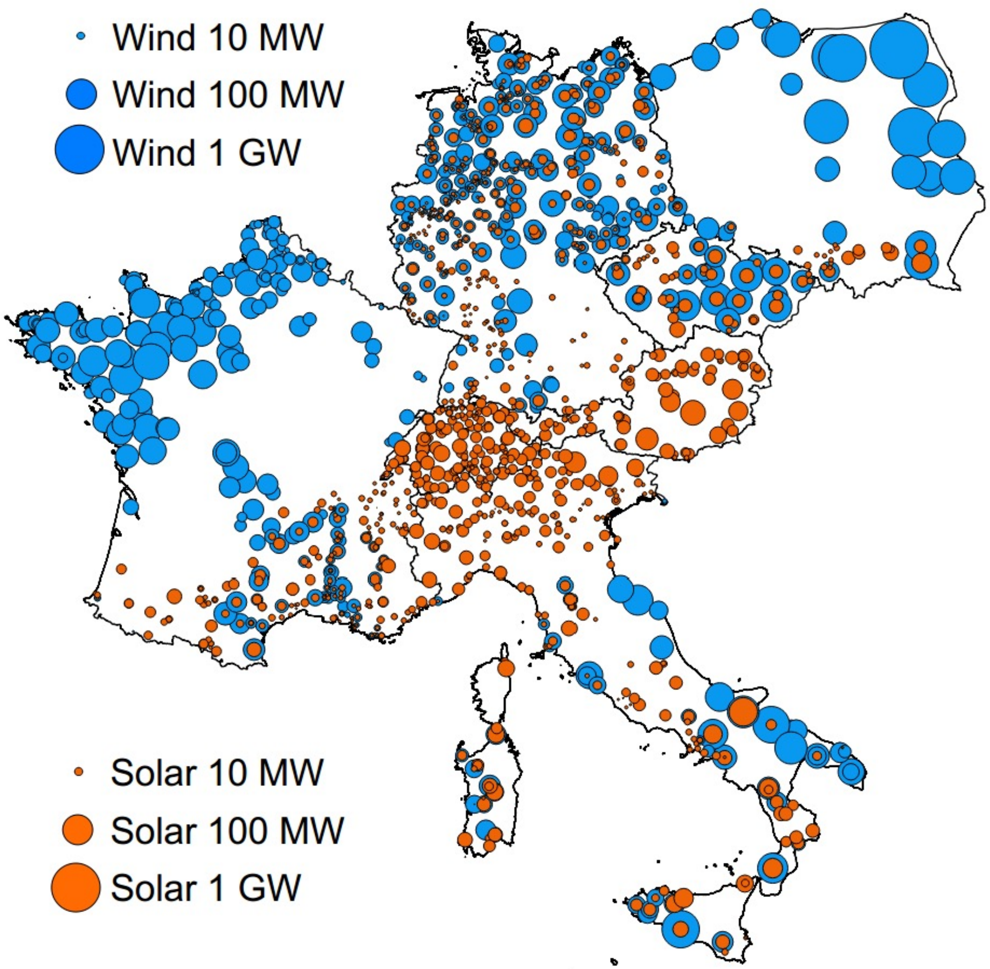
45%-RES study: Optimization target

- Optimum shall respect energy policy trilemma: Sustainability, competitiveness and security of supply
- Optimization target $$\min(C + (1 - E) + T + V)$$ $$while\ R \geq 45\%$$
- Where
  - Renewable share $$R = \frac{electricity\ from\ RES}{total\ electricity\ demand}$$
  - Curtailment $$C = 1 - \frac{dispatched\ RES\ electricity}{available\ RES\ electricity}$$
  - Energy capacity factor $$E = \frac{available\ RES\ electricity}{24h \times 365\ days \times installed\ RES\ power}$$
  - Transmission lines $$T = number\ of\ transmission\ lines\ to\ upgrade$$
  - Variability of residual load $$V = stdev(ResLoad(t)\ \forall t)$$ $$ResLoad(t) = total\ load(t) - nondispatchable\ RES(t)$$

Results: Optimal RES portfolio across Europe

- To achieve 45% RES target, 221 GW of wind and 82 GW of solar need to be installed across central Europe

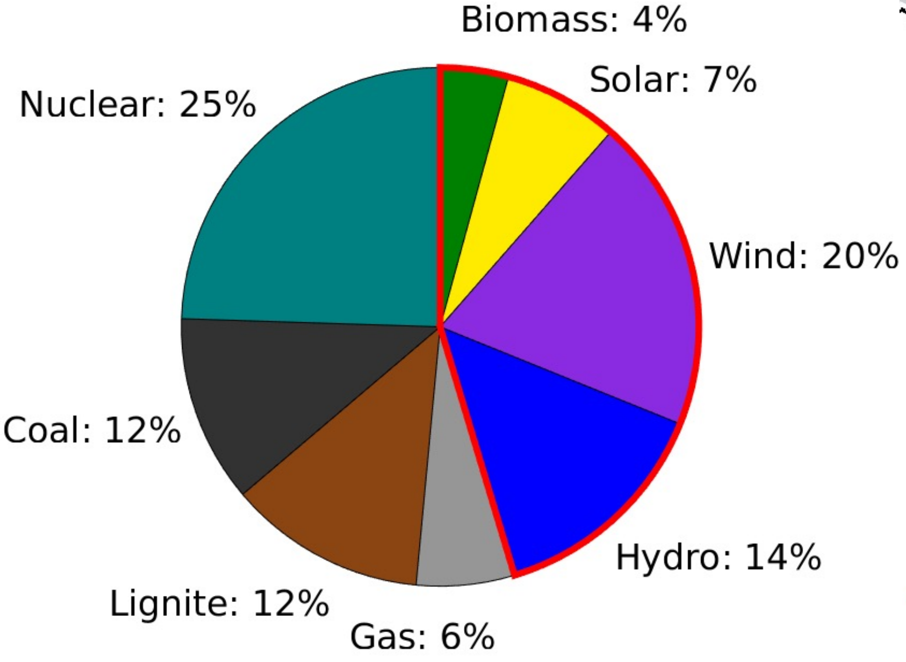
	Installed Wind [GW]	Installed Solar [GW]
AUT	2	12
CZE	14	6
DEU	60	15
FRA	72	9
ITA	33	26
POL	37	2
SUI	3	12
Total	**221**	**82**

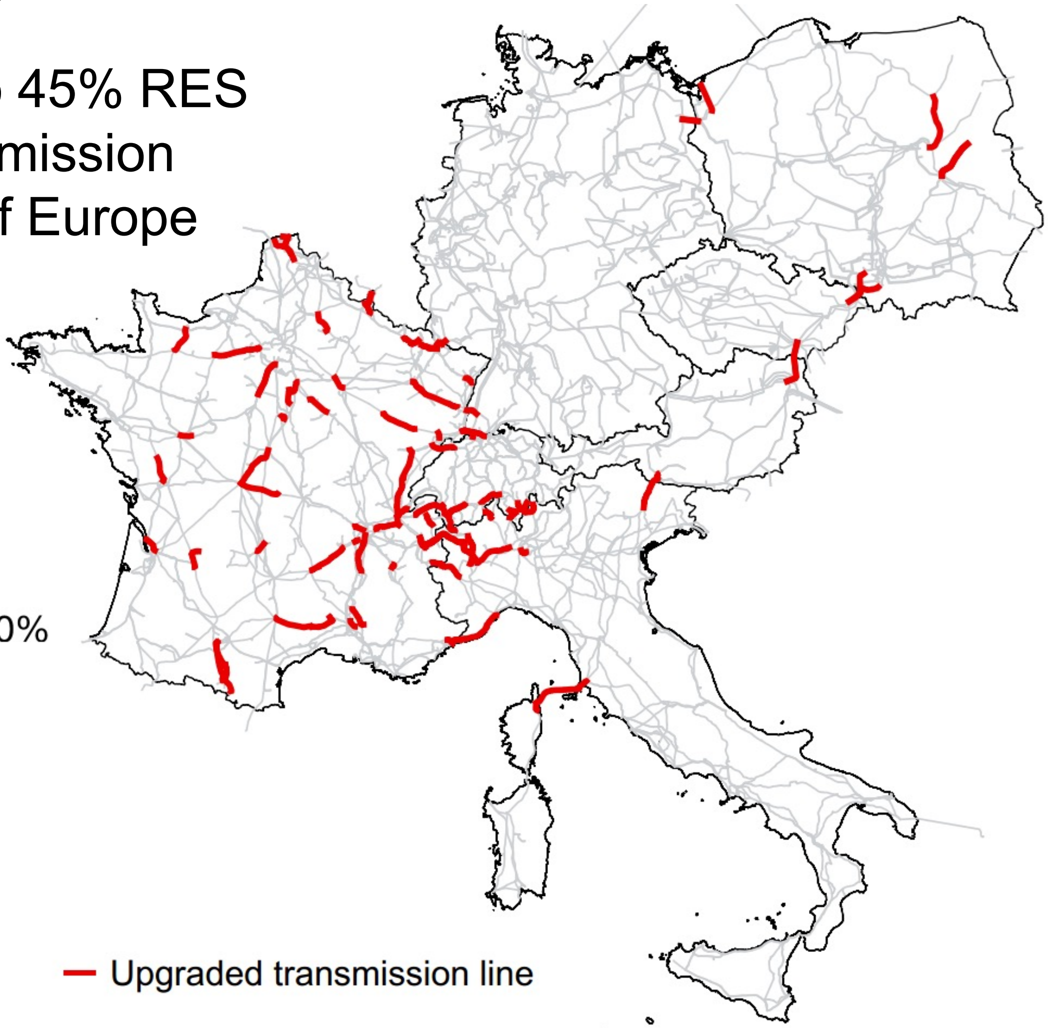


Optimal RES portfolio to achieve 45% renewable electricity in central Europe by 2030
P Eser, N Chokani, RS Abhari 2017 IEEE Power & Energy Society General Meeting, 1-5

Results: Transmission grid in Italy limits penetration of solar power

- Contribution of solar power to 45% RES goal is limited, because transmission lines between Italy and rest of Europe are bottlenecks





Exam topics

- Velocity triangles for compressors and turbines:
  - Relative and absolute velocities
  - Work, Power, Δh, Δp
- Calculate the thermodynamic properties in the process points around a cycle with and without tables
- Draw T-s and p-V diagrams
- Use the turbine/compressor efficiency
- Calculate work and heat
- Calculate the thermal efficiency
- Understand issues and potential solutions for carbon capture and storage

Cycles

- Rankine cycle
- Otto cycle
- Diesel cycle
- Brayton cycle
- Stirling cycle
- Carnot cycle: heat pump / refrigerator
- Combined cycles (combination of all the cycles above)