KTH Industrial Engineering
and Management

Combined Cycles integrated with a Heat Pump and Thermal Energy Storage system for air Pre-cooling

A Techno-economic Feasibility Analysis

Rafael Guédez, PhD
J. García, A. Nuutinen, G. Graziano, G. Martin, J. Chiu, B. Laumert

rafael.guedez@energy.kth.se

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Outline

- *Background – Motivation*
- *Cycle Layout and Operating Modes*
- *Techno-economic Modeling Approach*
- *Case Study*
  - *Scenario – Boundary Conditions*
  - *Performance Indicators*
- *Conclusions and Future Work*

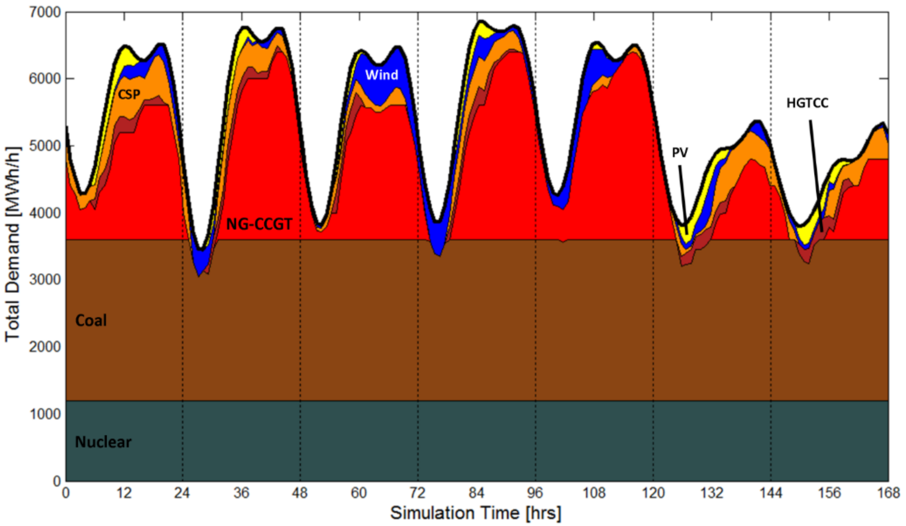
Background

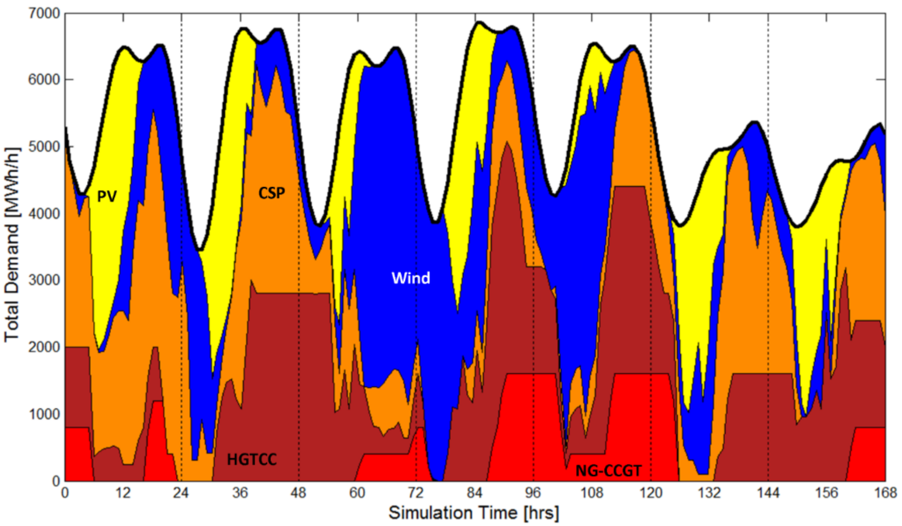
Increased share of “cheap” variable renewables in power markets

Thermal assets are recruited less and demanded to be more flexible

Background

- Indeed thermal power plants e.g. Combined Cycles are less recruited
- Energy-only markets: from mid-merit to variable recruitment patterns and faster ramps
- Current assets are not profitable enough or cannot cope with such fluctuations
- The electric grid still needs reliable and efficient installed thermal capacity





Background: PUMP HEAT H2020

The PUMP-HEAT Project

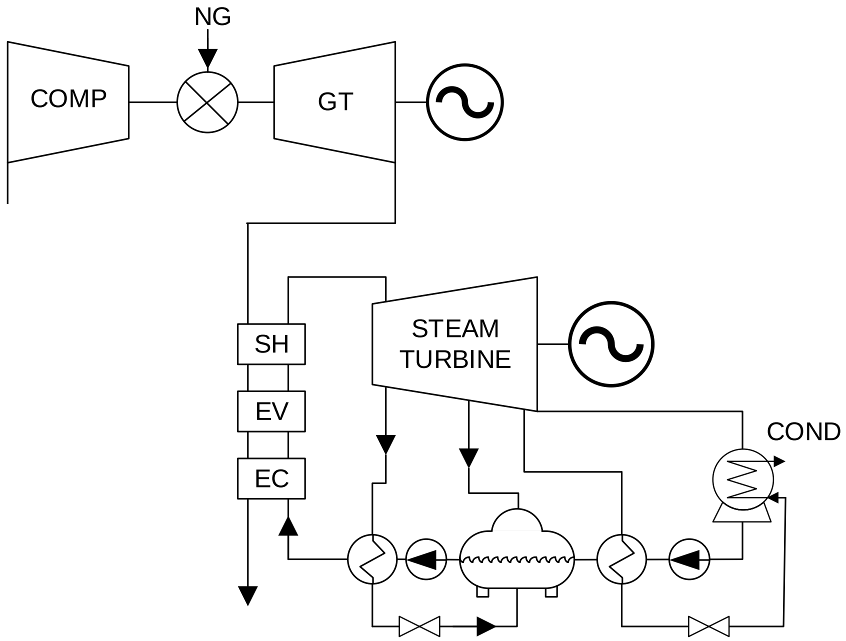
"Performance Untapped Modulation for Power and Heat via Energy Accumulation Technologies"

European Union's Horizon 2020 research and innovation program

Project Objective:
To investigate the viability of increasing the flexibility and cost-efficiency of Combined Cycle power plants by integrating thermal storage and heat pumps

Combined Cycle Gas Turbines (CCGT)

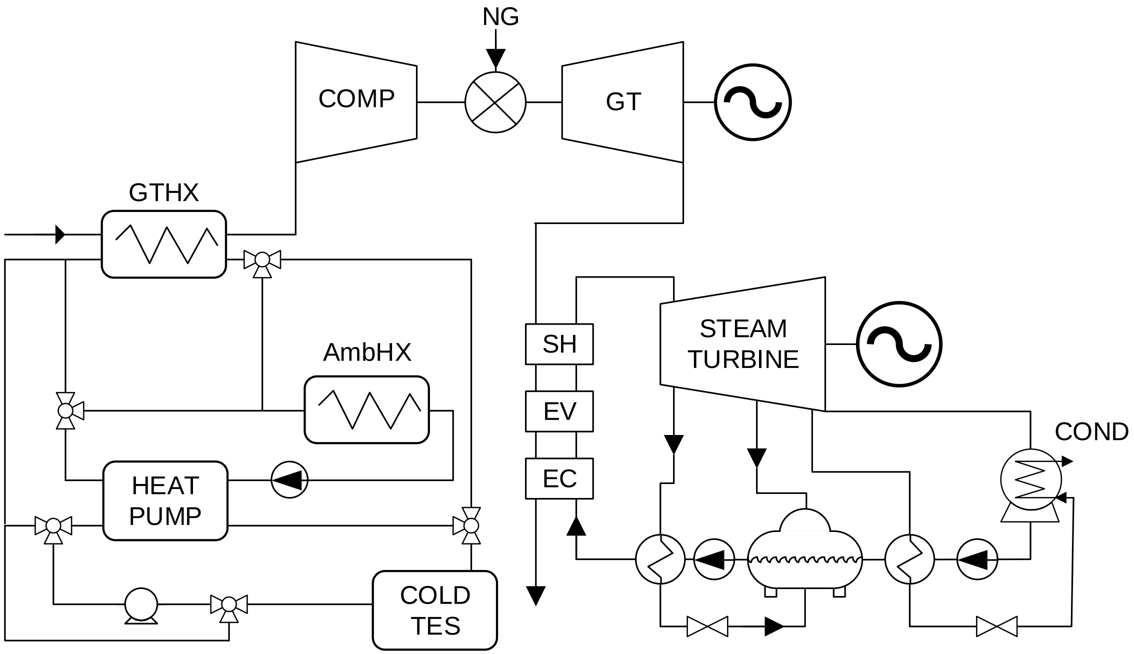
- Most efficient thermal cycle
  e.g. 50%-62% commercially
- Reliable and proven technology in wide range of capacities
- Can operate with different fuels
  e.g. bio-gas, natural gas
- Can provide ancillary services
- Can be designed to provide electricity and heat as end-products



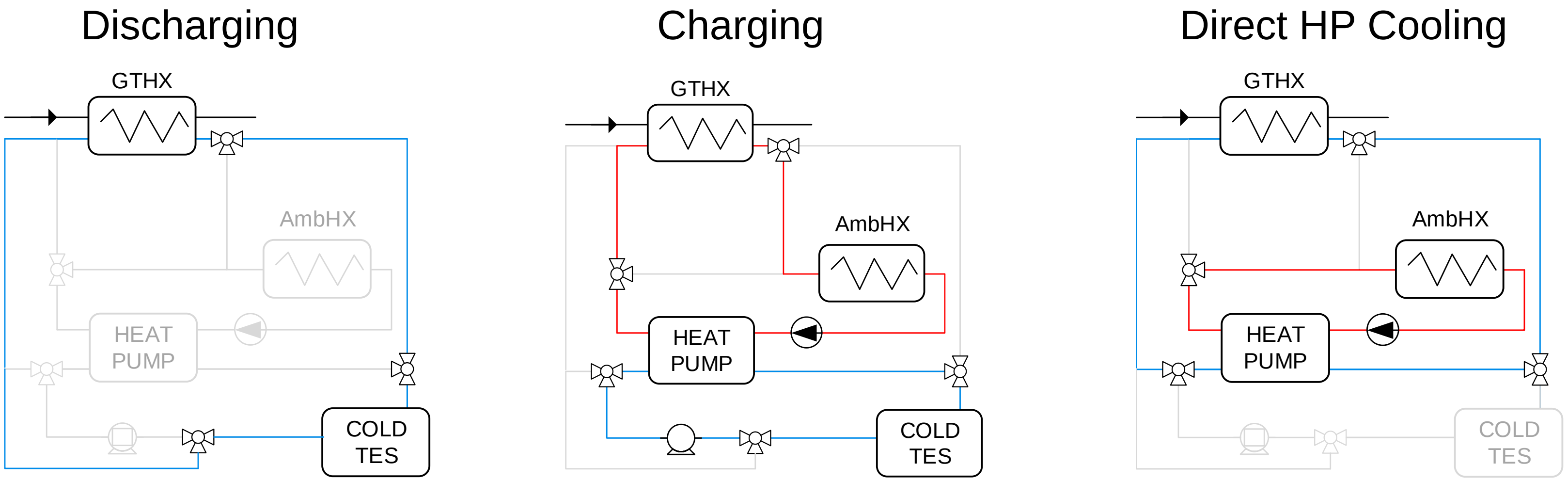
CCGT + Heat Pump + Thermal Energy Storage

Flexibility in energy-only markets to increase profitability by:

- Pre-cooling the air during peak-price hours
- Storing cold energy during off-peak periods



CCGT-HP-TES: Operation – added flexibility

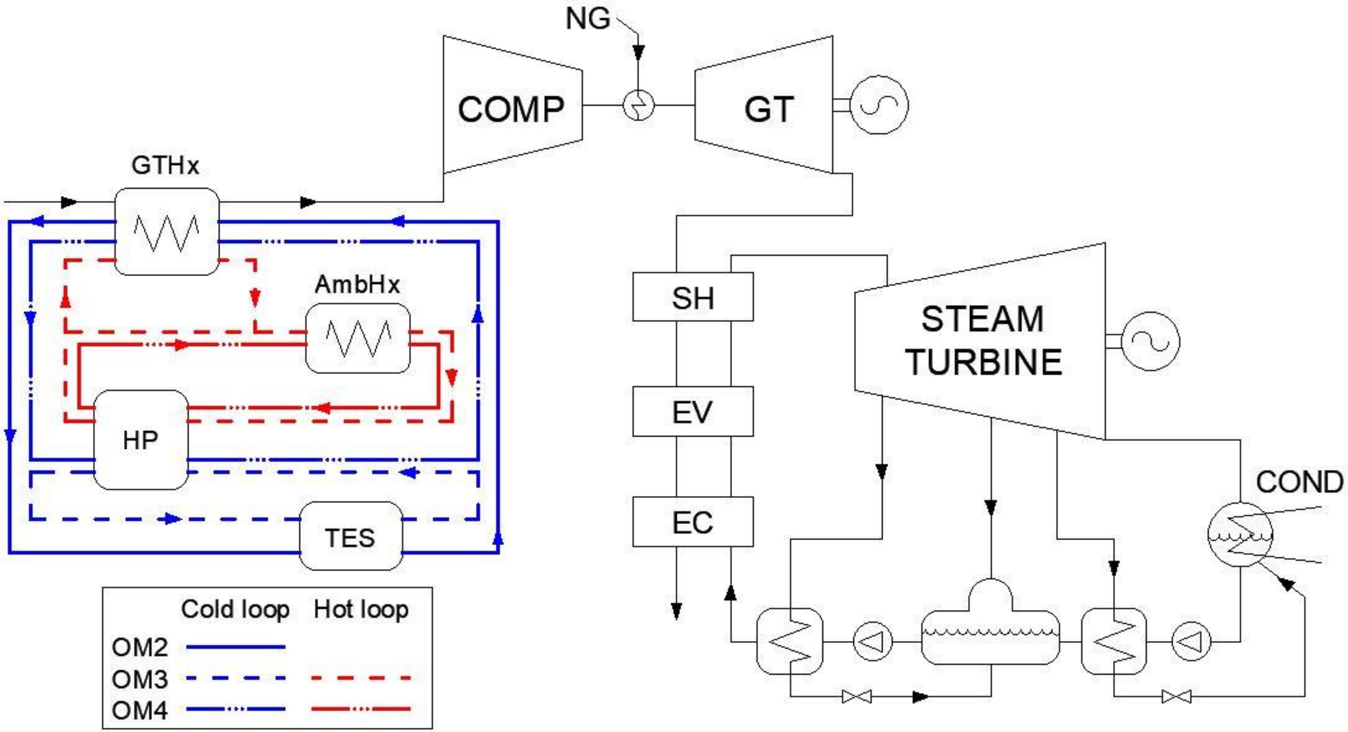


Operation Mode	Ambient temperature	Electricity price
Charging	-	Lowest price hours
Discharging	> Set Point Temp	Highest price hours
Continuous cooling	> Set Point Temp	< Mean price
Anti-ice	< GT icing Temp	-

CCGT-HP-TES: Operation – added flexibility

	Advantages	Disadvantages
TES	• Low on-peak parasitic power required • Lower investment cost than direct chilling for peaks lasting less than 8 hours	• More off-peak power required • Higher capital cost than direct chilling for peaks lasting more than 8 hours • More complex system than direct chilling • Chilled air available only part of the day
Continuous Cooling w/ HP	• Provides chilled air 24 hours a day • Simple and reliable • No off-peak parasitic power required • Very efficient • Higher operating hours	• Higher on-peak parasitic power required • Refrigeration equipment is sized for peak load → increased capital cost

CCGT-HP-TES: Operation – added flexibility



Objectives of this Research Work

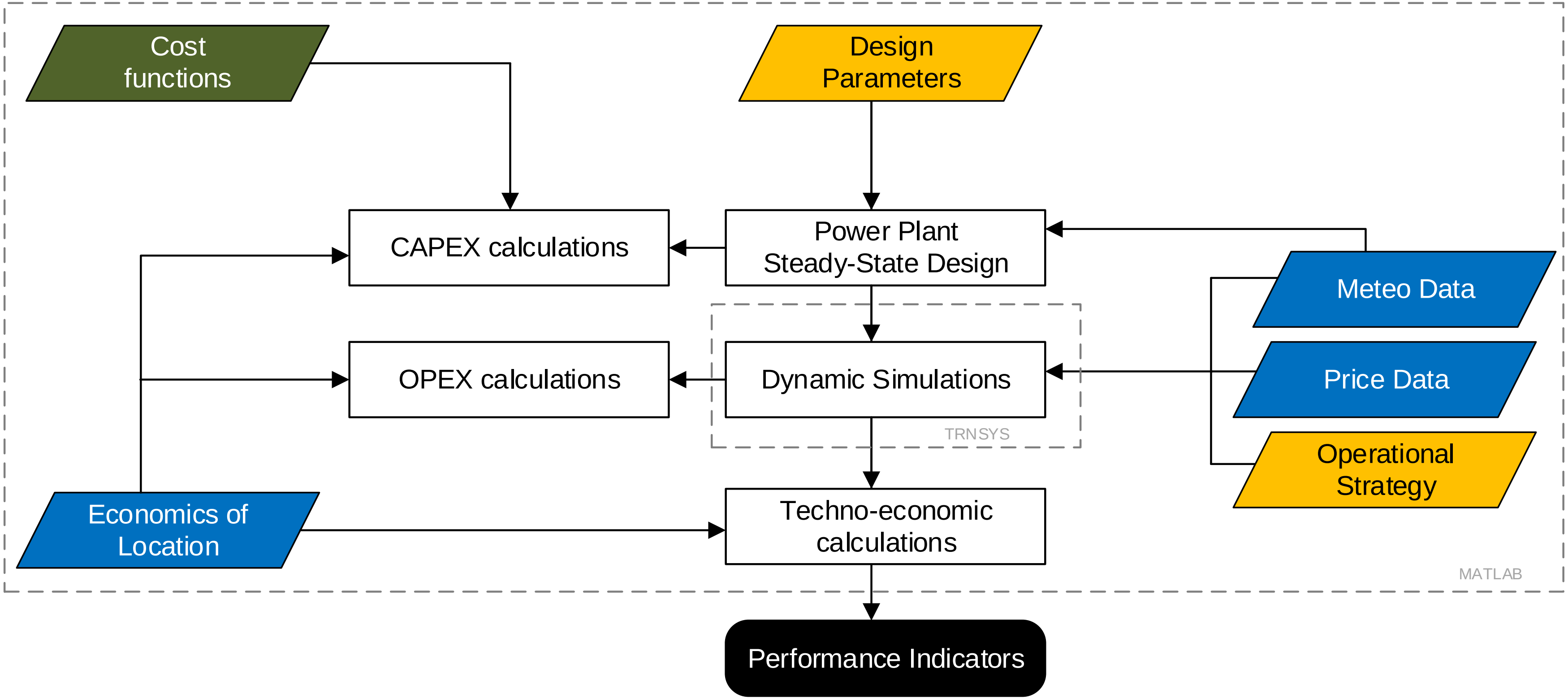
To identify promising configurations from a techno-economic performance standpoint, when considering energy-only market revenues in a specific location.

In doing so:

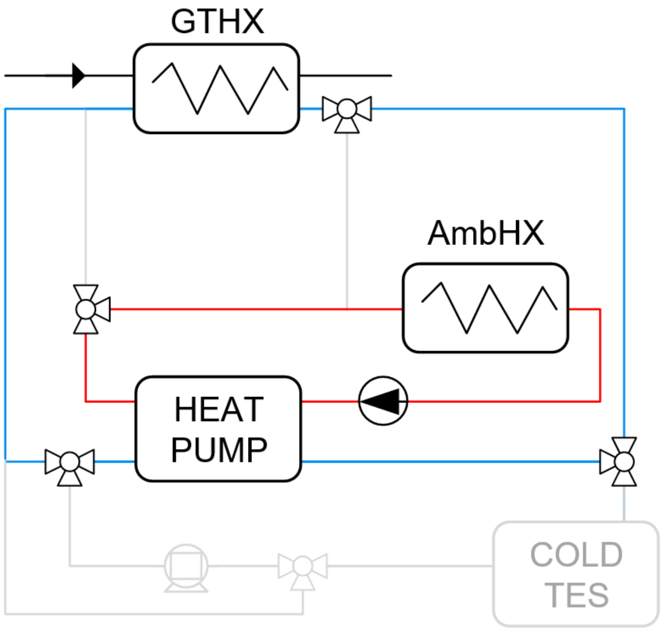
- To develop a flexible techno-economic performance model of proposed layout
- To perform a comparative analysis against reference CCGT plant
- To suggest future work and identify under which market conditions is the proposed layout more suitable

The work summarizes parts of the first deliverable from T1.3 of Pump Heat project
WP1: "Scenario Analysis, Requirements Definition and Business Models"
T1.3 "Thermo-economic models and key performance indicators"

Methodology: Modeling Approach



Methodology: Key Components: HP and HEx



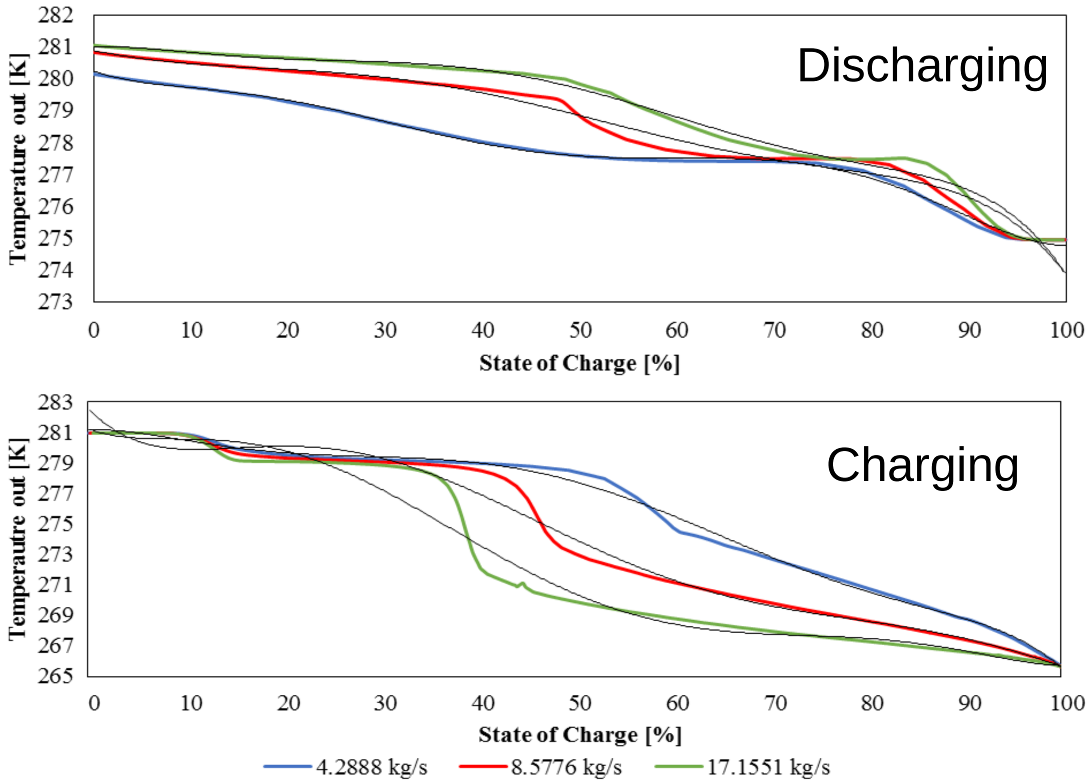
$$C_{p,WG} = (0.0006 \cdot T + 0.8652) \cdot 4.1868\ [kJ/kgK]$$

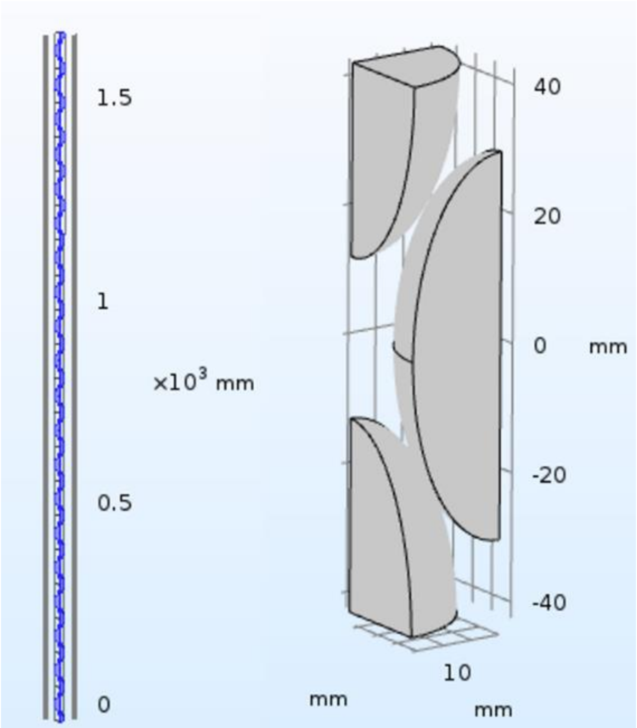
Design variable	Value
Ambient pressure	101 325 Pa
Air inlet	15°C
Air outlet	7.5°C
Pressure drop (constant)	2%
Liquid-side pinch temperature	2°C
Gas-side pinch temperature	3°C
Inlet WG mixture	0°C
Outlet WG mixture	25°C
Air mass flow	666 kg/s

$$COP_{cooling} = \frac{T_{evap,out}}{T_{cond,out} - T_{evap,out}}$$

$$COP_{heating} = \frac{T_{cond,out}}{T_{cond,out} - T_{evap,out}}$$

Methodology: Key Components: TES

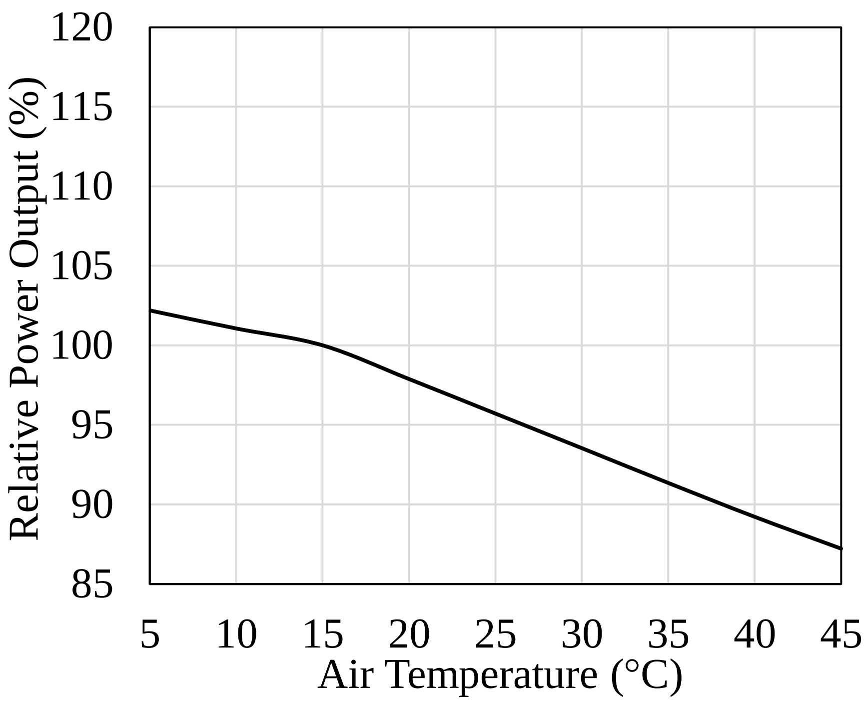




Methodology: Reference CCGT

GT nominal conditions	Value	Unit
GT power	268.50	MW_{el}
Compression ratio	18	-
Combustion temperature	1480	˚C
Fuel	Natural Gas	
Initial fuel temperature	15	˚C
Lower Heating Value	47.011	MJ/kg
Exhaust mass flow	662.74	kg/s
Exhaust temperature	575.4	˚C

ST nominal conditions	Value	Unit
ST power	132.4	MWe
HP stage pressure	93.56	bar
IP stage pressure	27.77	bar
LP stage pressure	4.58	bar
HPT inlet temperature	540	˚C
IPT inlet temperature	540	˚C
LPT inlet temperature	294	˚C
Condensate temperature	50	˚C



Methodology: Key Performance Indicators (KPIs)

Technical KPIs

$$\mathrm{E}_{\mathrm{el}} = \int \left(E_{GT} + E_{ST} - E_{para} \right) dt$$

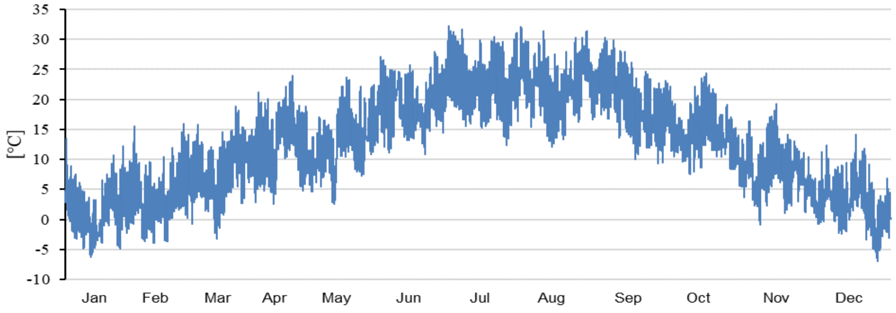
$$\eta_{el} = \frac{E_{el}}{\int \left(m_{fuel} \cdot LHV_{fuel} \right) dt}$$

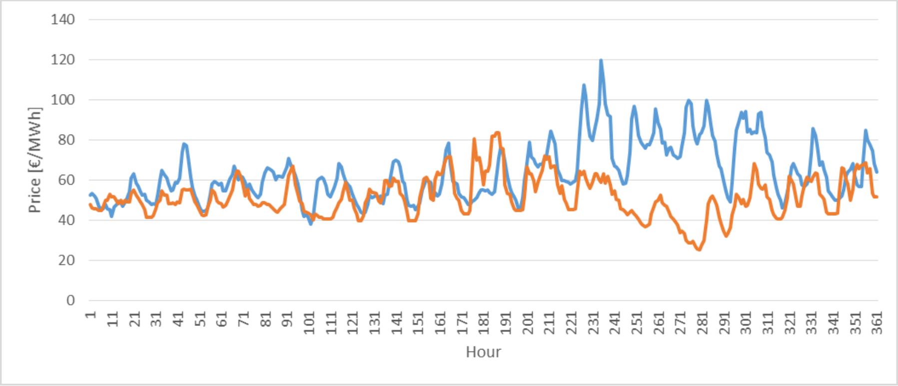
Economic KPIs

$$LCoE = \frac{\alpha * C_{inv} + \beta * C_{decom} + C_{oper} + C_{maint} + C_{labour}}{E_{el,net}}$$

$$IRR = r \; when \; \sum_{t=1}^{n} \left(\frac{B - C_{O\&M}}{(1+r)^t} \right) - C_{inv} = 0$$

Case Study: Boundary Conditions





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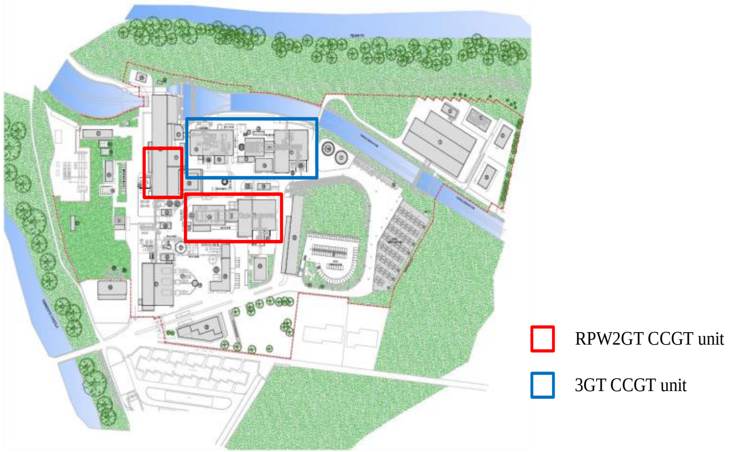
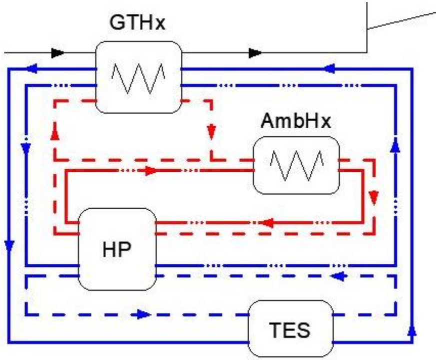


Case Study: Scenarios – Modeling Control

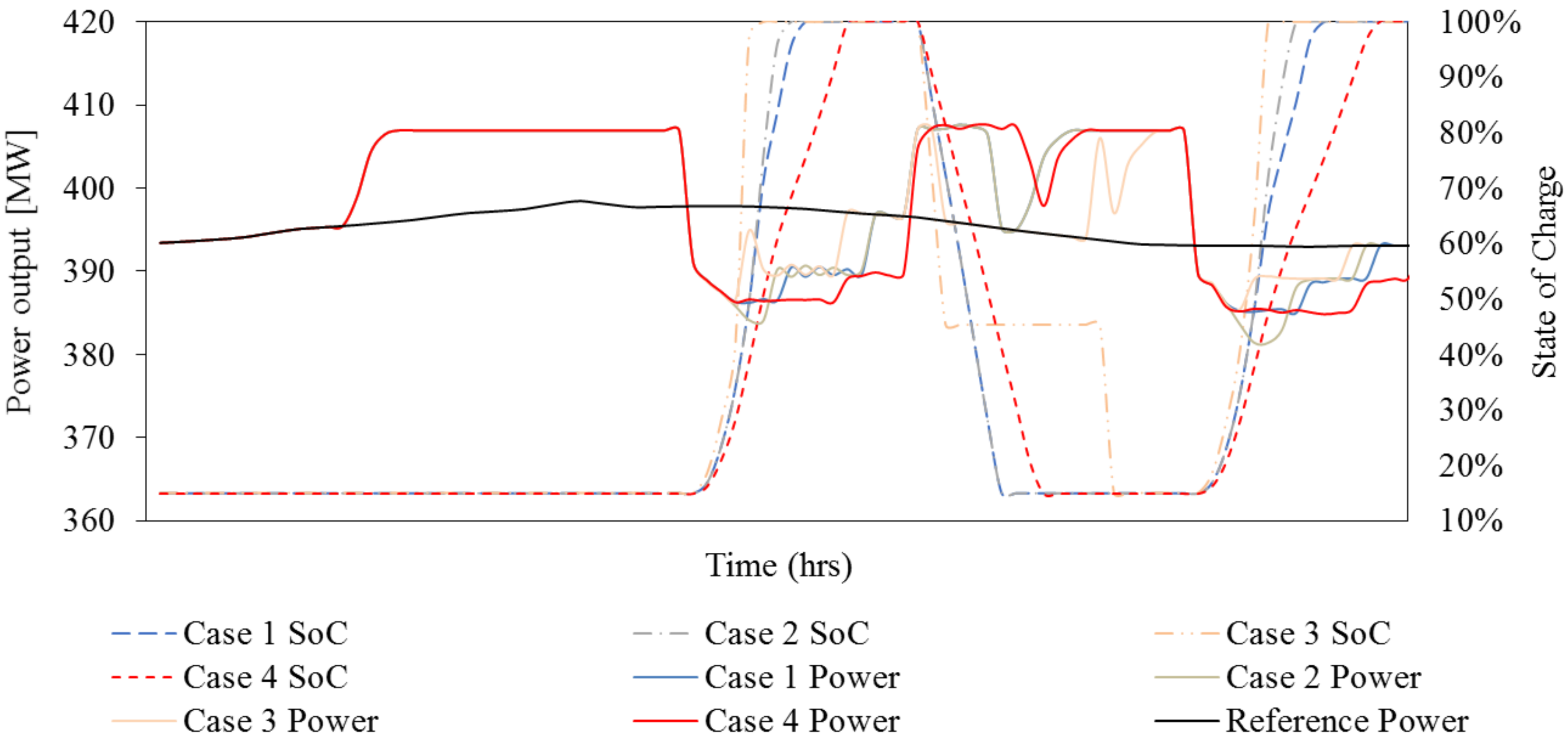
	Case 1	Case 2	Case 3	Case 4	Case 5
HP capacity	5 MW_{el}	5 MW_{el}	5 MW_{el}	5 MW_{el}	5 MW_{el}
TES capacity	12 MWh	12 MWh	6 MWh	18 MWh	-



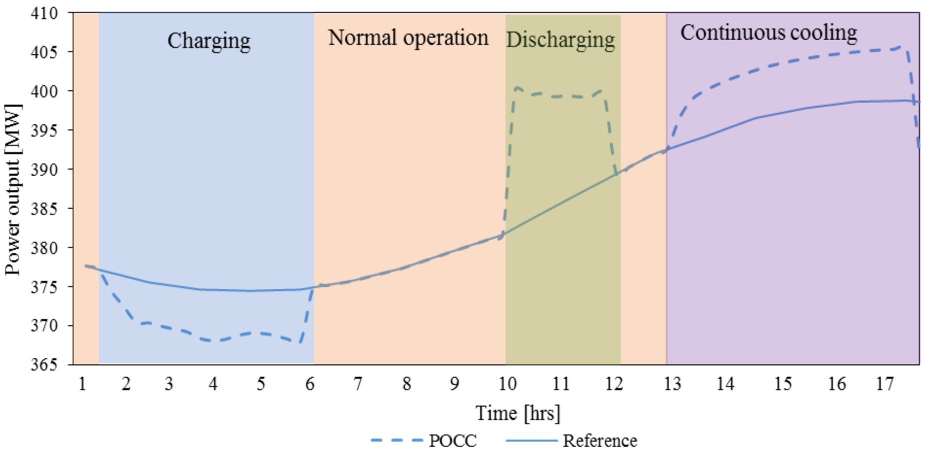
Design/Operation Considerations	Value
Design COP	4.5
Design CC mass flow	500 kg/s
Design AmbHX air mass flow	1800 kg/s
Max GT inlet temp during charging	20°C
GT inlet aim T during cont. cooling	15°C
Max ramp-up	5 MW_{el}/hour
Minimum state of charge	15 %
Continuous cooling T_{amb}	15°C

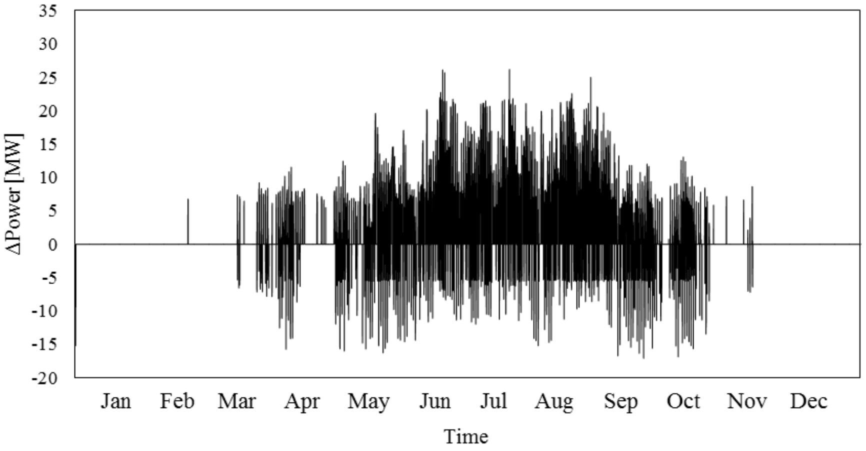
Operation Mode	Ambient T	Electricity price
Charging	-	Daily minimum
Discharging	>15°C	Daily maximum
Cont. cooling	>15°C	< Daily mean
Anti-ice	< 5°C	-

Case Study: Performance HP-TES cases

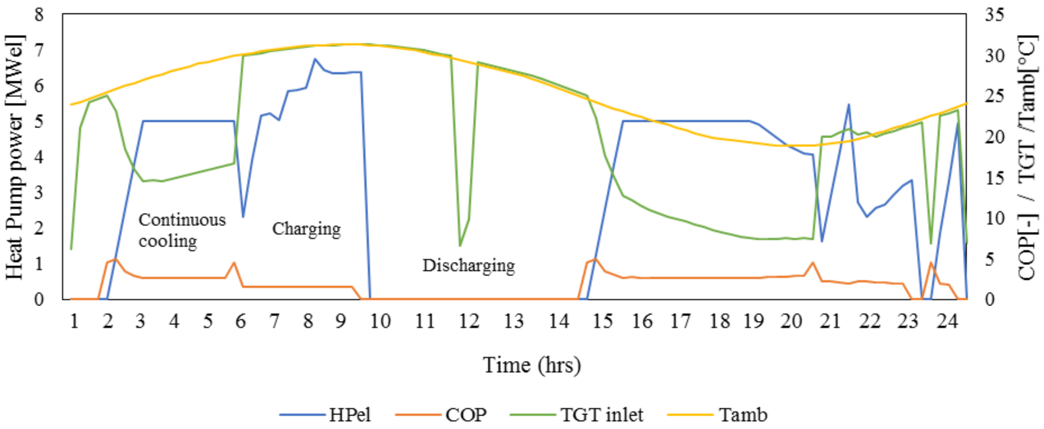


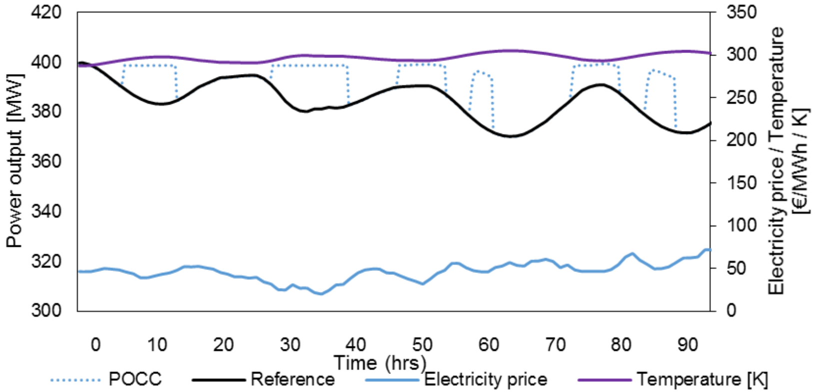
Case Study: Performance Results





Case Study: Results: Cont. Cooling (HP only)



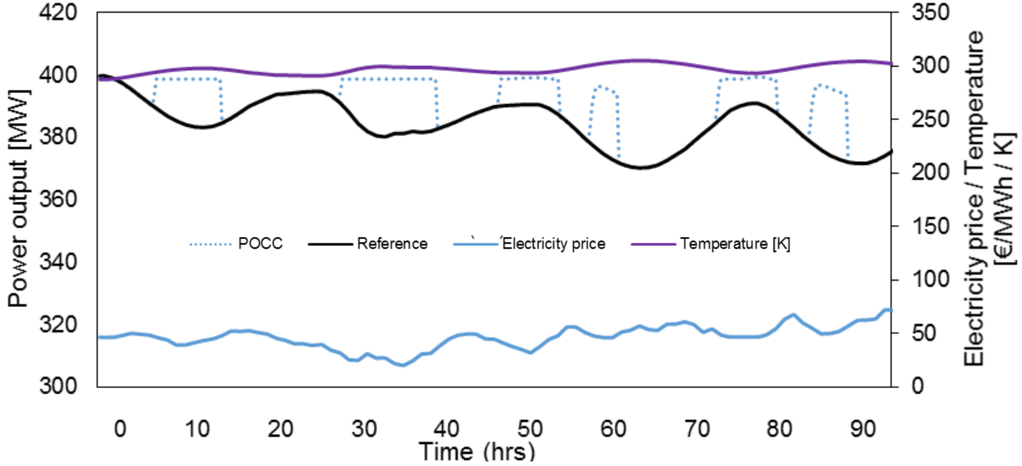


Case Study: Results: KPIs

	Total electricity (GWh_{el})	Mean power (MW)	Mean efficiency (%)	TES utilization factor (%) (1)	Mean HP ramp-up (MW/min)	NPV (M€)	LCOE (€/MWh)	IRR (%)
Reference	**3498**	**399.32**	**58.07**	**-**	**-**	771	52.71	2.48
Case 1 **5 MW_e + 12 MWh_{th}**	3508	400.41	58.23	161	0.052	774	53.45	1.98
Case 2 **7.5 MW_e + 12 MWh_{th}**	3508	400.49	58.24	161	0.062	774	53.57	1.90
Case 3 **5 MW_e + 6 MWh_{th}**	3509	400.53	58.25	121	0.054	775	53.17	2.15
Case 4 **5 MW_e + 18 MWh_{th}**	3507	400.33	58.22	106	0.047	773	53.72	2.08
Case 5 **5 MW_e + no TES**	3523	402.20	58.49	-	0.032	783	52.79	2.44

Case Study: Results: Continuous Cooling

Switch on Air Temp.	15°C	25°C	15°C	25°C	**REF**
GT aim Temp.	15°C	15°C	7.5°C	7.5°C	
Total electricity (GWh_{el})	3 516	3 503	3 523	3 504	3 498
Mean power (MW)	401.35	399.88	402.20	399.93	399.32
Mean efficiency (%)	58.37	58.16	58.49	58.16	58.07
NPV (M€)	779	772	783	772	771
LCOE (€/MWh)	52.90	53.10	52.79	53.09	52.71
IRR (%)	2.57	2.47	2.62	2.47	2.48

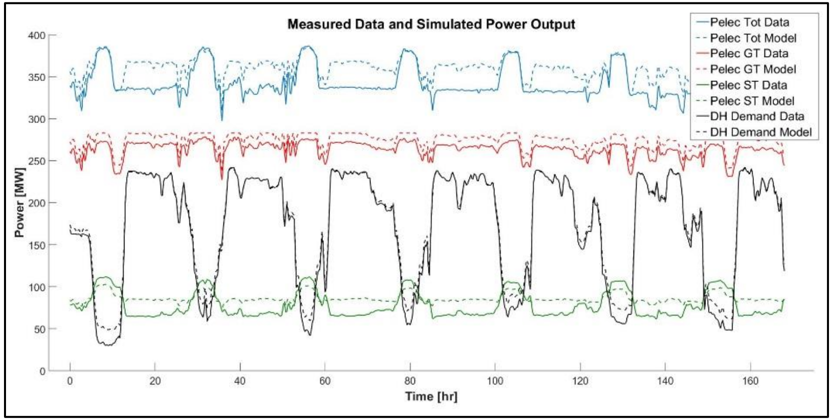


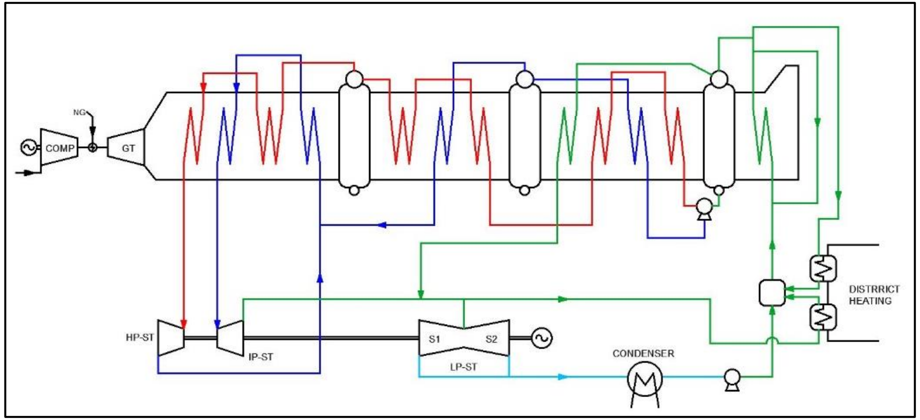
Conclusions

- A techno-economic model of an innovative CCGT integrated with an inlet GT mass flow pre-cooling loop consisting of a heat pump and a cold TES unit has been developed and used to evaluate the feasibility of such a concept.
- The proposed layout is shown to increase the annual yield by increasing the output of CCGT during times of peak electricity prices and at high ambient temperatures.
- The study shows that, for given cost assumptions and market considered, the proposed layout would be less profitable than a conventional CCGT → new markets / cost studies
- However, even at costs assumed, implementing the heat pump alone is shown to potentially bring cost-effective benefits to the cycle performance – besides flexibility.
- It is identified that a market with higher price volatility and more pronounced peaks would potentially benefit the proposed layout (especially with flexibility revenue streams)

Future and On-going Work

- Thermodynamic and transient model improvements.
- Sensitivity to costs and operating conditions.
- Evaluation of new markets and inclusion of additional revenue streams.
- Evaluation of new layouts: including heat as end-product.





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