

Analysis of part-load operation and plant size effects on combined cycle power plants with post-combustion CO₂ capture

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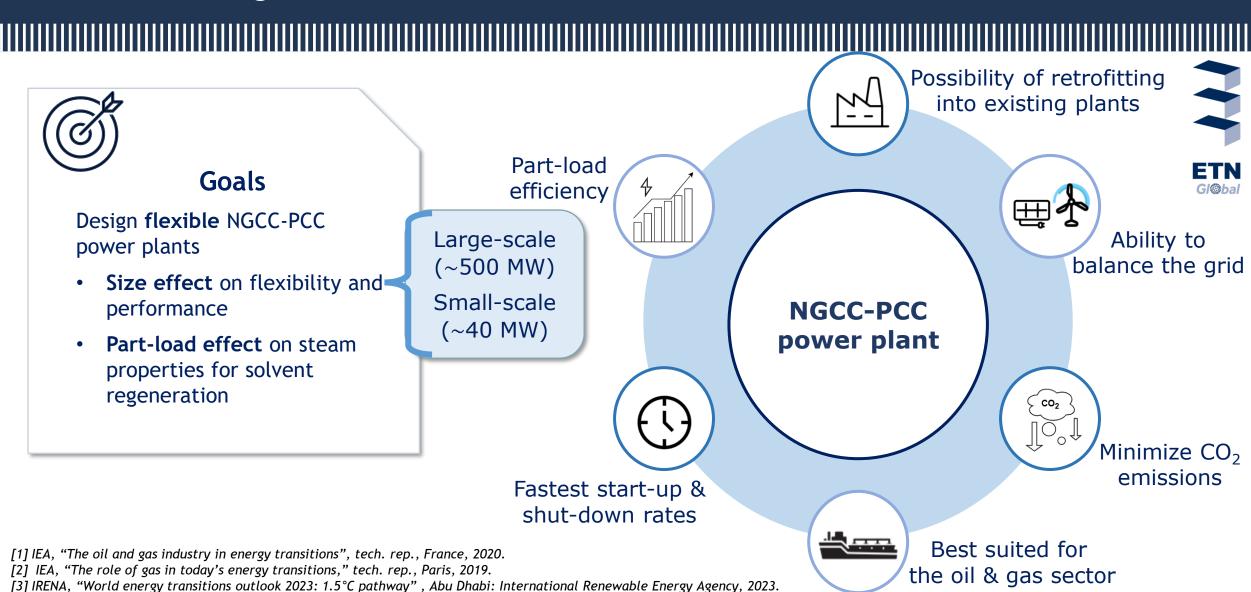
AY: 2023-2024

Outline

1	Motivations & goals	
2	Power plants layout	
3	Model & numerical assumptions	
4	Case studies & results	
5	Conclusions & future perspectives	



Motivations & goals



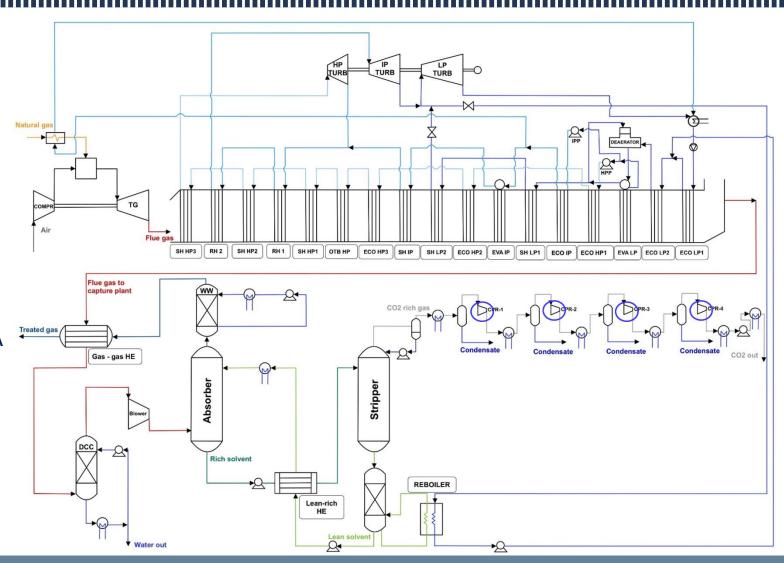
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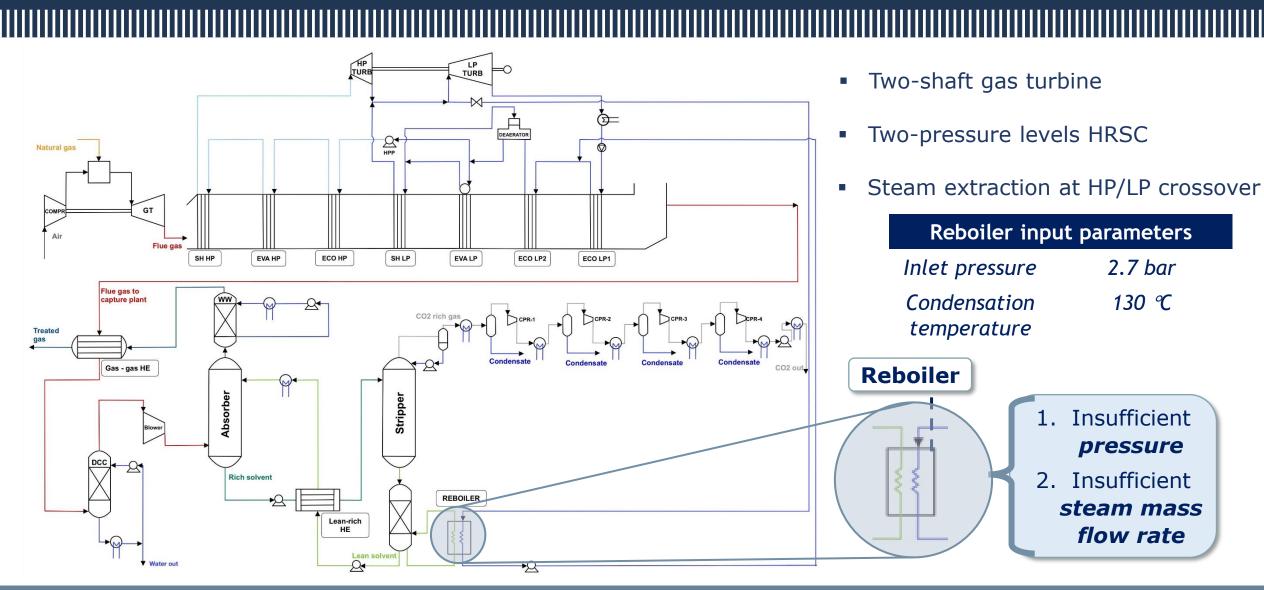


Large-scale power plant layout

- Single-shaft gas turbine
- Three-pressure levels HRSC
- Fuel pre-heater
- Steam extraction at IP/LP crossover
- CO₂ absorption process based on MEA
- 4 intercooled compressors



Small-scale power plant layout



Solutions to control reboiler extraction pressure

Reboiler input parameters

Inlet pressure 2.7 bar

Condensation 130 ℃

temperature

Evaporation 120 ℃

temperature

Outlet condition saturated liquid

hot side

At least 15% of steam expands in the LP steam turbine Low-pressure turbine with steam compressor

To the condenser

G

MEA

OUT

Reboiler

MEA

LP TURBINE

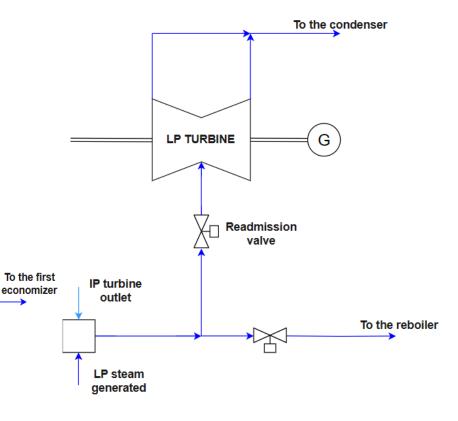
IP turbine

outlet

LP steam

generated

Low-pressure turbine with readmission valve



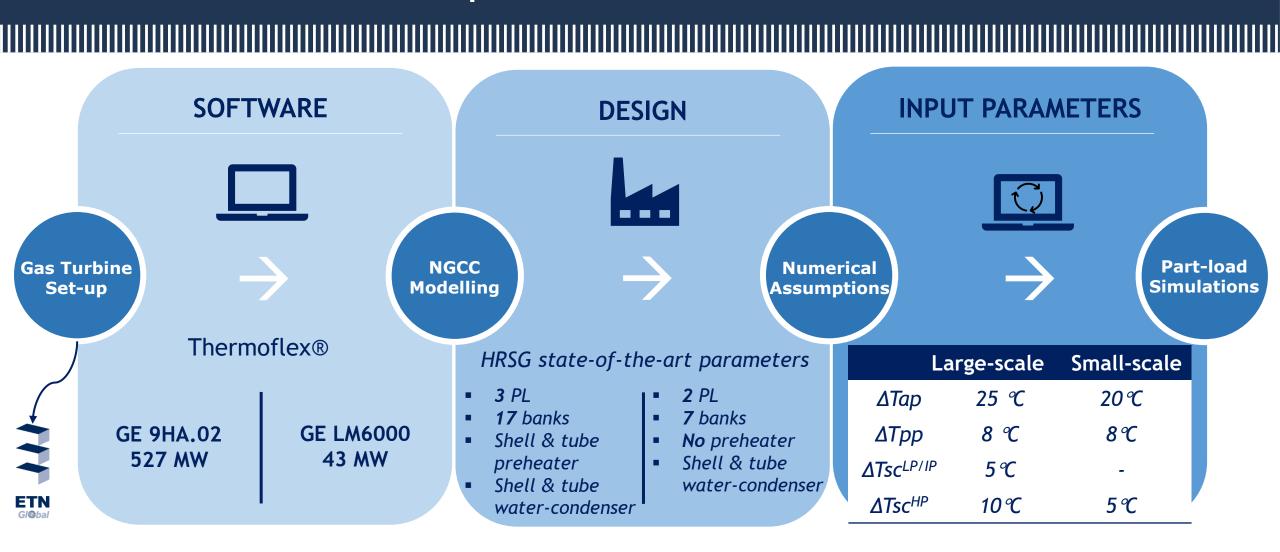


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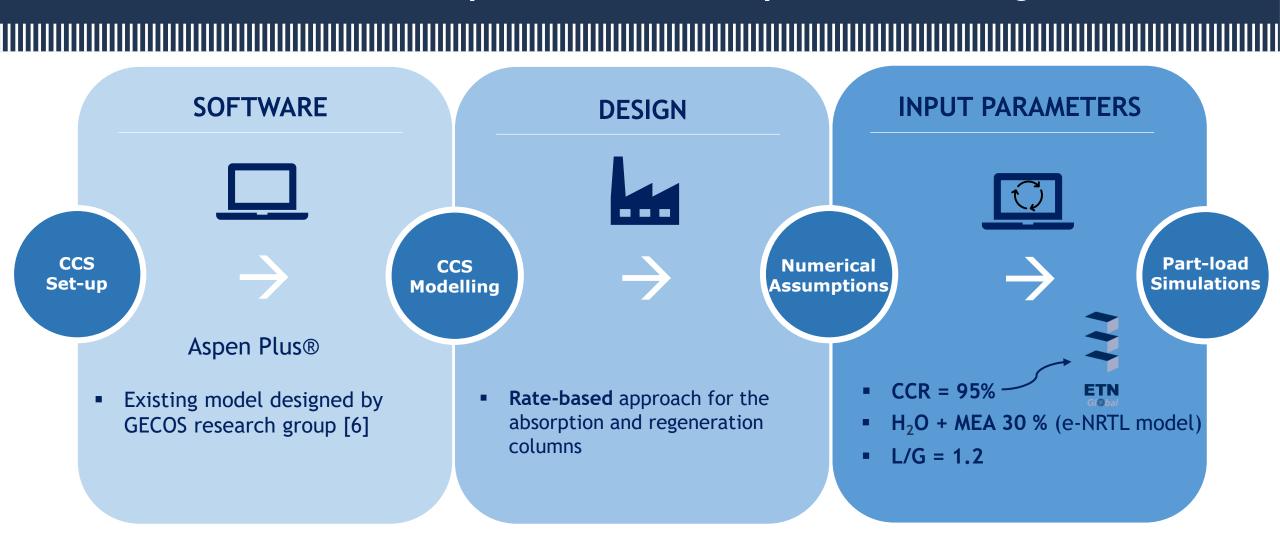
Model and numerical assumptions - Power block



[5] Martelli, E, Girardi, M, & Chiesa, P. "Breaking 70% Net Electric Combined Cycle Efficiency with CMC Gas Turbine Blades." Proceedings of the ASME Turbo Expo 2022: Turbomachinery Technical Conference and Exposition, 2022.



Model and numerical assumptions - Carbon capture and storage



[6] D. Terreni, "Technical assessment of MEA-based solvent and mixed salts process for CO2 capture in cement industry.", 2020.

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Case studies

Minimum load

- **30%** → Large-scale plant
- **40%** → Small-scale plant

Specific primary energy consumption for CO_2 avoided

$$SPECCA \left[\frac{MJ}{kgCO_2} \right] = \frac{HR_{ccs} - HR_{ref}}{e_{ccs} - e_{ref}} = \frac{3600 \left(\frac{1}{\eta_{ccs}} - \frac{1}{\eta_{ref}} \right)}{e_{ccs} - e_{ref}}$$

$$\eta = \frac{Net \ power \ output}{Thermal \ power \ input}$$

Reference case

- Benchmark case
- No CCS facility
- Sliding pressure part-load control strategy

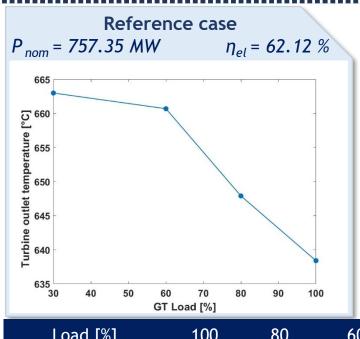
Greenfield case

- 'Capture ready' power plant
- Simultaneous operation with CCS

Retrofit case

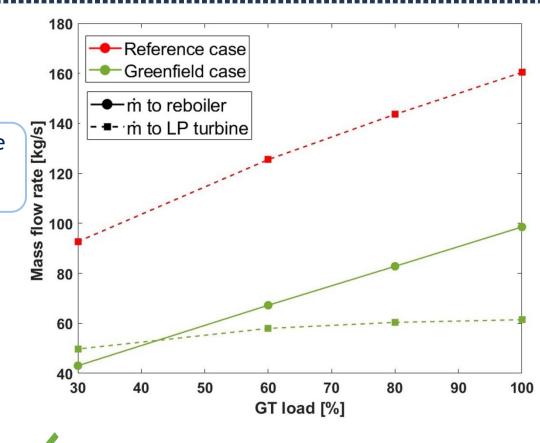
- Existing plant (reference plant)
- Pipe integration for steam extraction

Large-scale power plant results - Greenfield case



Greenfield power plant viable down to 30% following sliding pressure control

	0 70 80 「Load [%]	90 1	00	
Load [%]	100	80	60	30
ṁ _{eg} [kg/s]	984	864.1	737.9	549.8
P_{GT} [MW]	527.48	424.65	320.42	161.52
P _{ST} [MW]	173.28	157.91	141.48	109.96
P _{NET} [MW]	657	544.69	432.37	249.32
η _{el} [%]	53.99	52.48	50.70	44.50
Δη w.r.t ref. plant	-8.19	-8.25	-7.90	-8.14
SPECCA [MJ/kgCO ₂]	2.82	2.93	2.90	3.40

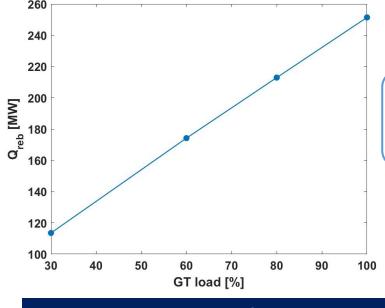


Pressure above 2.7 bar \rightarrow 4.98 bar at 30%

Minimum steam mass flow rate to LP turbine

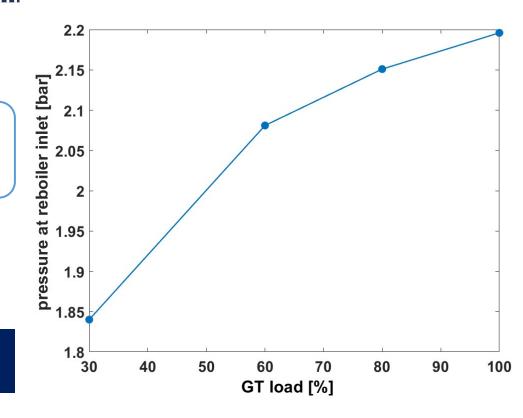


Large-scale power plant results - Retrofit case



Retrofit power plant can operate down to 30% only if design modifications are implemented

	St	Steam compressor				Readmission valve			
Load [%]	100	80	60	30	100	80	60	30	
P _{ST} [MW]	187.39	171.39	153.17	117.13	183.45	166.22	147.44	110.99	
P _{NET} [MW]	662.96	547.41	434.14	249.36	665.74	548.72	434.82	249.13	
η _{el} [%]	54.48	52.71	50.77	44.48	54.71	52.83	50.85	44.44	
Δη w.r.t ref. plant	-7.70	-8.02	<i>-7.83</i>	-8.16	-7.47	-7.90	<i>-7.7</i> 5	-8.20	
SPECCA [MJ/kgCO ₂]	2.63	2.84	2.87	3.40	2.54	2.78	2.84	3.43	



X Pressure above 2.7 bar at every GT load

Minimum steam mass flow rate to LP turbine



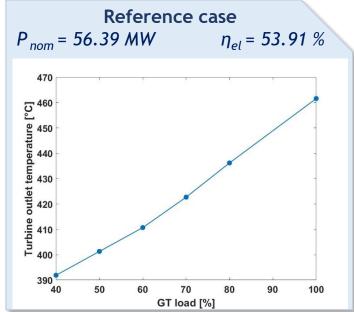
Large-scale power plant results - Comparison

Pressure at LP crossover Net electric efficiency Net power output 800 Reference case 5.5 Retrofit with valve case - Retrofit with compressor case Pressure at crossover [bar] Greenfield case **MM** 600 Net plant efficiency [%] output 000 Greenfield case Retrofit with valve case power 400 Reference case Net Retrofit with compressor case Retrofit with valve case 300 Reference case Greenfield case 1.5 200 30 70 80 100 30 30 70 50 90 50 80 90 100 50 60 80 90 100 GT load [%] GT load [%] GT load [%]

- All the large-scale designed NGCCs with PCC display good flexibility and very similar efficiencie
- The Greenfield NGCC has lower efficiency than Retrofit plants due to suboptimal LP pressure
- Conducting same analysis starting from a lower pressure
- Replacing throttling valve with a single-stage steam turbine

15

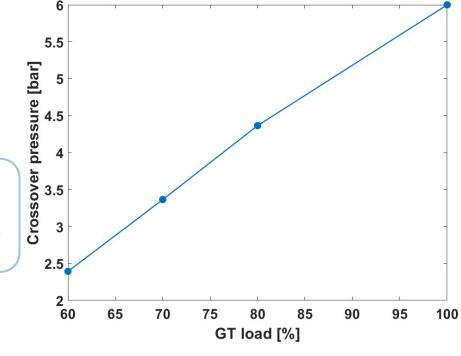
Small-scale power plant results - Greenfield case

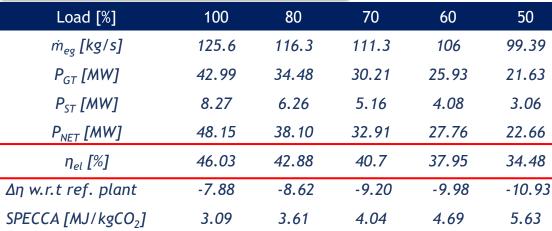


Greenfield power plant viable down to 70% following sliding pressure control

Design modifications to enhance the NGCC flexibility

**	Greenfield with
	readmission valve
	can operate down
	to 50%



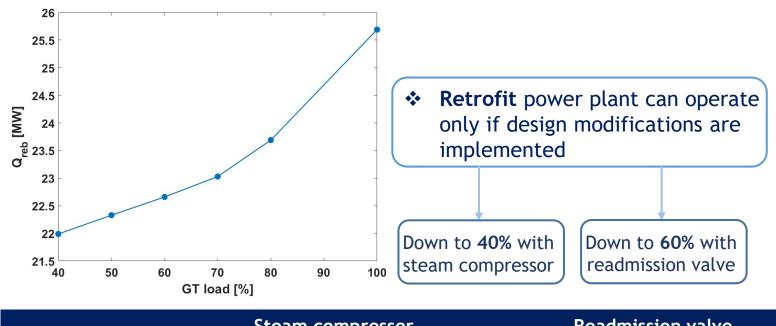


Pressure above 2.7 bar at every GT load

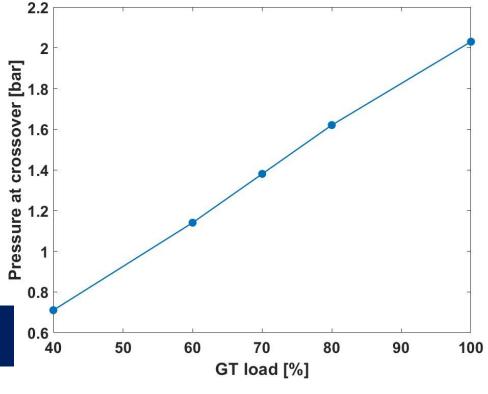
Minimum steam mass flow rate to LP turbine



Small-scale power plant results - Retrofit case



01 load [///]											
	Steam compressor							Readmission valve			
Load [%]	100	80	70	60	40	100	80	70	60		
P _{ST} [MW]	9.42	7.61	6.67	5.76	4.21	8.94	6.70	5.52	4.41		
P _{NET} [MW]	48.36	39.35	34.38	27.13	16.36	48.62	38.44	33.24	28.05		
η _{el} [%]	46.24	44.33	42.52	37.09	28.14	46.49	43.31	41.11	38.34		
Δη w.r.t ref. plant	-7.67	-7.17	-7.38	-10.84	-14.17	-7.42	-8.19	-8. <i>7</i> 9	-9.59		
SPECCA [MJ/kgCO ₂]	3.00	2.90	3.10	5.21	8.93	2.88	3.39	3.82	4.46		



X Pressure above 2.7 bar at every GT load

X Minimum steam mass flow rate to LP turbine

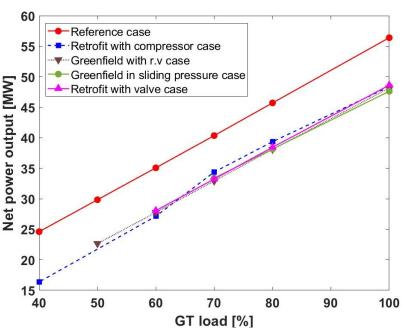


Small-scale power plant results - Comparison

Pressure at LP crossover Net electric efficiency 55 Reference case ■ Greenfield with r.v case Pressure at crossover [bar] 50 [MM] 45 45 40 <u>%</u> Retrofit with valve case Net plant efficiency

50

Net power output



- All the small-scale designed NGCCs with PCC display very similar efficiencies
- The steam compressor is the only solution that can operate until the minimum GT load → best flexibility

60

Greenfield in sliding pressure case

80

90

100

·─▼···· Greenfield with r.v case - Retrofit with compressor case

Retrofit with valve case Reference case

GT load [%]

60

GT load [%]

50

Reference case

80

90

100

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Conclusions and future perspectives

- Large-scale configurations have good flexibility and high efficiency down to 30% ($\sim 54\%$)
 - ❖ Sliding pressure control strategy does not ensure Retrofit plant operation without design modifications
- For a small-case NGCC with PCC the operational flexibility is more critical
 - Greenfield power plant following a sliding pressure part-load control strategy can operate down to 70%
 - Retrofit power plant face insufficient pressure

Readmission valve
 installation extends
 operation down to 60%

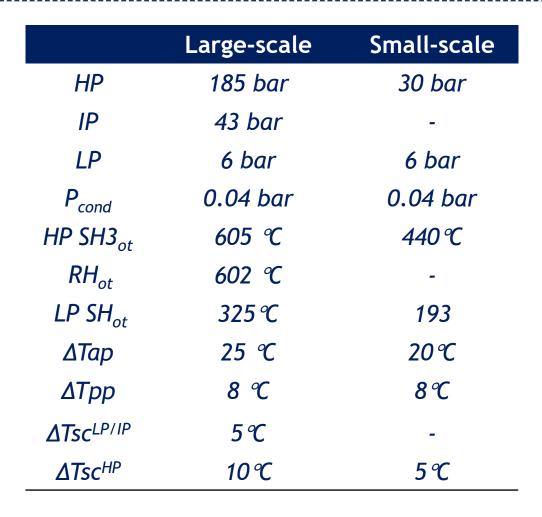
2. Only steam compressor installation allows to operate at minimum load

Economic Analysis



Thank you for your attention!

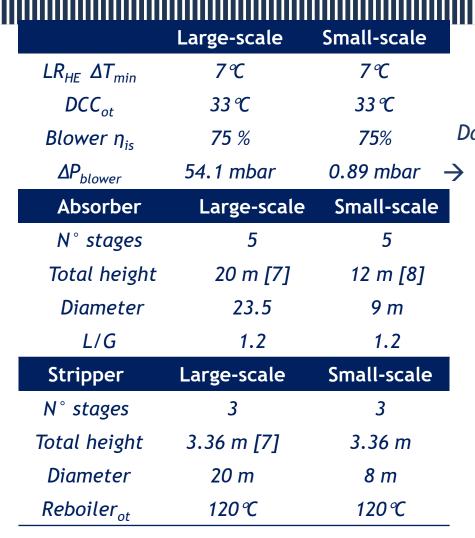
Modelling assumptions - Power block

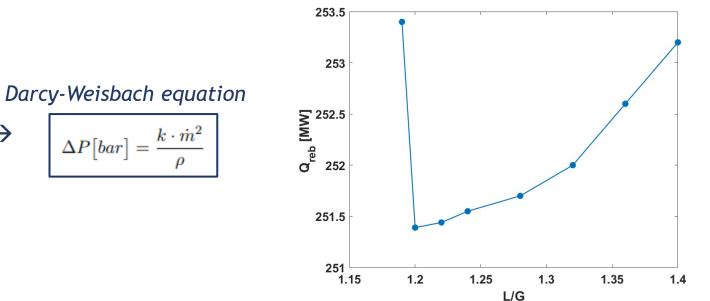


Fuel composition

CH_4	89%
C_2H_6	7 %
C_3H_8	1%
C_4H_{10}	0.1%
C_5H_{12}	0.01%
CO_2	2%
N_2	0.89%

Modelling assumption - Carbon capture and storage section





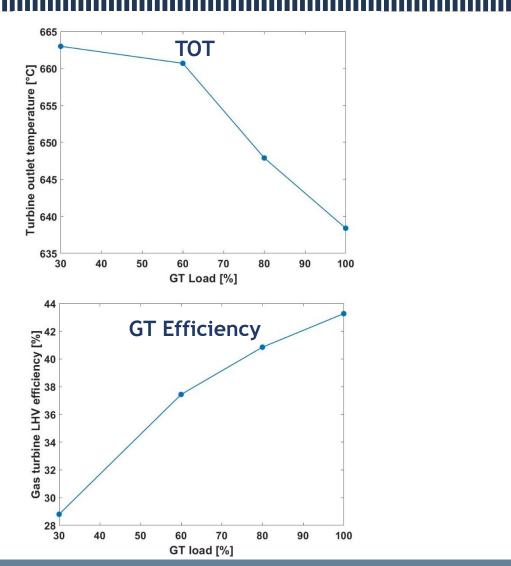
Compressors	Large-scale	Small-scale
N°	4	4
η_y	85 %	<i>85</i> %
P_{CO2}	110 bar	110 bar
$Condensate_{ot}$	40℃	40℃

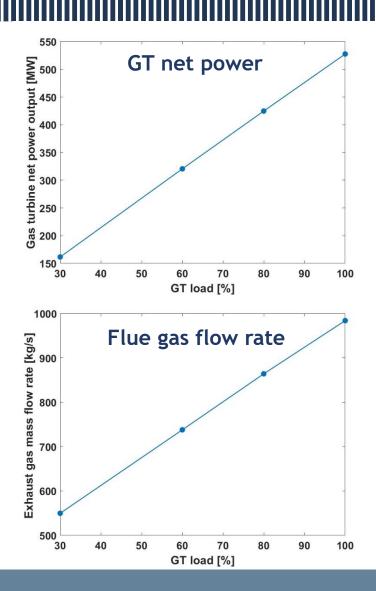
^[7] A. Zelaschi, "Development, modelling and optimization of reheated gas turbines and combined cycles for post-combustion CO2 capture and storage", 2022.

^[8] Gjernes, S. et al., "Documenting modes of operation with cost saving potential at the technology centre mongstad," in 14th Greenhouse Gas Control Technologies Conference Melbourne, 2018



GE 9HA.02 performance plots (valid for all the cases)







Large scale plant

Carbon capture section consumption

• $7 \text{ MW} \rightarrow 3.9 \text{ MW}$ (5.9 MW due to the reboiler)

Compressors train

• $20.7 \text{ MW} \rightarrow 9.6 \text{ MW}$

Specific heat of the reboiler [MJ/kgCO₂]

• $3.79 \text{ MJ/kgCO}_2 \rightarrow 3.71 \text{ MJ/kgCO}_2$

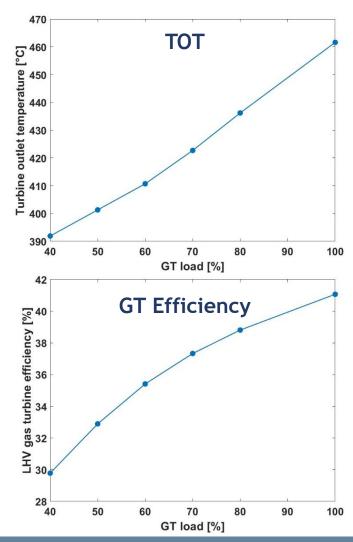
GT load [%]	100	80	60	30
TOT [°C]	638.40	647.90	660.70	663.00
$\dot{m}_{eg} \; [{ m kg/s}]$	984.00	864.10	737.90	549.80
GT net power [MW]	527.48	424.65	320.42	161.52
ST net power [MW]	173.28	157.91	141.48	109.96
Plant net power [MW]	657.00	544.69	432.37	249.32
Net total electric efficiency [%]	53.99	52.48	50.70	44.50
$\Delta \eta$ w.r.t. reference plant [%]	-8.19	-8.25	-7.90	-8.14
CO_2 emissions $[kgCO_2/MWh_{el}]$	18.94	19.59	20.27	21.53
SPECCA $[MJ/kgCO_2]$	2.82	2.93	2.90	3.40
LP steam pressure [bar]	6.00	5.94	5.76	4.98

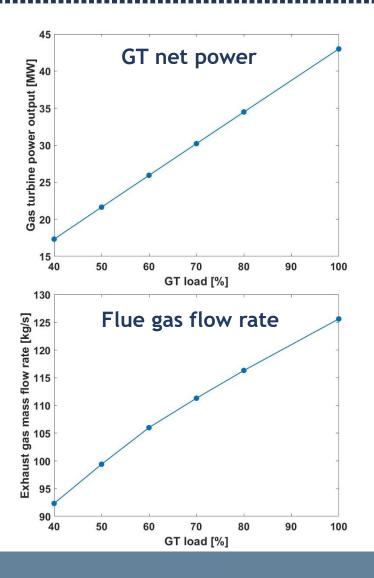
Table 5: Greenfield configuration main results

	Compressor				Readmission valve			
GT load [%]	100	80	60	30	100	80	60	30
ST net power [MW]	187.39	171.39	153.17	117.13	183.45	166.22	147.44	110.99
Plant net power [MW]	662.96	547.41	434.14	249.36	665.74	548.72	434.82	249.13
Net total electric efficiency [%]	54.48	52.71	50.77	44.48	54.71	52.83	50.85	44.44
$\Delta \eta$ w.r.t. reference plant [%]	-7.70	-8.02	-7.83	-8.16	-7.47	-7.90	-7.75	-8.20
CO_2 emissions $[kgCO_2/MWh_{el}]$	18.77	19.50	20.19	21.53	18.69	19.45	20.15	21.55
$\mathrm{SPECCA} \; [\mathrm{MJ/kg}CO_2]$	2.63	2.84	2.87	3.40	2.54	2.78	2.84	3.43
LP steam pressure [bar]	2.20	2.15	2.08	1.84	2.7	2.7	2.7	2.7

Table 6: Retrofit configuration main results

LM6000 performance plots (valid for all the cases)







LM6000 results

Carbon capture section consumption

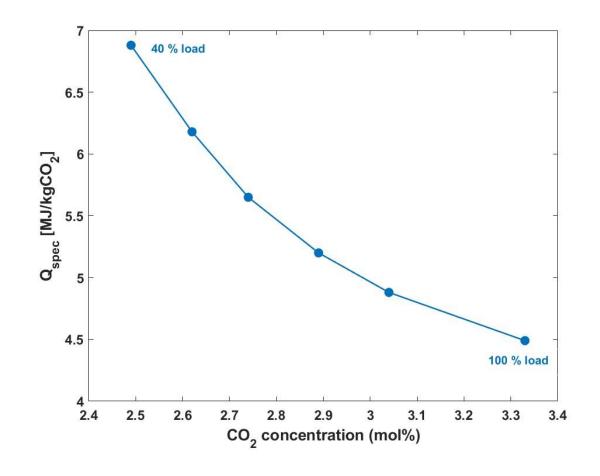
• $0.16 \text{ MW} \rightarrow 3.9 \text{ MW}$

Compressors train

• 2 MW → 1 MW

GT load [%]	100	80	70	60	50	40
O_2	15.25	15.75	16.01	16.27	16.47	16.69
CO_2	3.33	3.04	2.89	2.74	2.62	2.49
N_2	80.45	80.25	80.14	80.03	79.94	79.85
Ar	0.97	0.97	0.97	0.96	0.96	0.96

Table 7: Reference power plant dry flue gas composition (mol.%)



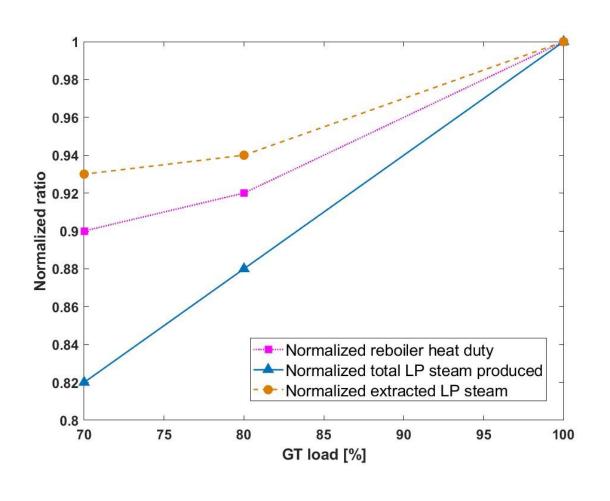
LM6000 results - Greenfield case

GT load [%]	100	80	70
TOT [°C]	461.6	436.2	422.7
$\dot{m}_{eg} \; [{ m kg/s}]$	125.60	116.3	111.3
GT net power [MW]	42.99	34.48	30.21
ST net power [MW]	7.77	6.37	5.68
Plant net power [MW]	47.62	38.14	33.40
Net total electric efficiency [%]	45.53	42.97	41.31
$\Delta \eta$ w.r.t. reference plant [%]	-8.38	-8.53	-8.59
CO_2 emissions $[kgCO_2/MWh_{el}]$	10.84	8.54	7.10
SPECCA $[MJ/kgCO_2]$	3.33	3.56	3.72
LP steam pressure [bar]	6	4.37	3.36

Table 8: Greenfield in sliding pressure configuration main results

GT load [%]	100	80	70	60	50
TOT [°C]	461.6	436.2	422.7	410.7	401.3
$\dot{m}_{eg} \; [{ m kg/s}]$	125.60	116.3	111.3	106	99.39
GT net power [MW]	42.99	34.48	30.21	25.93	21.63
ST net power [MW]	8.27	6.26	5.16	4.08	3.06
Plant net power [MW]	48.15	38.10	32.91	27.76	22.66
Net total electric efficiency [%]	46.03	42.88	40.7	37.95	34.48
$\Delta \eta$ w.r.t. reference plant [%]	-7.88	-8.62	-9.20	-9.98	-10.93
CO_2 emissions $[kgCO_2/MWh_{el}]$	10.72	8.56	7.17	6.14	5.18
SPECCA $[MJ/kgCO_2]$	3.09	3.61	4.04	4.69	5.63

Table 9: Greenfield with readmission valve configuration main results



LM6000 results - Retrofit case

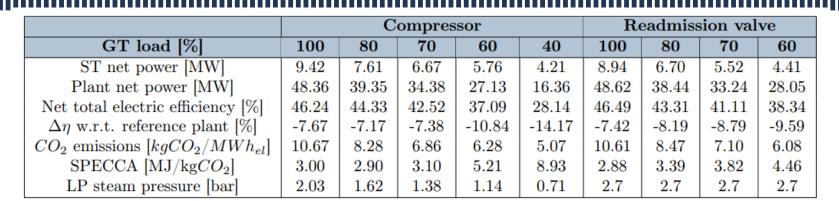
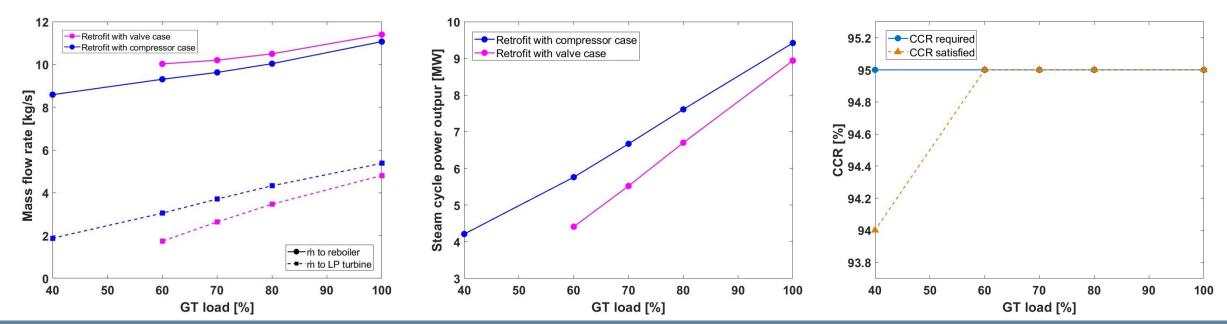
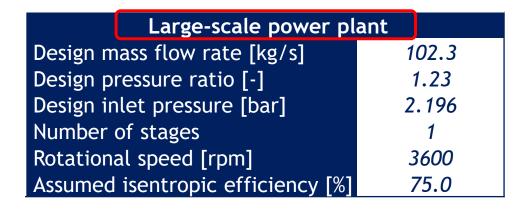


Table 10: Retrofit configuration main results



Steam compressor preliminary sizing



Small-scale power p	lant
Design mass flow rate [kg/s]	11.07
Design pressure ratio [-]	1.33
Design inlet pressure [bar]	2.03
Number of stages	1
Rotational speed [rpm]	6000
Assumed isentropic efficiency [%]	<i>7</i> 5.0

