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NextGen Geothermal Power

NGP makes CO_2 work!

Geothermiekongress München, 20.11.2019
Robin Sudhoff, Siemens AG

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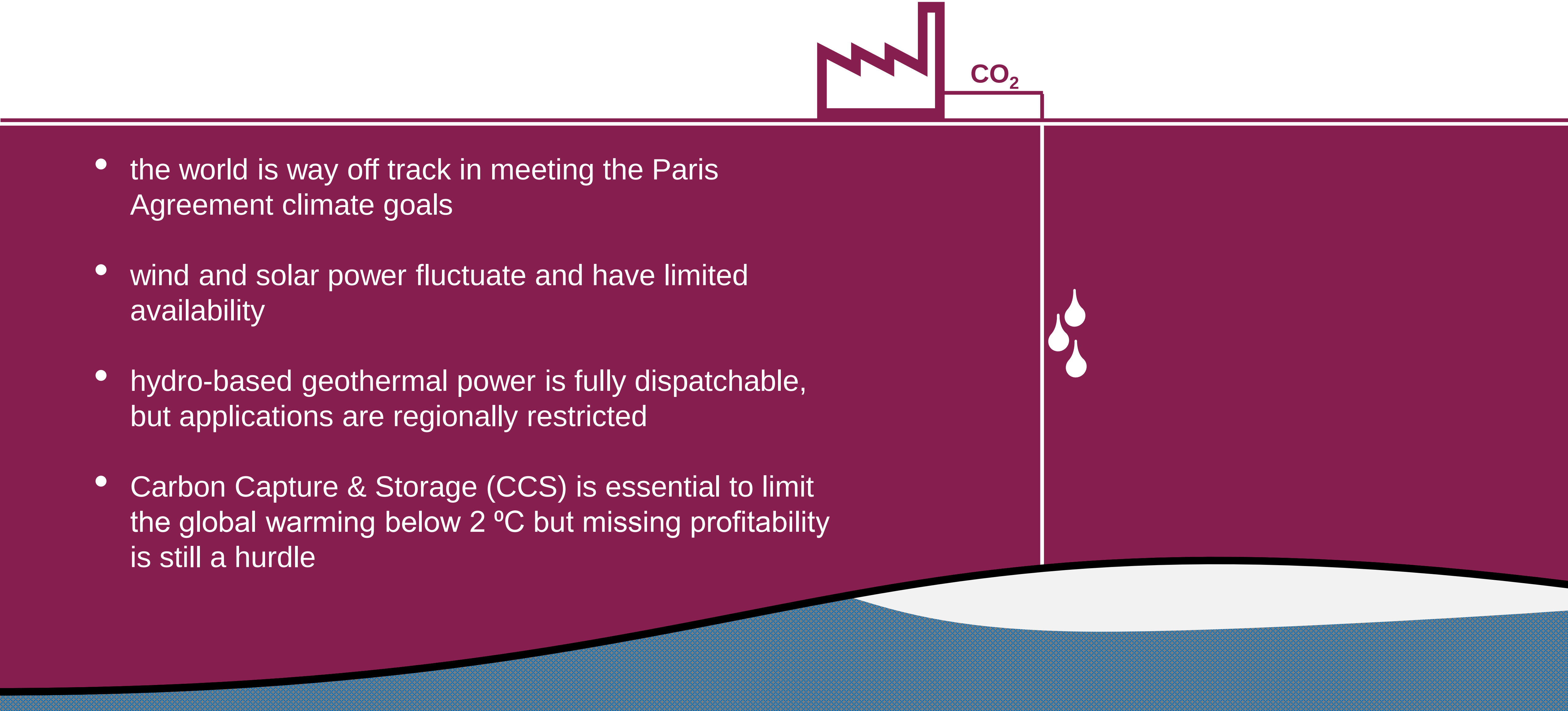
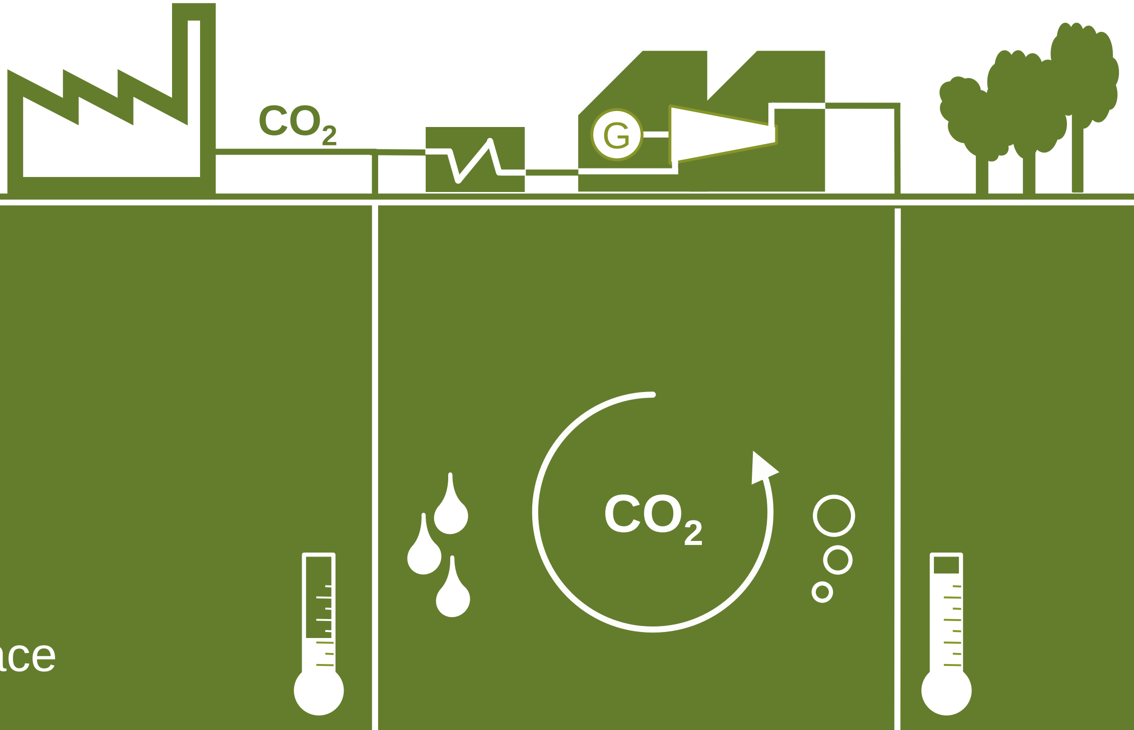
How to push renewables and carbon capture & storage to meet climate goals?



- the world is way off track in meeting the Paris Agreement climate goals
- wind and solar power fluctuate and have limited availability
- hydro-based geothermal power is fully dispatchable, but applications are regionally restricted
- Carbon Capture & Storage (CCS) is essential to limit the global warming below 2 ºC but missing profitability is still a hurdle

Combination of geothermal energy with carbon capture & storage

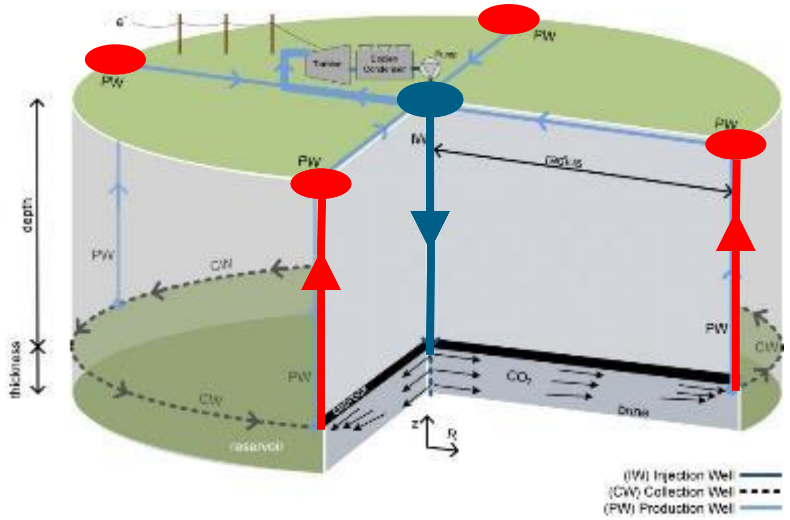


- NGP combines sCO_2-based geothermal energy with CCS and transforms CCS to CCUS
- CO_2 is injected in sedimentary basins that host high-permeability reservoirs overlain by cap rocks
- heated by geothermal energy, CO2 flows to the surface and expands in a turbine to generate electricity
- NGP creates valuable power that makes CCS comfortable

Assessment of NGP Systems

Geologic conditions – Base Case

Coordination number	1 (5-spot-system)
Depth	2500 m
Well diameter	0,41 m
Permeability-thickness product (κh)	15.000 mD·m
Temp. gradient	35 K/km



Saar, Adams; Subsurface Energy Storage with CO_2; 2018

Power Cycle Variants

<table>
<tr><th colspan="2">direct | sCO₂</th><th colspan="2">indirect | Brine - Isobutane</th></tr>
<tr><td>Thermosiphon only</td><td>with supplemental pumping</td><td>single pressure</td><td>dual pressure</td></tr>
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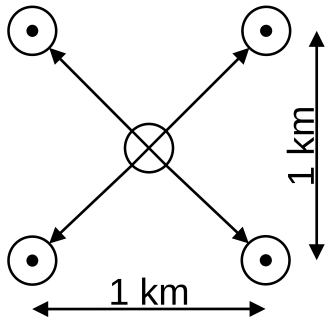
Base Case well pattern

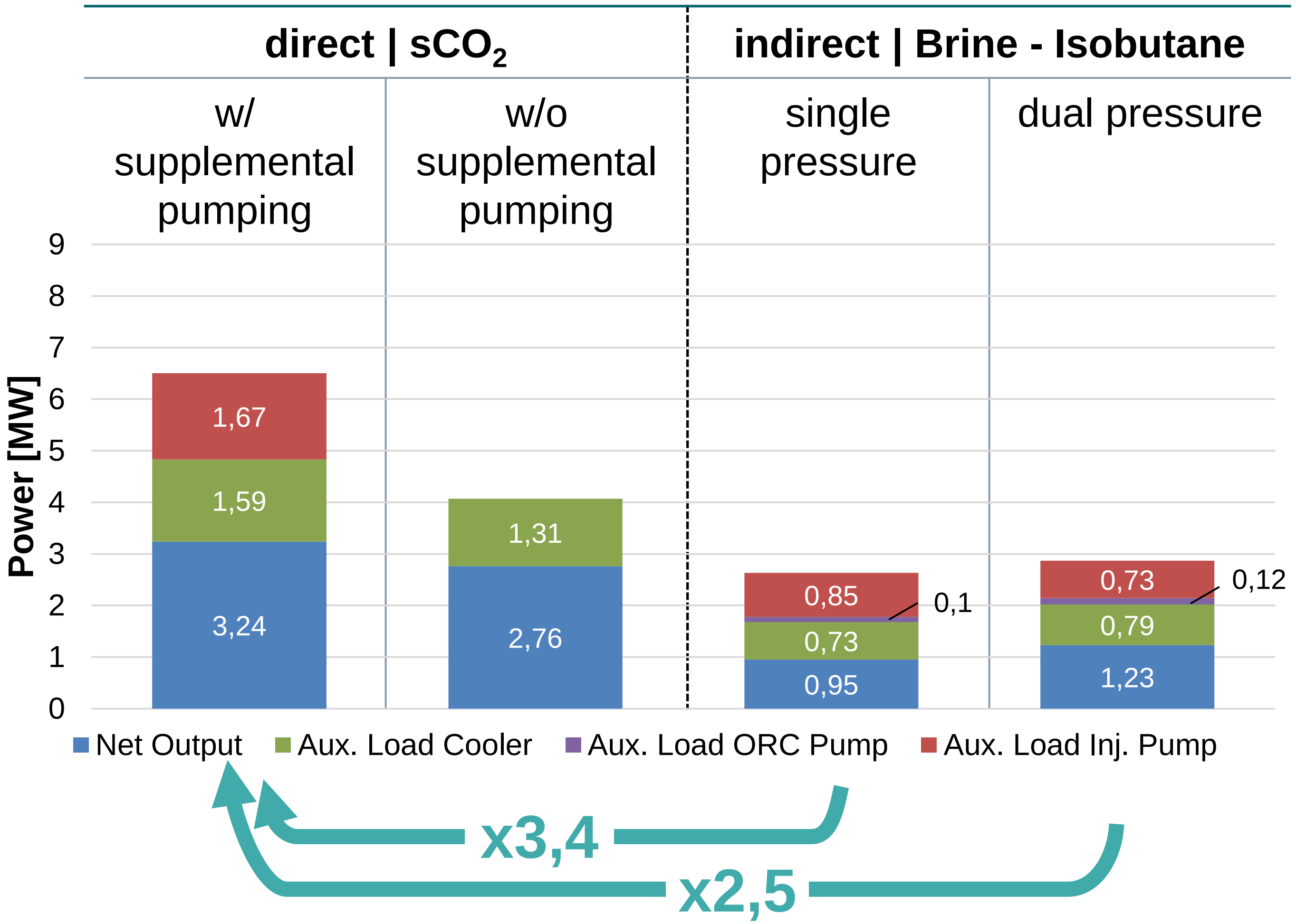
⊙ production well

⊗ injection well



Calculation results for NGP base case

Power Cycle Variants



Reservoir conditions:
base case

Depth	2500 m
Temp. gradient	35 K/km
Permeability-thickness product* (κh)	15.000 mD·m
injection-/ production well diameter	0,41 m

Assumptions:

$T_{ambient}$	15°C
ΔT-Pinch Condenser	7 K
ΔT-Pinch HX	5 K

2,5-3,4 times higher net output
compared to brine based systems at base case

Calculation results for NGP base case optimized heat rejection

Update: optimized cycle *presented in Poster session (P23)*

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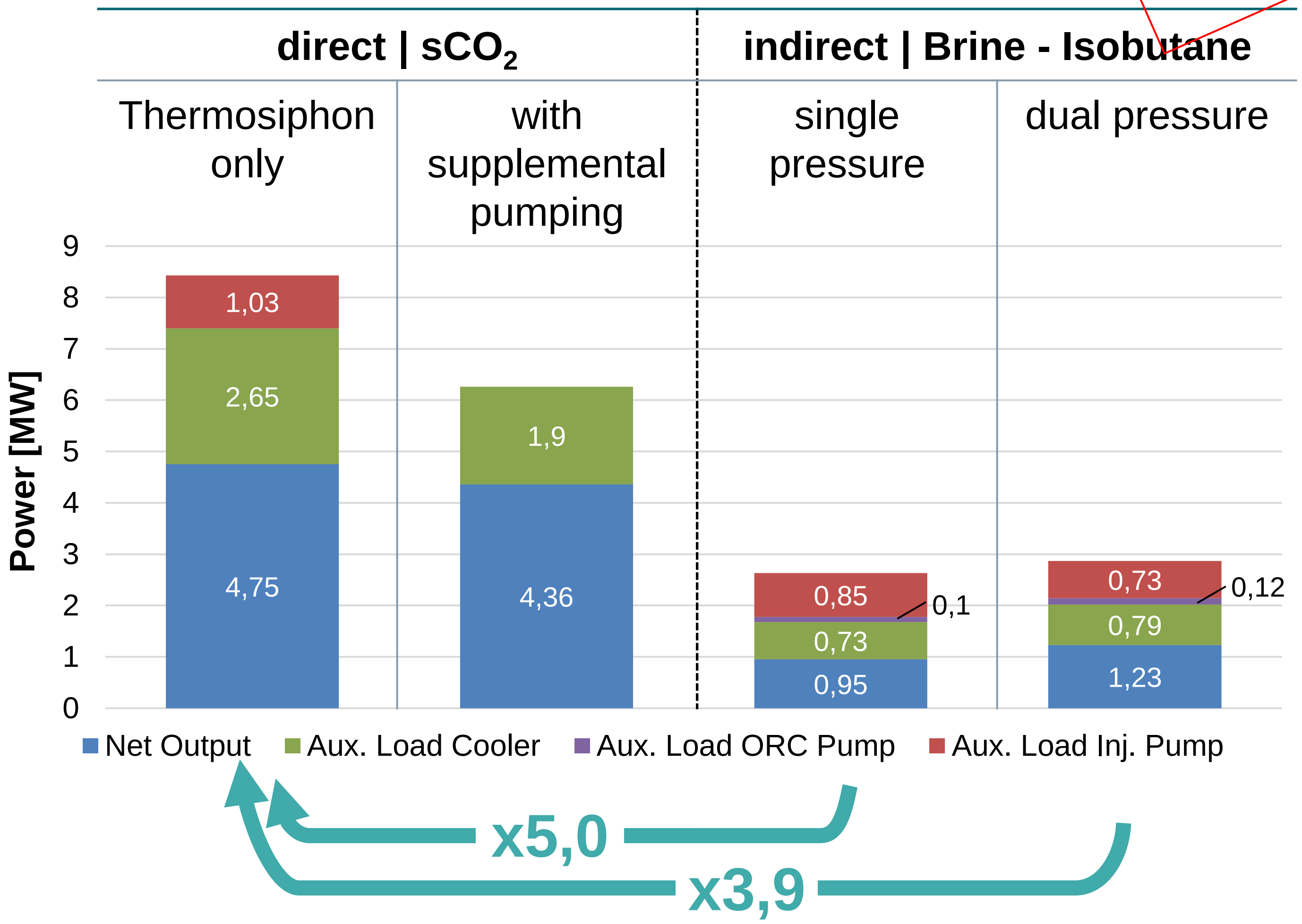
Power Cycle Variants



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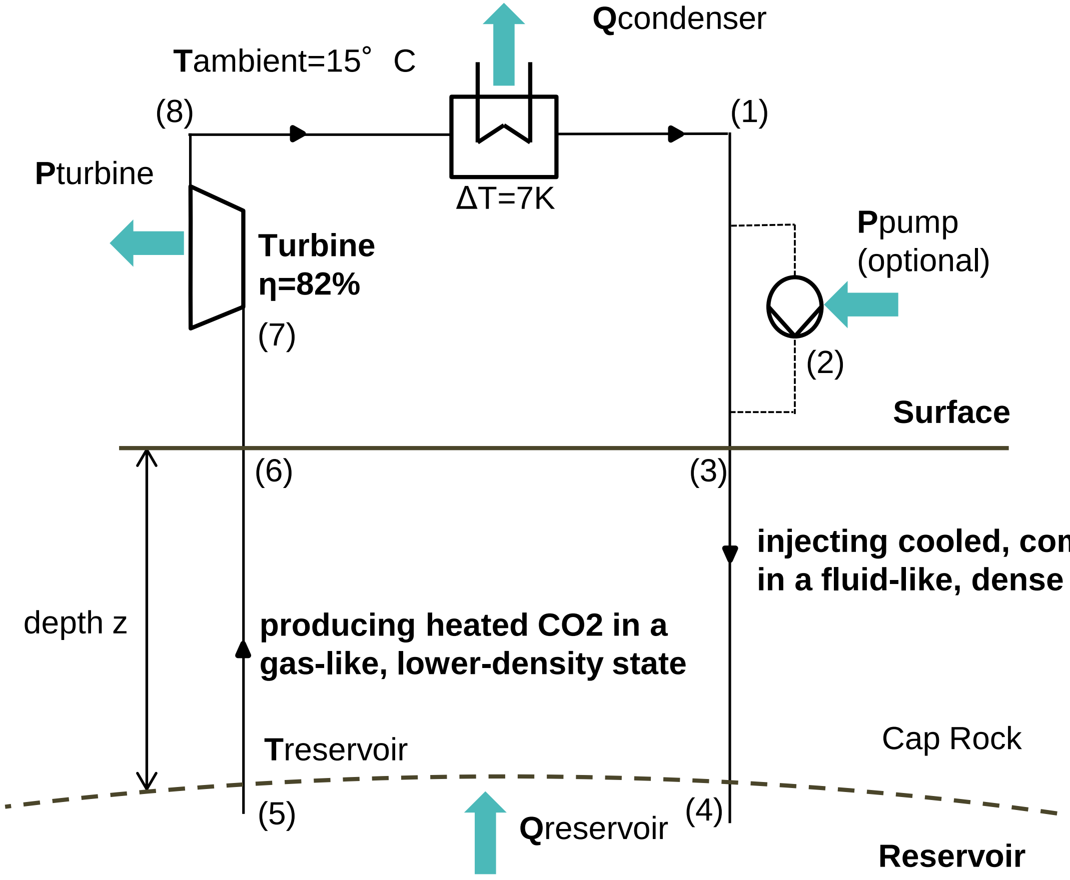
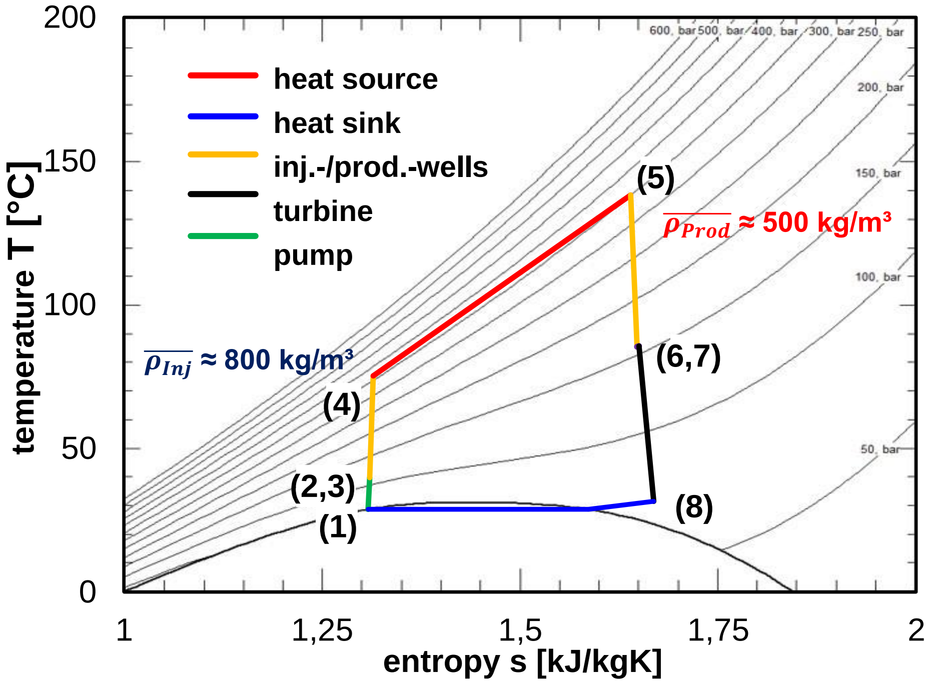
ΔT-Pinch Condenser	7 K
ΔT-Pinch HX	5 K

3,9-5,0 times higher net output
compared to brine based systems at base case

Advantages of CO2 as a geothermal working medium thermosyphon effect



$$\Delta p_{reservoir} = \frac{\mu \cdot L}{\rho \cdot A} \cdot \frac{\dot{m}}{\kappa} = M \cdot \dot{m}$$ (Darcy‘s law)

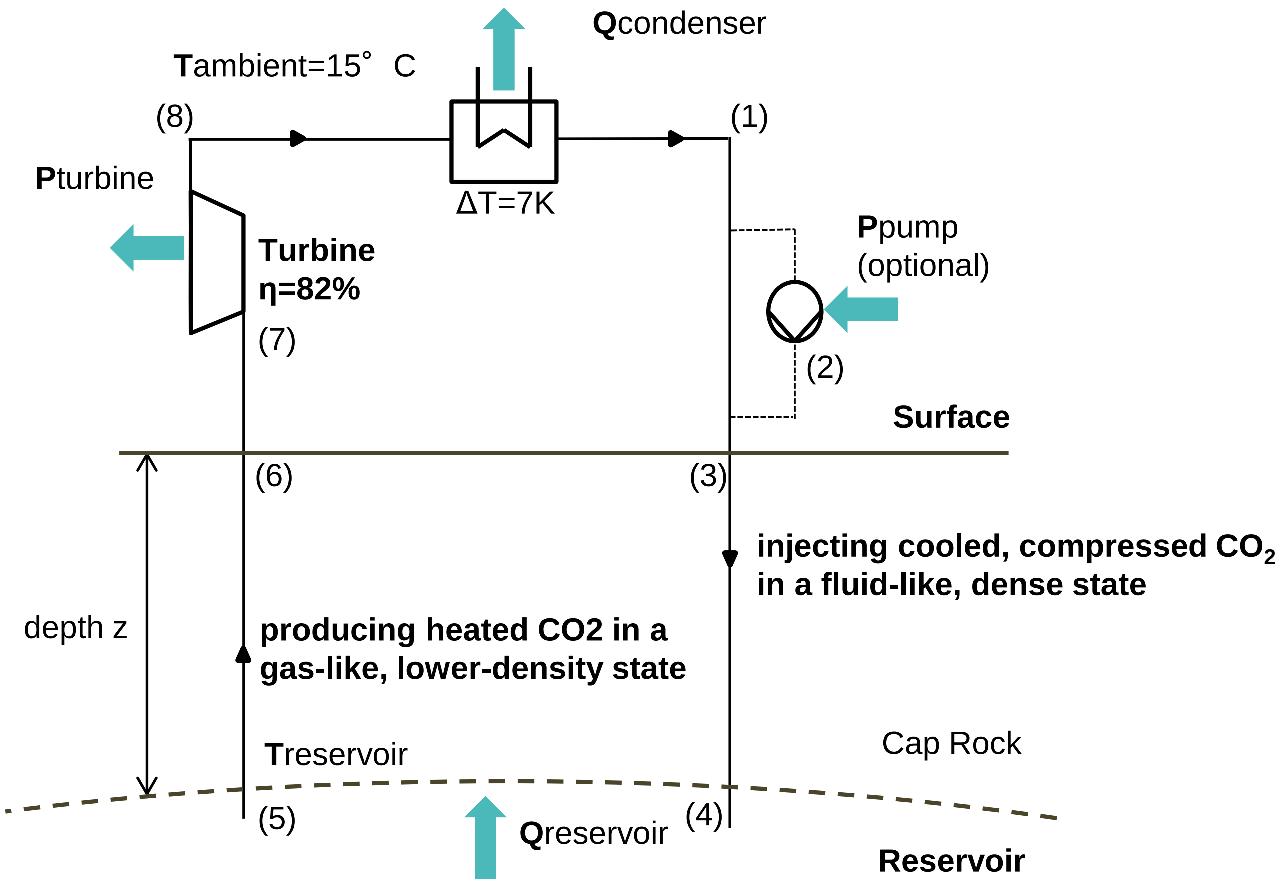


- due to the geothermal heat supply, a density difference between injection and production arises
- the pressure gradient along the wells is different in size and leads to a difference between the well heads

$$\Delta p_{TS} = \left(\bar{\rho}_{Inj} - \bar{\rho}_{Prod}\right) \cdot g \cdot \Delta z$$

- driven by the thermosyphon, pumping work is reduced

Advantages of the working medium CO2 reservoir mobility



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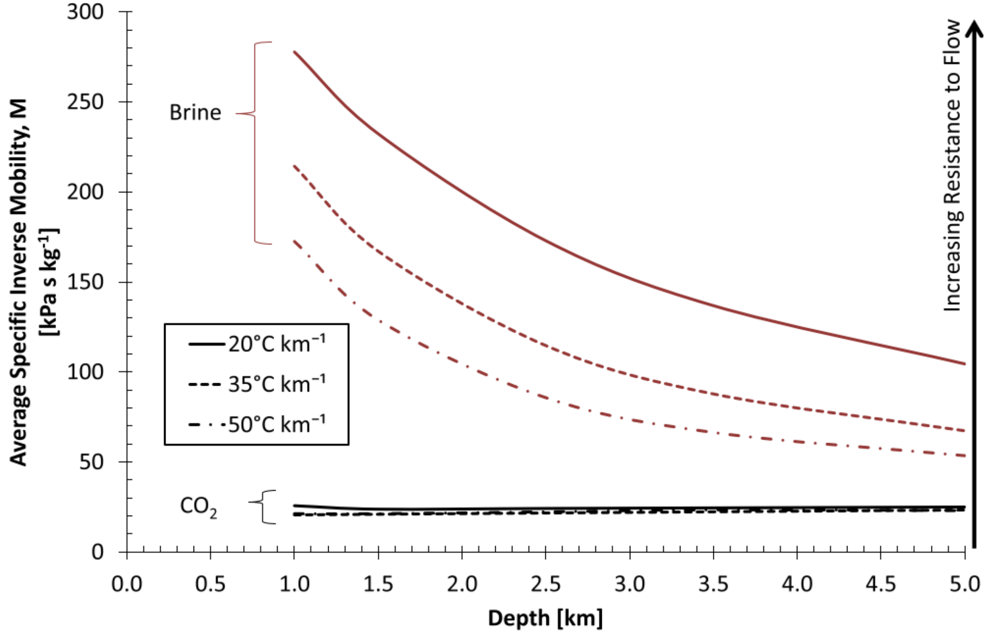
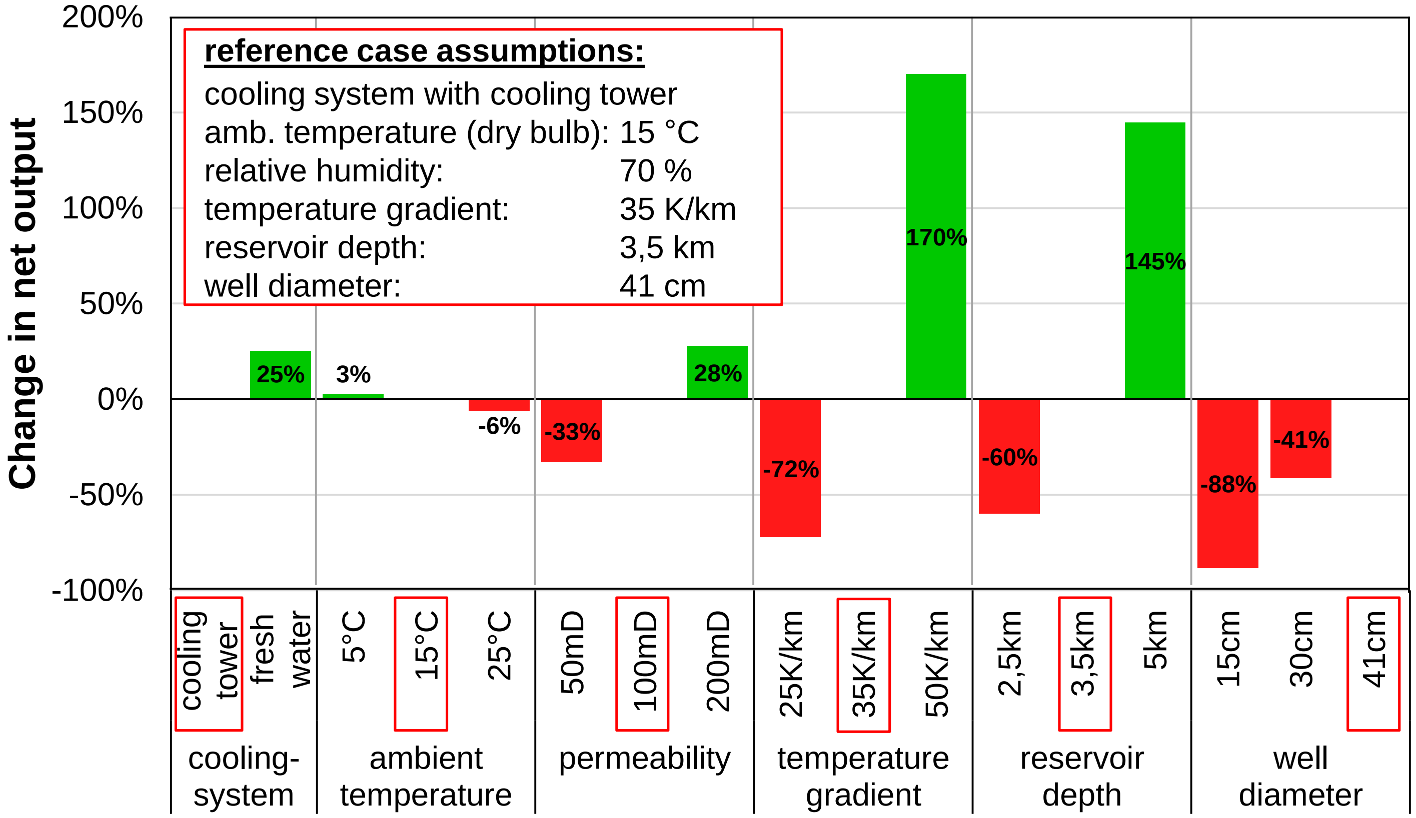


- reservoir flow resistance, expressed by M, decreases with depth for brine but is higher than that of CO2
- as a result mass flow and heat extraction rates achieved by CO2 exceed those for brine

Adams et al.: On the importance of the thermosiphon effect in CPG power systems

Effects of geologic and ambient boundary conditions on net output



- For fresh water cooling, net power output increases due to a lower temperature of heat rejection and the elimination of auxiliary power for a mechanical draft cooling tower.
- The increase at lower ambient temperature is smaller, as the reservoir temperature also lowers.
- Regarding geological conditions, power rises with high permeability, temperature gradient and depth
- Large wells reduce pressure losses, the diameter must be determined depending on the permeability

scaled geothermal cycle – wellfield pattern

Configuration Number N:
equals the number of five-spot pattern on a side

N = 1
(five-spot pattern)

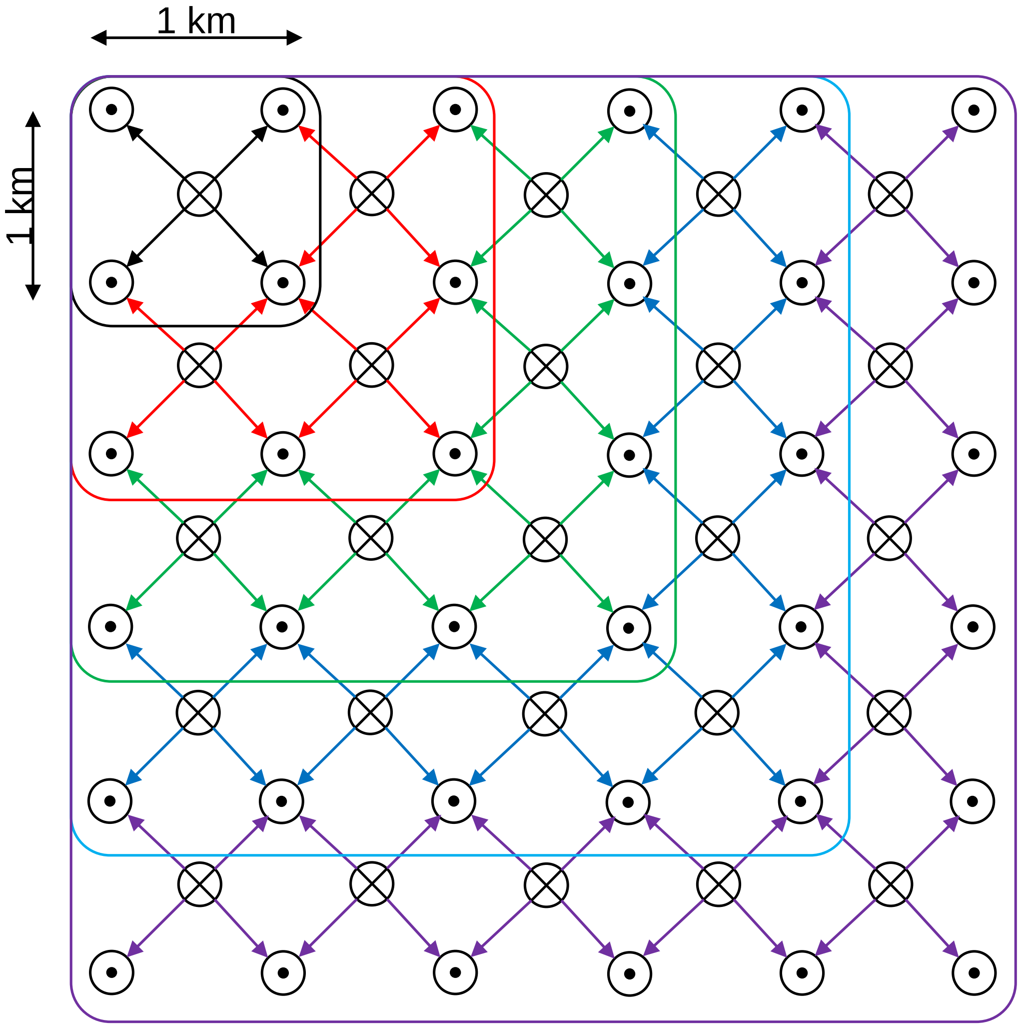
N = 2

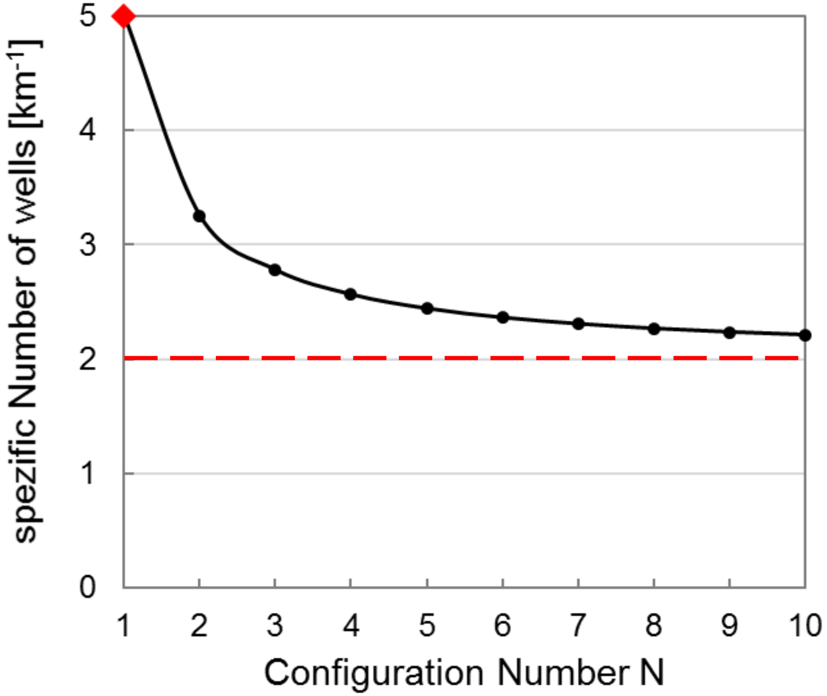
N = 3

N = 4

N = 5

⊙ production well
⊗ injection well





significant savings by scaling from N = 1 to N = 2

almost no further savings when scaling larger than N = 5

identifing suitable locations for geothermal power plants

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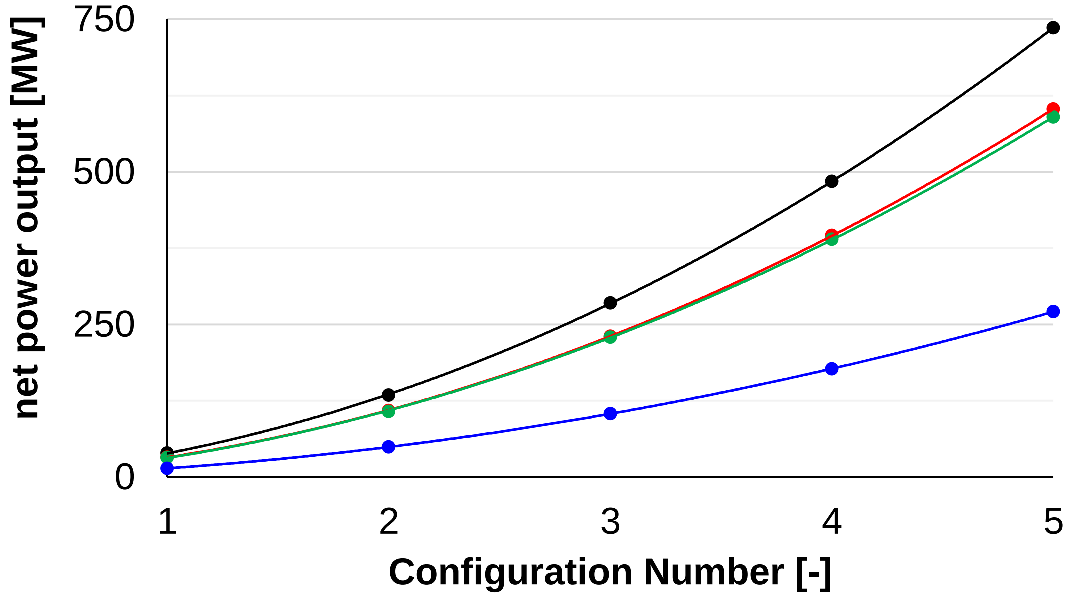
1 **political framework conditions**
Target region: North America (USA, Canada)
12 of 18 large-scale CCS projects in operation in this region

2 **reservoir analysis**
deep reservoirs, large temp. gradients, high permeability

3 **heat rejection conditions**

4 **coverage of CO2 demand**
Proximity to large, stationary CO2 emitters

5 **population and building density**



Reservoir 1	
depth:	5 km
temp.gradient:	35 K/km
permeability:	200 mD
thickness:	100 m
amb. temp.:	10 ºC
direct cooling	

Reservoir 2	
depth:	3,5 km
temp.gradient:	50 K/km
permeability:	100 mD
thickness:	100 m
amb. temp.:	10 ºC
cooling tower	

Reservoir 3	
depth:	5 km
temp.gradient:	35 K/km
permeability:	200 mD
thickness:	100 m
amb. temp.:	15 ºC
cooling tower	

Reservoir 4	
depth:	3,5 km
temp.gradient:	35 K/km
permeability:	100 mD
thickness:	200 m
amb. temp.:	5 ºC
cooling tower	

Turbine blade path design

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speed:
60Hz → 30Hz

optimized
geometry

1 first approach

Siemens intermediate-pressure turbine I50-V4-M2A-60Hz

→ unfavorable pressure-to-enthalpy drop ratio

2 half-speed turbine

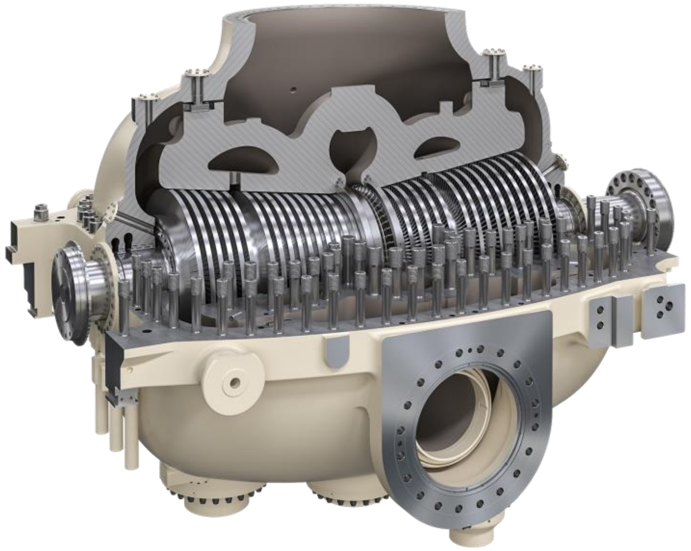
with same geometry

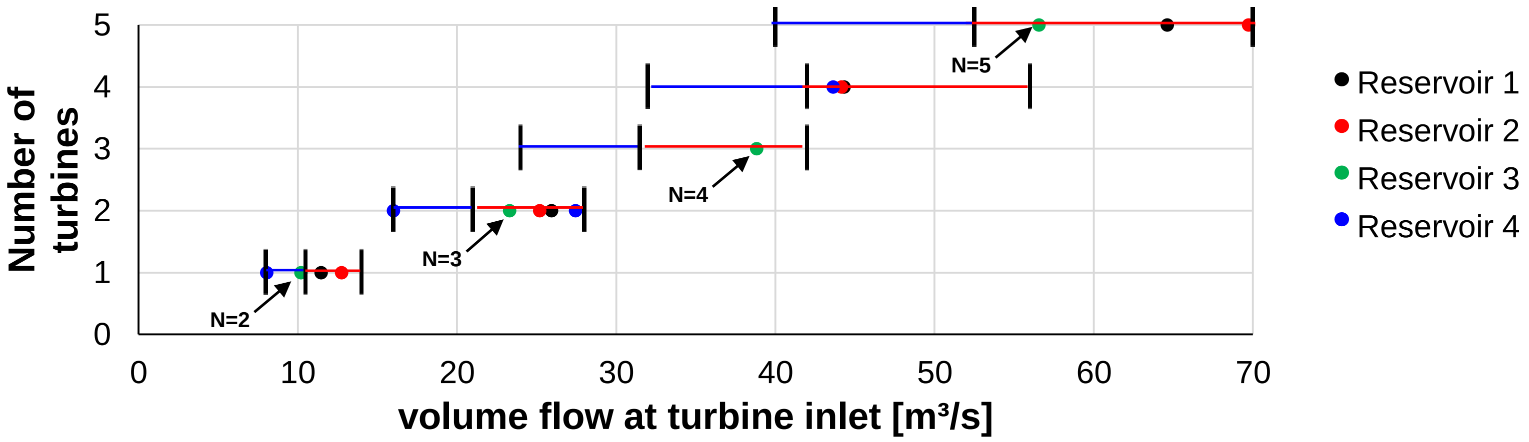
→ increased blading efficiency, lowered root stresses

3 CO2 turbine

geometry adjusted acc. to:
shaft-to-tip ratio
groove-to-shaft ratio

→ two compact designs with high efficiency and low root stresses





Assessment of Capital expenditure and LCOE

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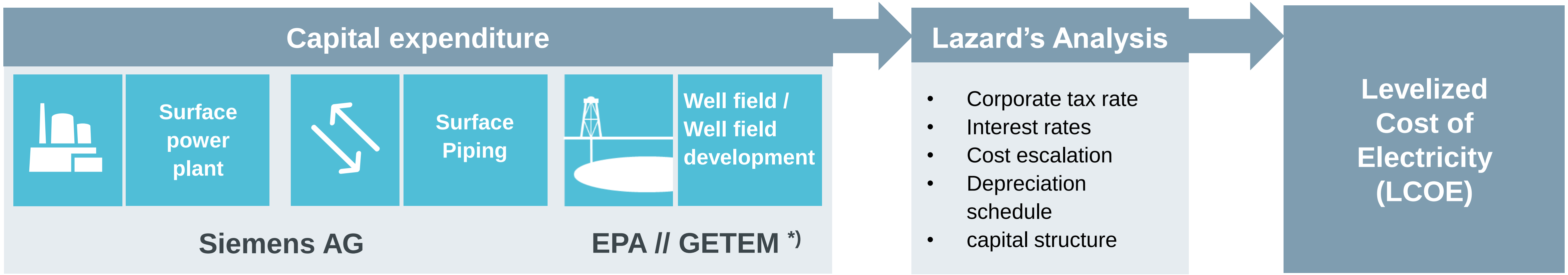


Capital expenditure

Surface power plant

Surface Piping

Well field / Well field development

Siemens AG

EPA // GETEM *)

Lazard's Analysis

- Corporate tax rate
- Interest rates
- Cost escalation
- Depreciation schedule
- capital structure

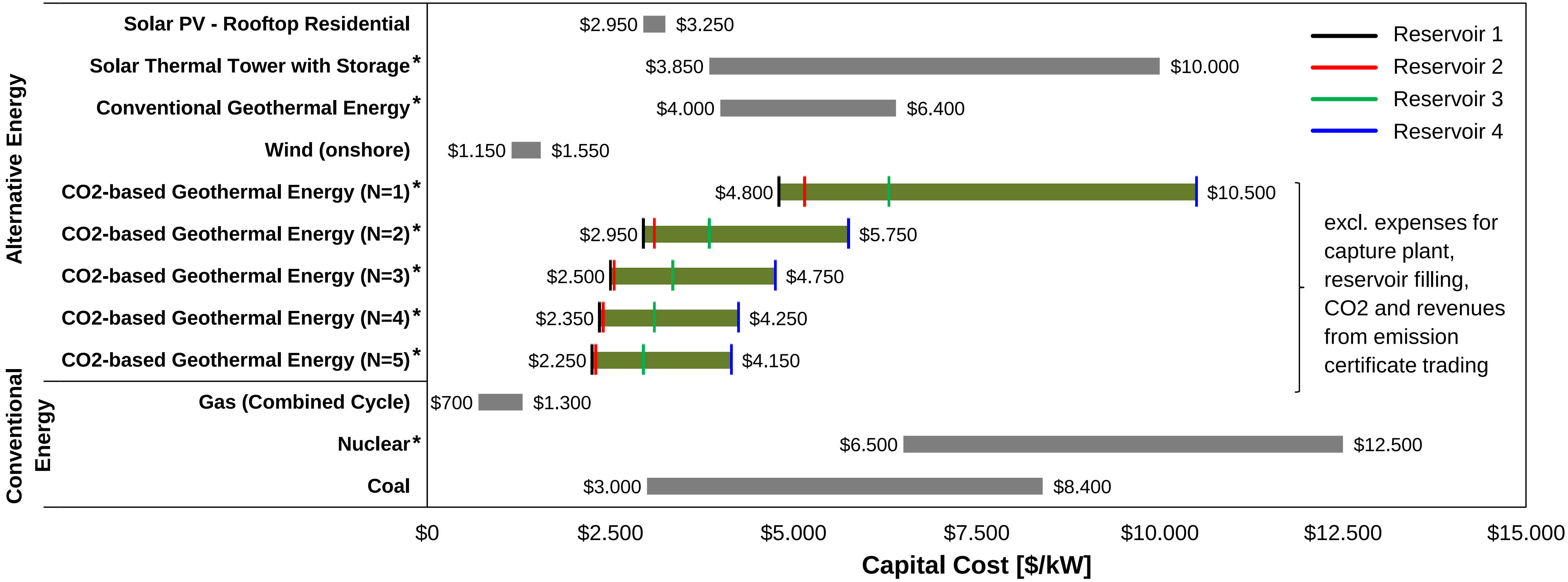
Levelized Cost of Electricity (LCOE)

Surface Power Plant	→ turbine train, gas cooler, pump, cooling tower, civil & small systems, electrics, engineering, project management, logistics, erection, commissioning
Surface Piping	→ pipelines between wells and surface power plant incl. raw material, fabrication, transportation, installation, engineering
Well field	→ wells incl. drilling, corrosion protection, engineering, project management
Well field development	→ development incl. (well) monitoring equipment, stimulation, engineering, project management

$$NPV = \sum_{t=1}^{n} \frac{\overbrace{\overbrace{LCOE \cdot M_{t,el}}^{\text{Revenue}} - \overbrace{(I_t + A_t)}^{\text{Cost}}}^{\text{Cash Flow}}}{\underbrace{(1+i)^t}_{\text{weighted average cost of capital}}} \overset{!}{=} 0$$

NPV: net present value, $M_{t,el}$: electricity produced in year t,
I_t: capital expenditures in year t, A_t: annual expenses in year t,
n: operation lifetime, i: interest rate

Capital Cost - Comparison of technologies, locations and scaling



excl. expenses for capture plant, reservoir filling, CO2 and revenues from emission certificate trading

- **strong dependence of capital costs on size and ambient conditions of the plant.**
- **absolute values are in the range of other baseload-capable and carbon-neutral plants (*).**

LCOE - Comparison of technologies, locations and scaling

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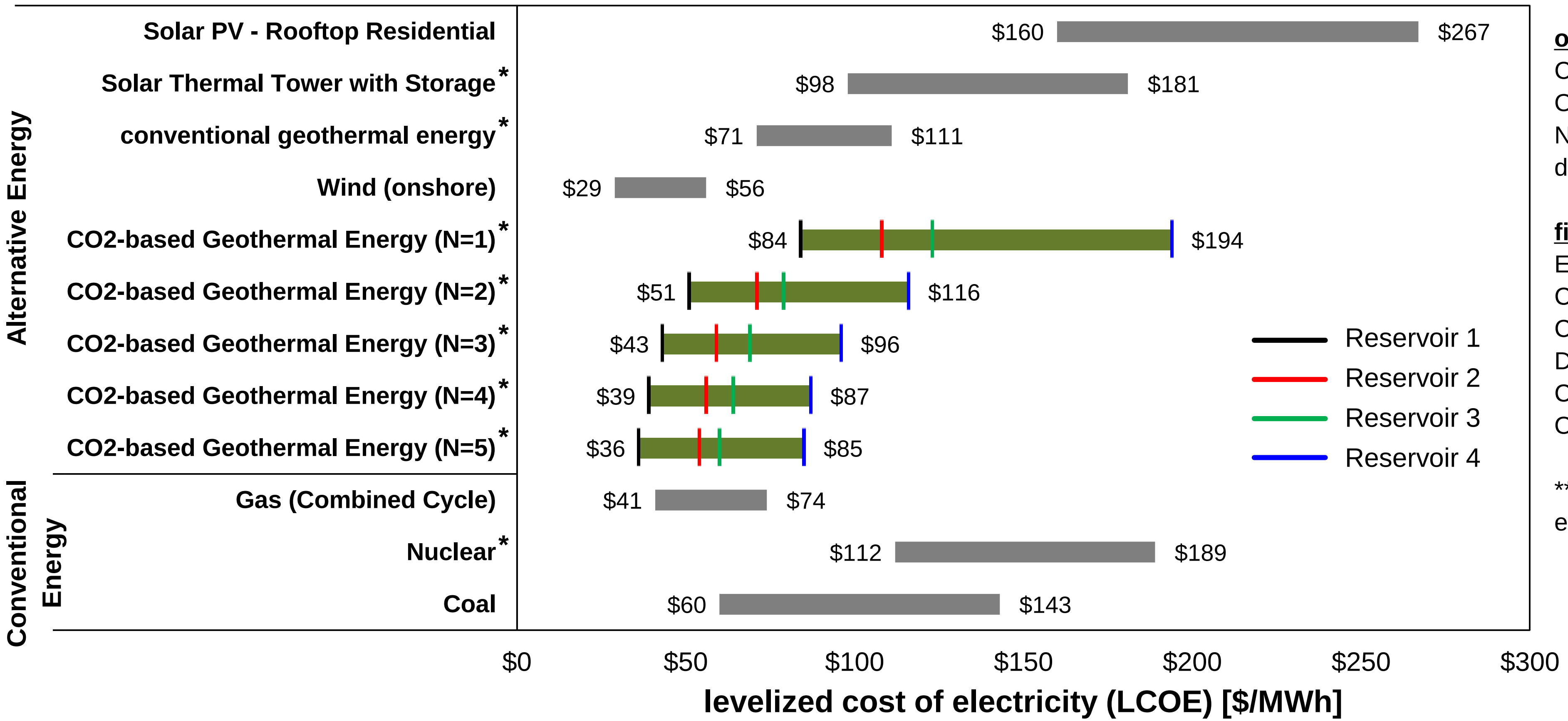

operating conditions: **)
Capacity factor: 90 %
Operation lifetime: 25 years
No significant thermal decline during lifetime

financial boundaries:
Equity – Debt: 40 % - 60 %
Cost of Equity: 12 %
Cost of Debt: 8 %
Debt Payback Period: 25 years
Combined Tax Rate: 40 %
O&M escalation rate: 2,25 %/year

**): for sCO2-based geothermal energy

- wide spread of LCOE shows the importance of a well targeted selection of the location
- results show the competitiveness of CO2-based geothermal energy, especially when scaled

Conclusion and Outlook

- verification of performance benefits of direct CO2 systems
- increased power output of NGP plants by optimized heat rejection and scaling of the well pattern
- significant reduction of LCOE
- need for a well-targeted selection of plant site due to strongly fluctuating site-specific power output
- competitive with other fully dispatchable and emission-free power plants

→ proof of concept / realization of NGP demonstrator

→ verification of the overall business case

→ realization of commercial projects

Thank you for your attention.

Additional information on NGP:
poster session (P23)
2nd congress day | lunch break