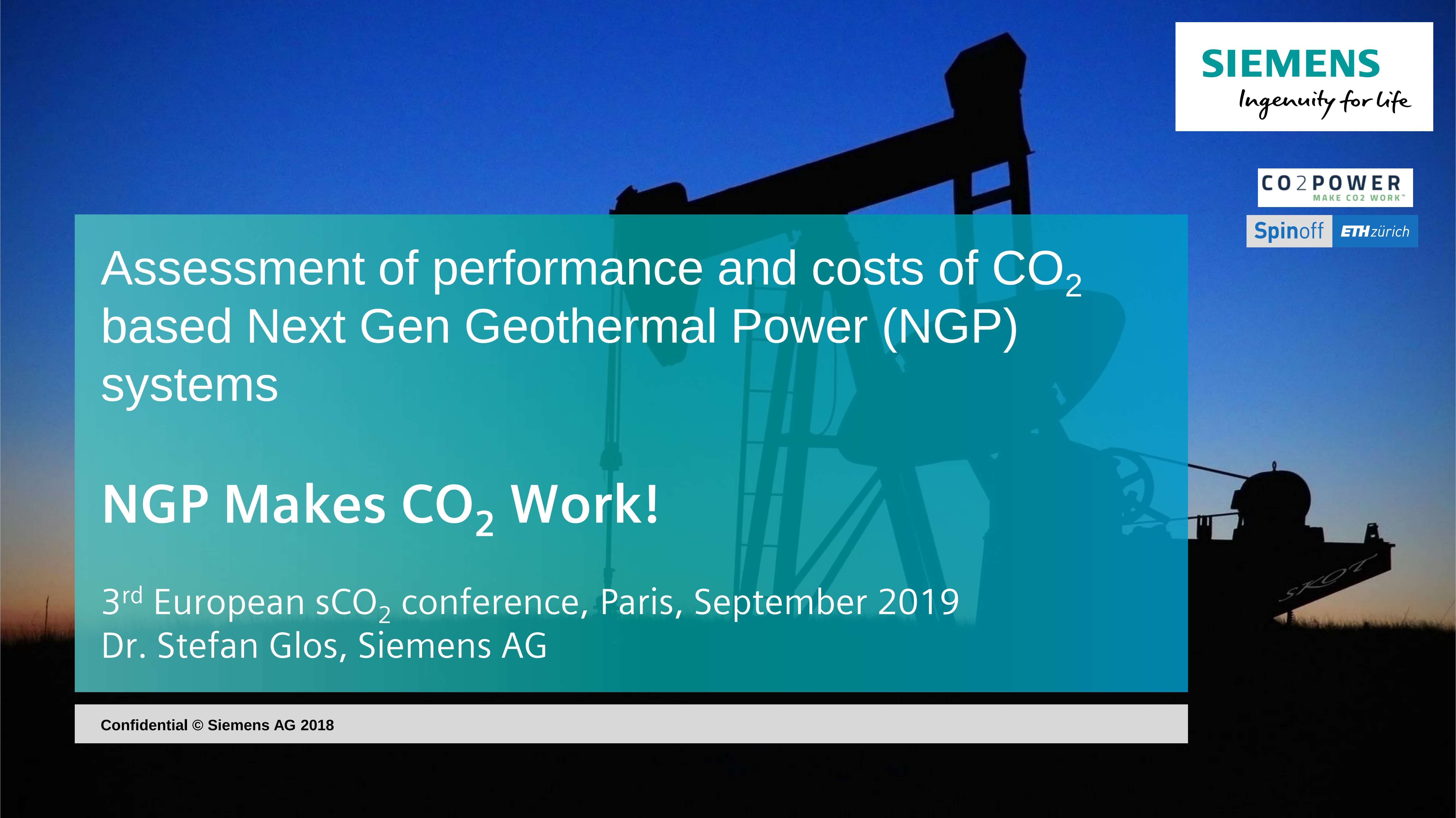

Assessment of performance and costs of CO_2 based Next Gen Geothermal Power (NGP) systems

NGP Makes CO_2 Work!

3rd European sCO_2 conference, Paris, September 2019
Dr. Stefan Glos, Siemens AG

Assessment of performance and costs of CO_2 based Next Gen Geothermal Power (NGP) systems

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Agenda

1. CO_2-based geothermal power generation

   Application range, basic concept, technology description, potential benefits

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   Cycle design, performance results, sensitivities, first component estimations

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   Key approach, calculation results, cost optimization potentials

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Application space of sCO_2 power cycles

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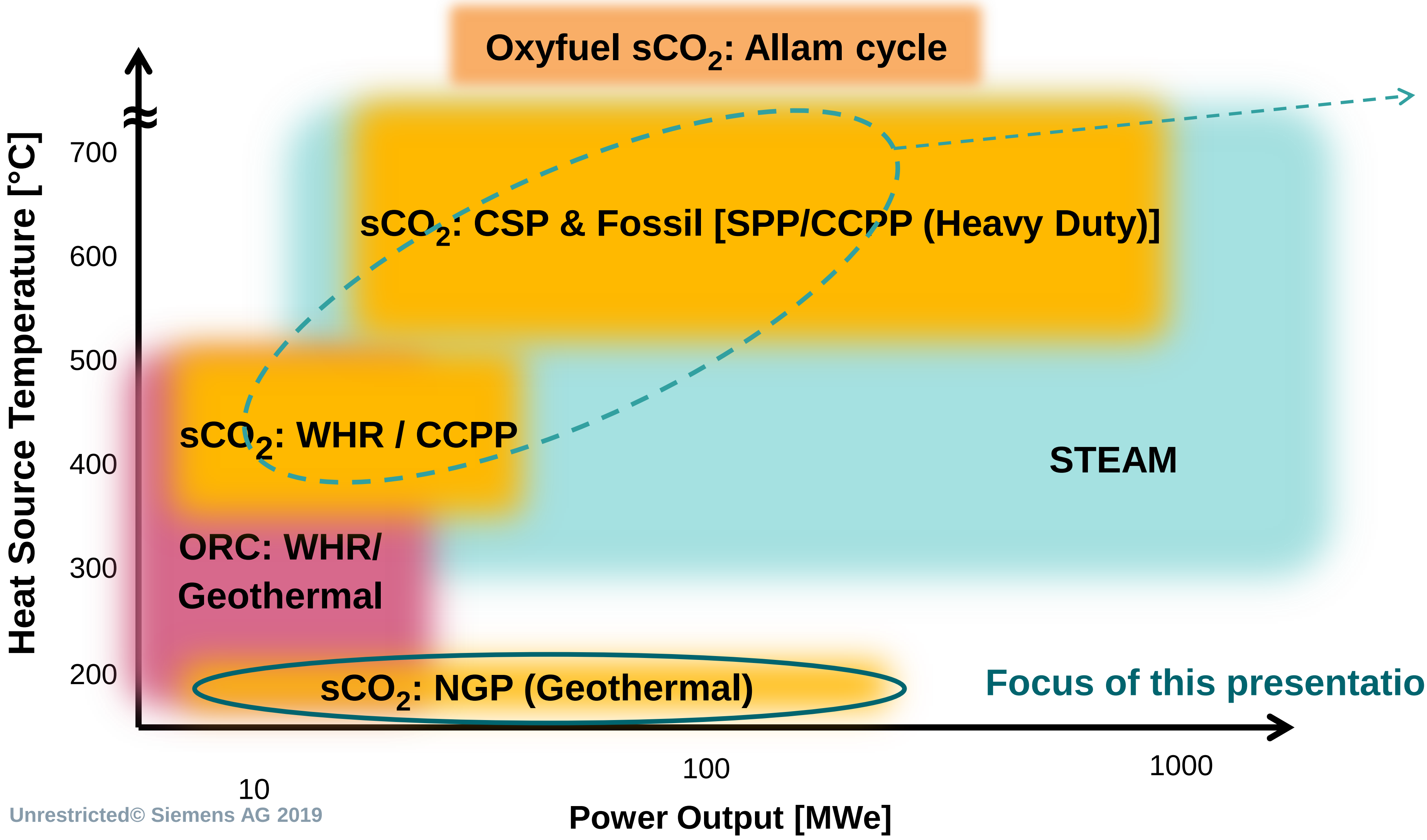

Oxyfuel sCO_2: Allam cycle

sCO_2: CSP & Fossil [SPP/CCPP (Heavy Duty)]

sCO_2: WHR / CCPP

STEAM

ORC: WHR/ Geothermal

sCO_2: NGP (Geothermal)

Focus of this presentation

CARBOSOLA

Bundesministerium für Wirtschaft und Energie
SIEMENS
TECHNISCHE UNIVERSITÄT DRESDEN
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
DLR

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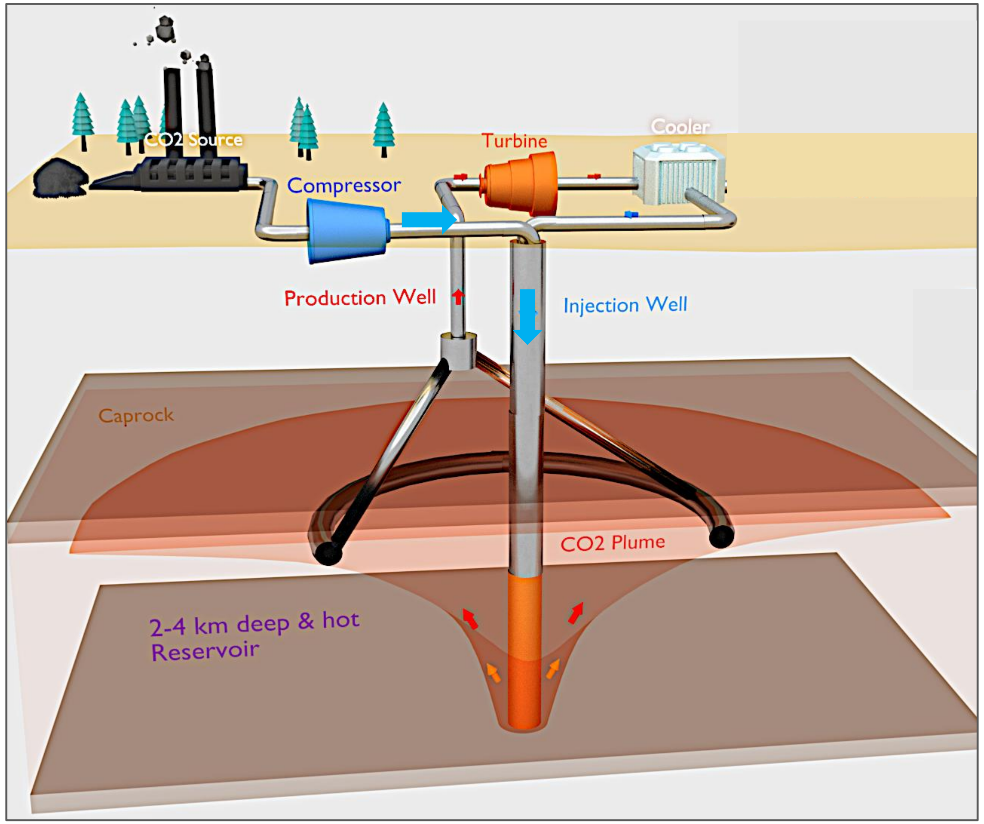
Innovative idea:
CO_2-based geothermal power generation



Randolph and Saar, 2011; Saar et al., 2012; Adams et al., 2014; Adams et al., 2015; Garapati et al., 2015

1) CO_2 captured at fossil-fueled power plants, cement manufacturers, etc. is stored underground (standard CCS or EOR/EGR thus far)

2) CO_2 forms a plume and heats up geothermally in the reservoir

3) CO_2 rises buoyantly through production wells and is expanded in a turbine to generate electric power

4) CO_2 is cooled and reinjected with the main CO_2 stream (coming from the CO_2 capture facility) through an injection well

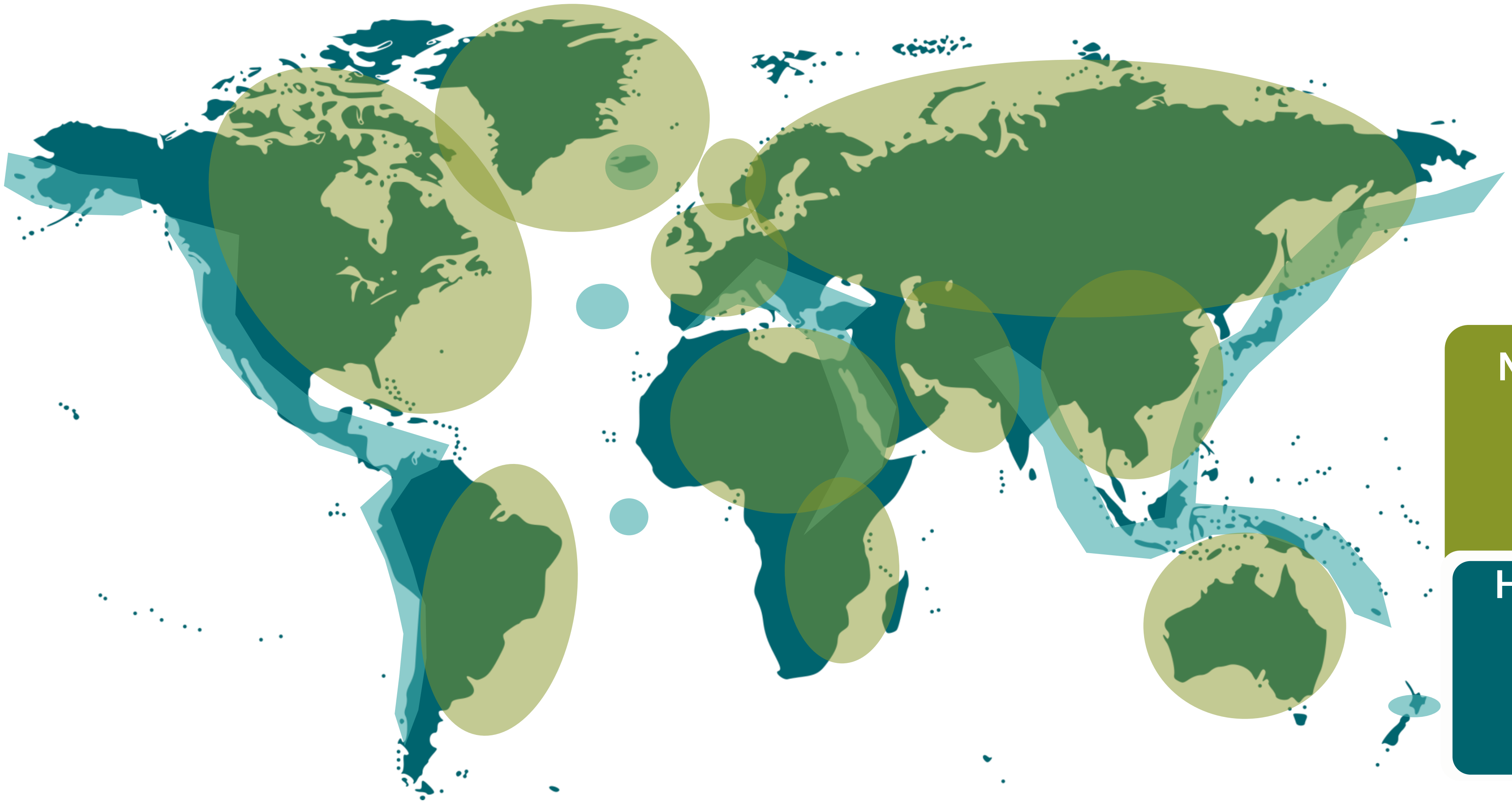
➔Electricity generation 4 times more, compared to conventional, hydrothermal power generation

➔NGP has a significant larger potential than Hydrothermal

+ Click here or copy-and-paste URL for more CPG-related publications:
https://geg.ethz.ch/publications-result-code/?code=9hfqZIW

CO2POWER MAKE CO2 WORK™ Spinoff ETHzürich

NGP has a significant larger potential than Hydrothermal



NextGen Geothermal Power

Technical potential
~2000 GW_{el}

Hydrothermal

Technical potential
~200 GW_{el}

Source:

GEA[1], 2016 &

ETH Zurich
with SIEMENS,
2018

NGP and CCS can be materialized worldwide

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[1] Geothermal Energy Association

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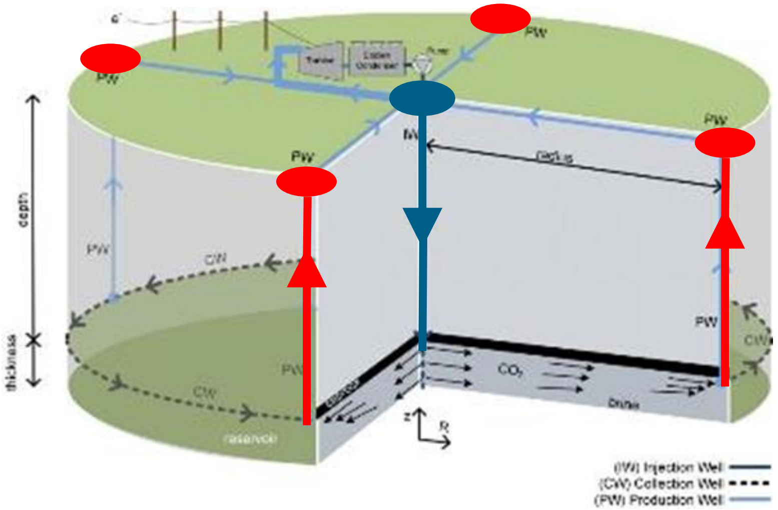
Assessment of NGP Systems
Investigation scope

Geologic conditions – Base Case

Coordination number	1 (5-spot-system)	
Depth	2500 m	3500 m
Well diameter	0,41 m	
Reservoir permeability	50 mD	100 mD
Temp. gradient	35 °C/km	

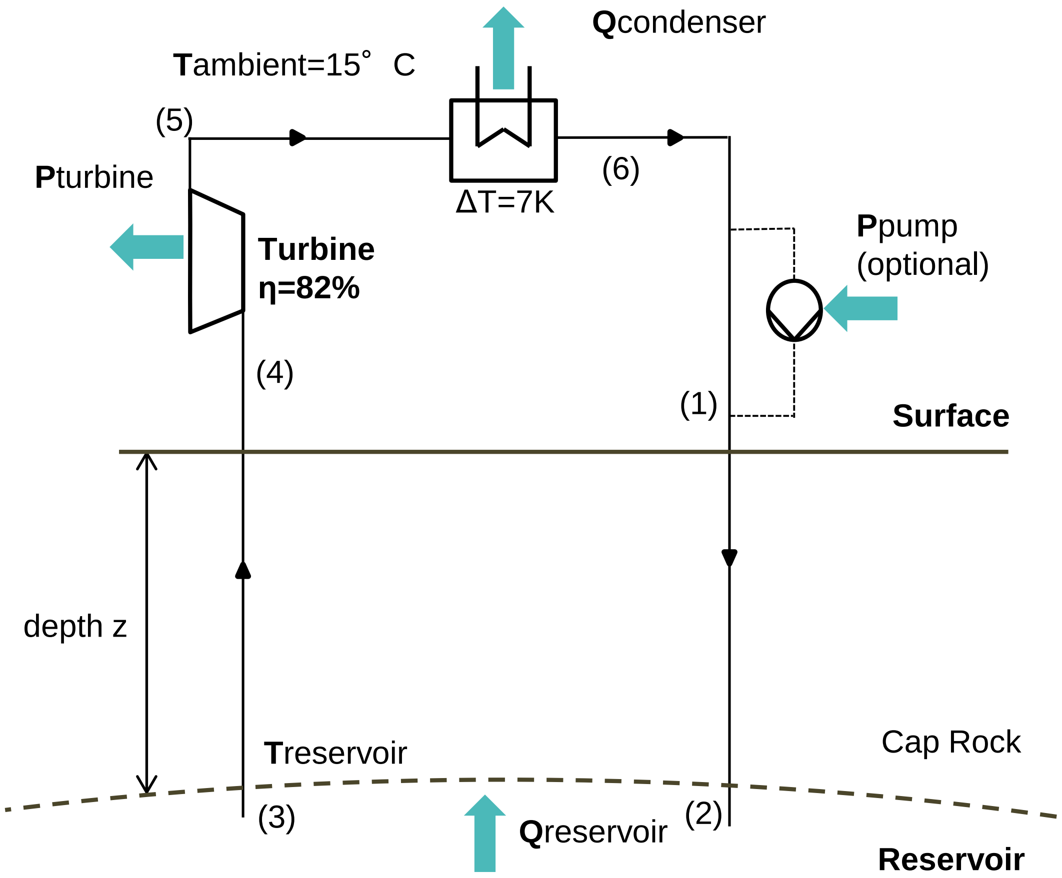


Saar, Adams; Subsurface Energy Storage with CO_2; 2018

Power Cycle Variants

direct		**indirect**			
sCO_2		**sCO_2**		**brine**	
with thermosiphon	with supplemental pumping	sCO_2	Isobutane/ R245fa/ R1234ze	sCO_2	Isobutane/ R245fa/ R1234ze

Direct cycle design (NGP)



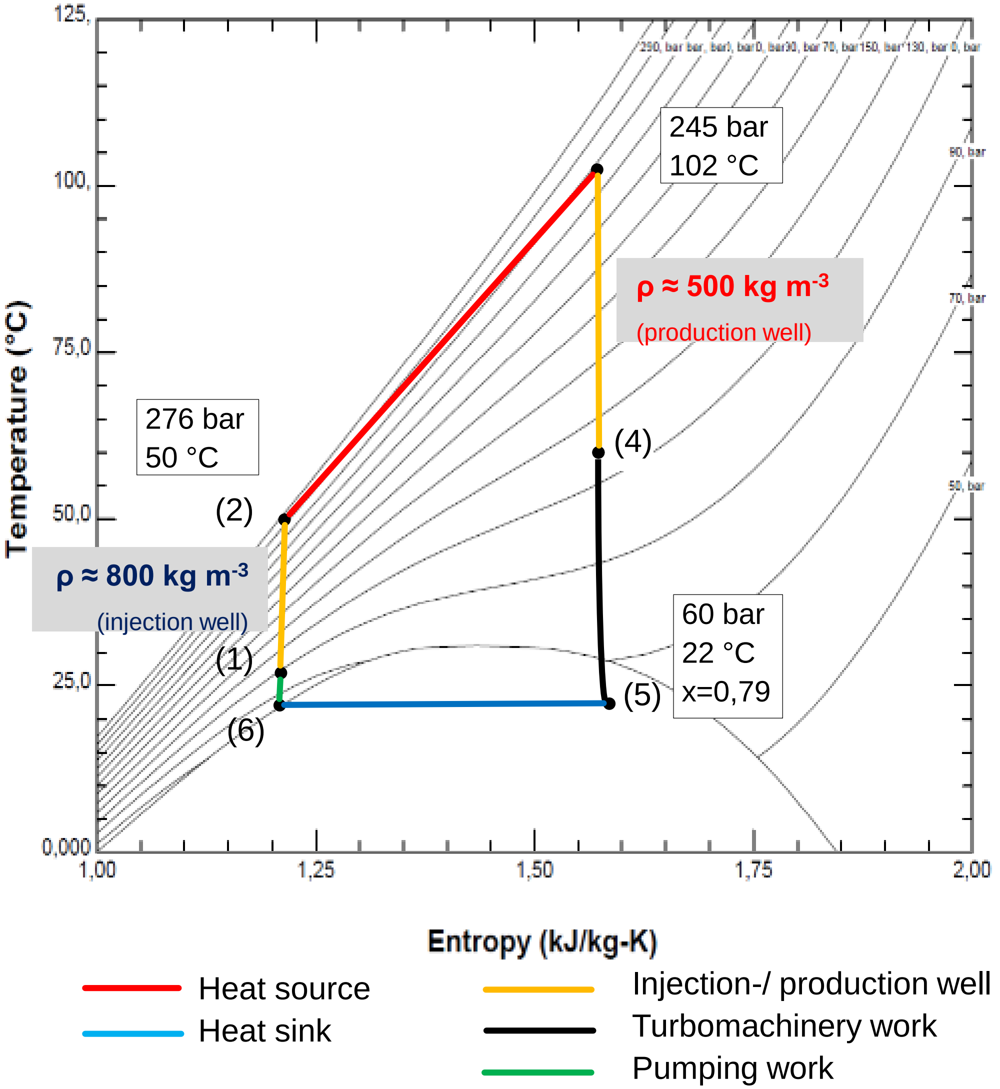
$$\Delta p = \frac{\mu \cdot L}{\rho \cdot A} \cdot \frac{\dot{m}}{\kappa} = S \cdot \frac{\dot{m}}{\kappa} = M \cdot \dot{m}$$

(Darcy‘s law)

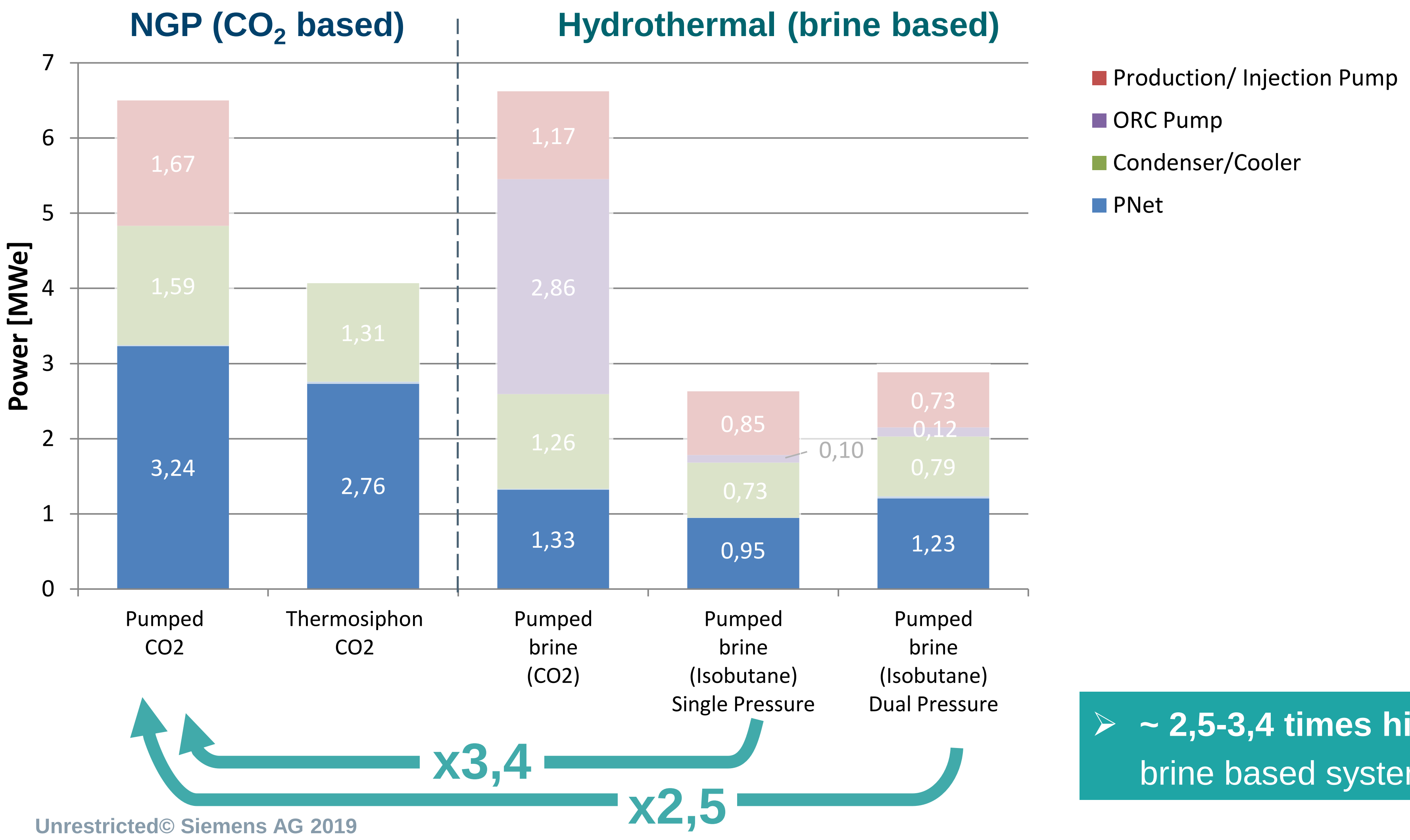
κ = reservoir permeability

M = mean spec. inverse mobility

Example for direct sCO_2 (pumped)



Calculation results for base case conditions



Reservoir conditions:
NPG base case

Depth	2500 m
Temp. gradient	35 K/km
Reservoir permeability	50 mD
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 P_{Net}** compared to brine based systems at base case conditions

Impact of depth and permeability

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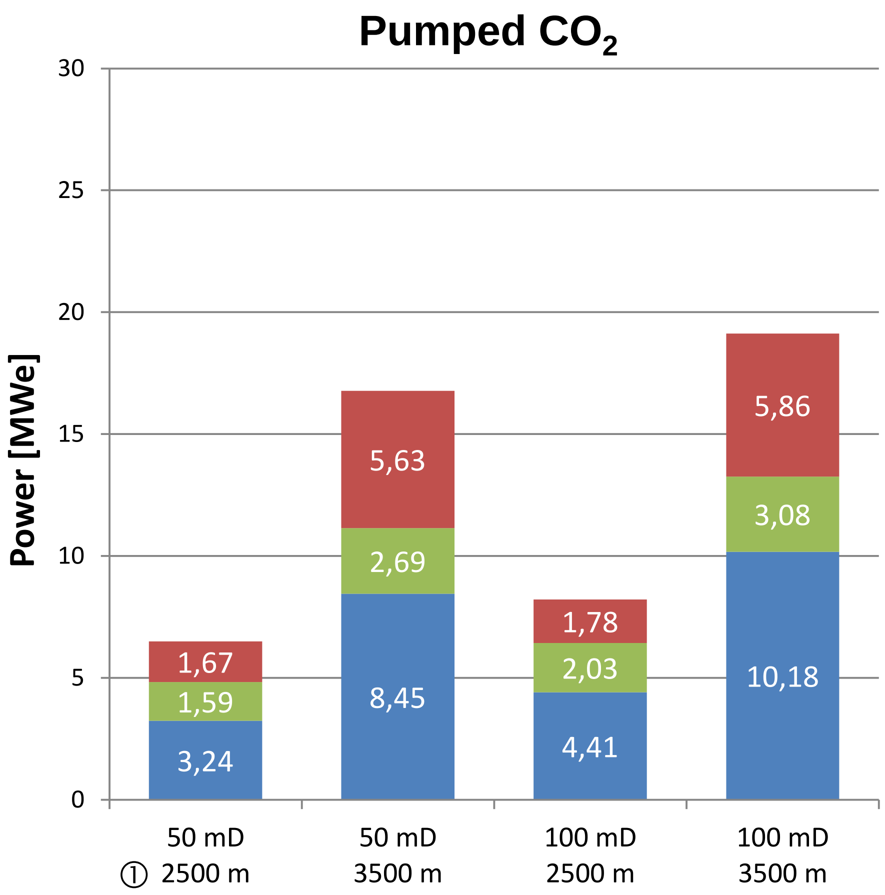
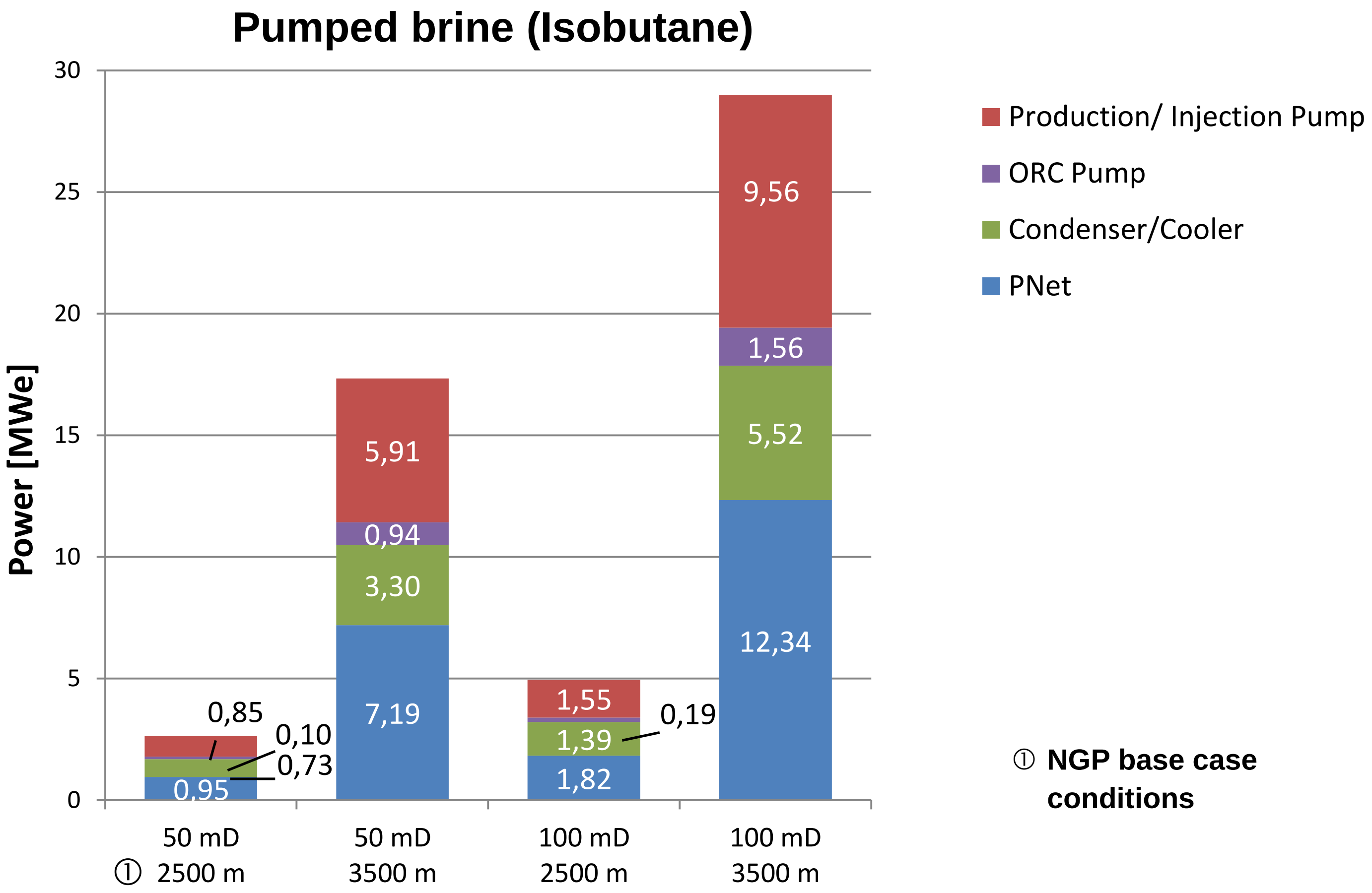
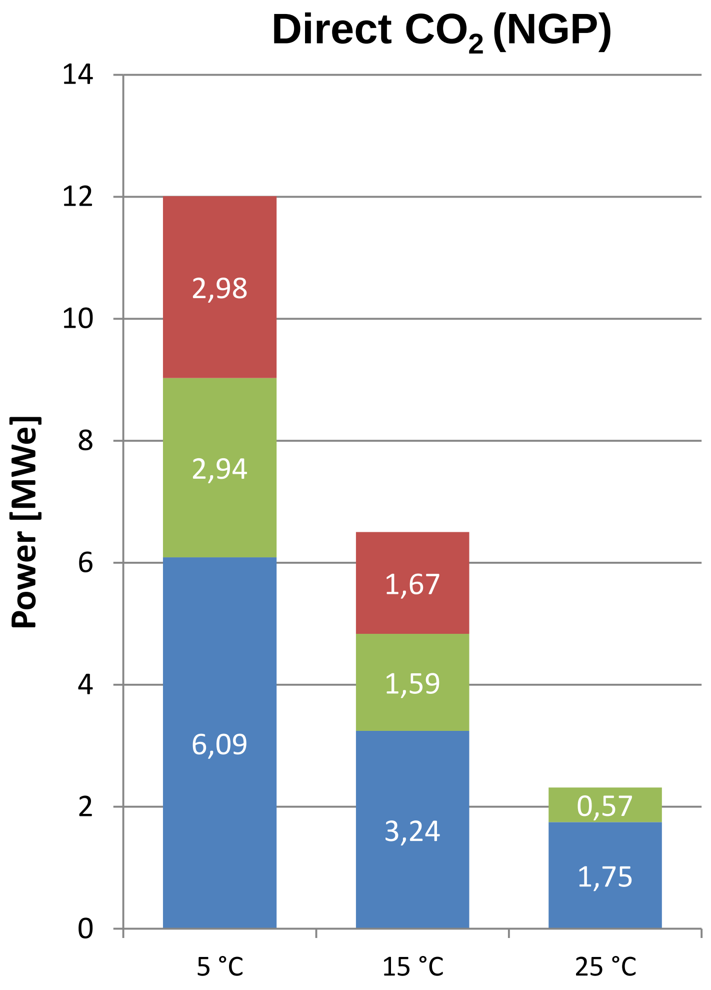




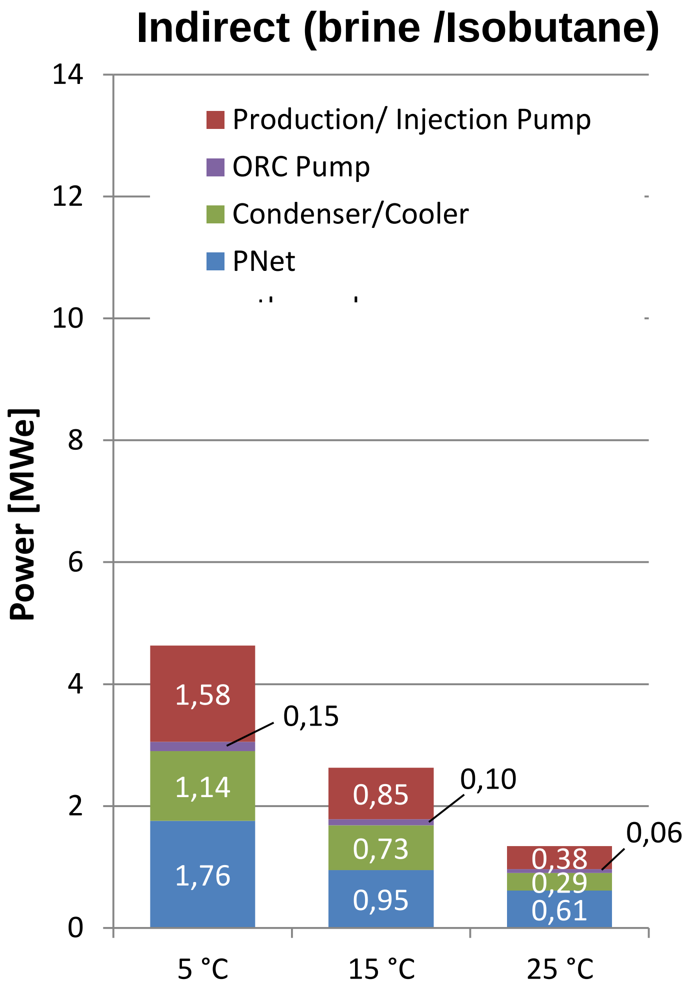
① **NGP base case conditions**

➢ Performance differences strongly depending on reservoir conditions

Impact of ambient temperature



Direct CO_2 (NGP)

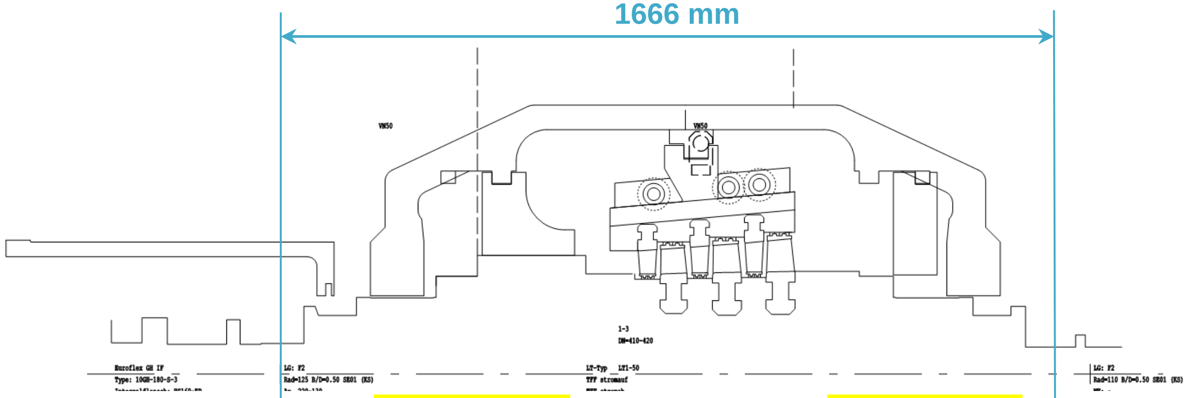


Indirect (brine /Isobutane)

- ➢ Higher sensitivity of NGP system to cooling conditions
- ➢ NGP system achieves for lower ambient temperatures even higher net output

Turbine dimension – Base case

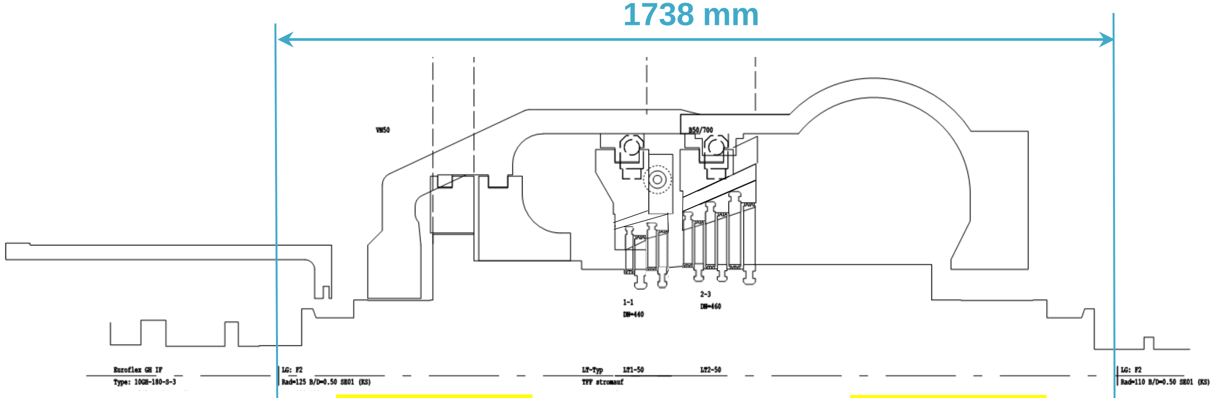
NGP (Pumped CO_2)



p_{in} 119 bar
T_{in} 60 °C

p_{out} 61 bar
T_{out} 23 °C

Pumped brine (Isobutane)



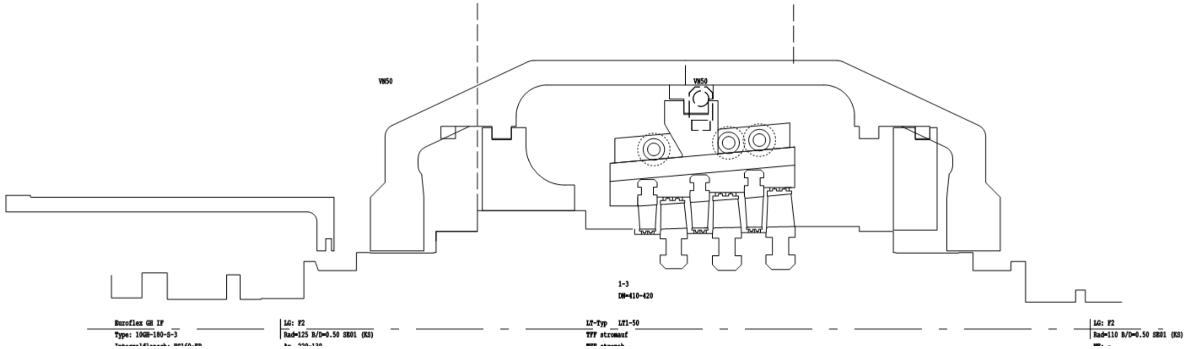
p_{in} 10 bar
T_{in} 69°C

p_{out} 3 bar
T_{out} 33 °C

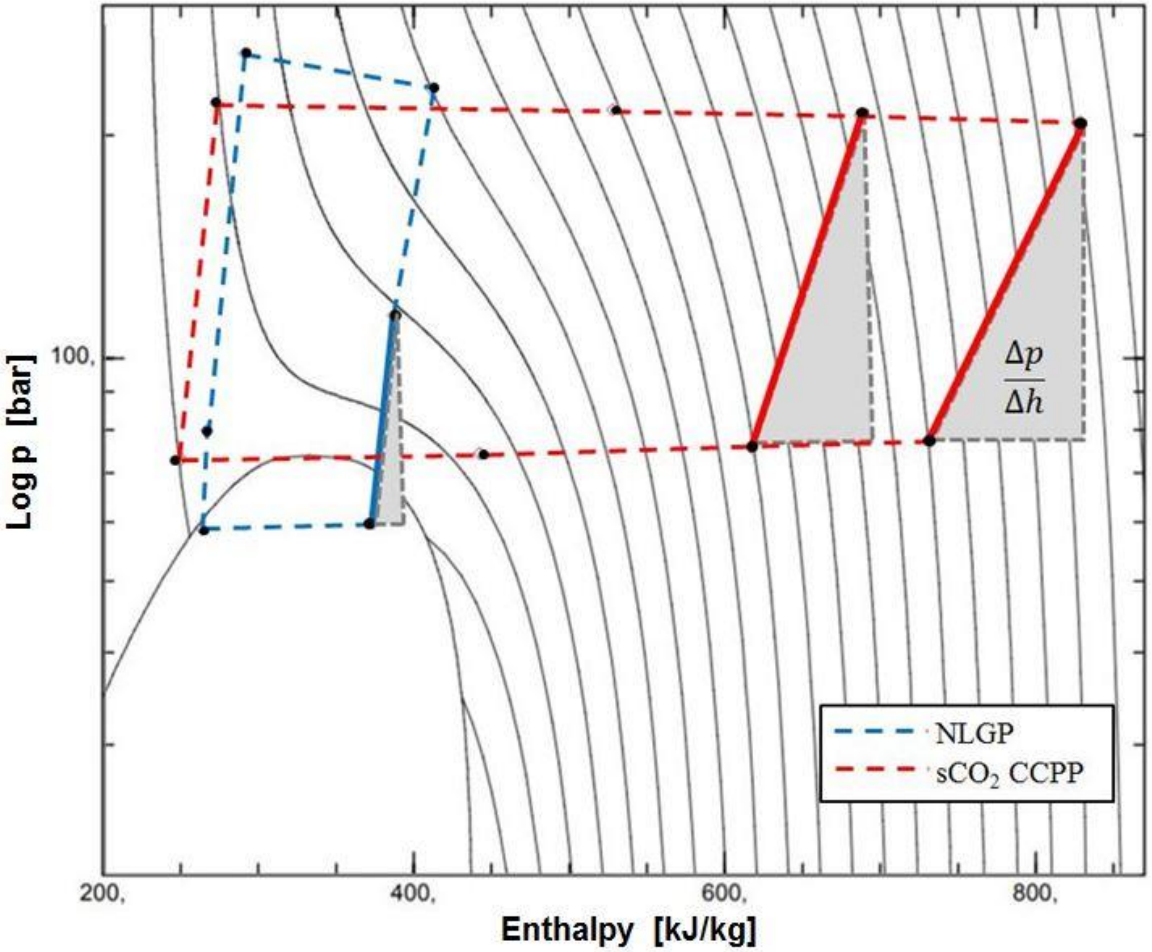
		Pumped CO_2	**Brine (Isobutane)**
$\dot{V}_{turbine,inlet}$	[m³/s]	1,3	2,3
$\dot{V}_{turbine,\text{outlet}}$	[m³/s]	2,2	7,7
Δh	[kJ/kg]	14,5	41,2
Δp	[bar]	58	7

- Lower volumetric flow in CO_2 turbine
- Lower enthalpy difference
- Higher pressure levels

Turbine dimension – Base case



- ➢ Low enthalpy drop & high pressure difference
- ➢ High bending forces
- ➢ Large chord length and root sizes



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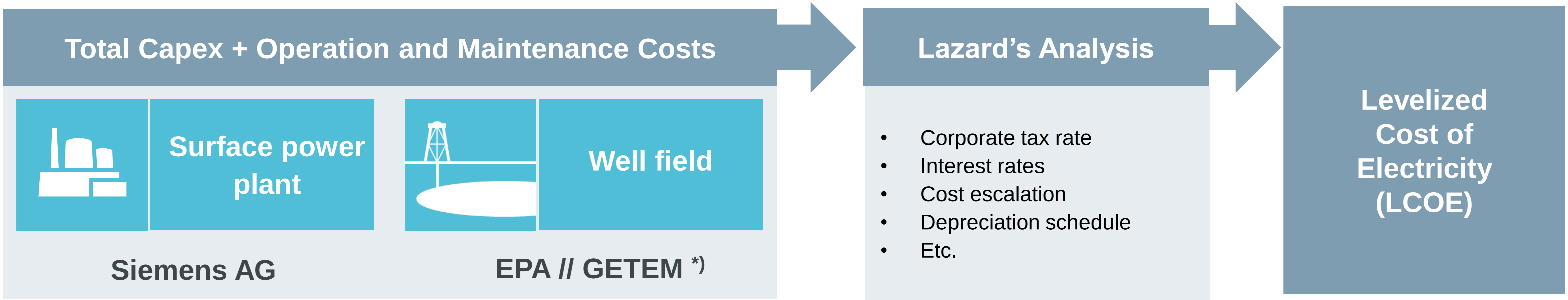
CO_2-based geothermal power generation
Key approach for cost assessment

- No significant thermal decline during lifetime
- Operating lifetime: 25 years (No significant thermal decline)
- Wellfield size: 5 x 5 km (25x injection wells + 36x production wells)
- Surface piping: 65km (Ø ~1 – 1,2m)
- Turbine train design for 60°C/ 115bar
- Location: USA

	(1)	**(2)**
Reservoir depth	2,5 km	3,5 km
Reservoir permeability	50 mD	100 mD
	52 MW	157 MW



Total Capex + Operation and Maintenance Costs

Surface power plant

Siemens AG

Well field

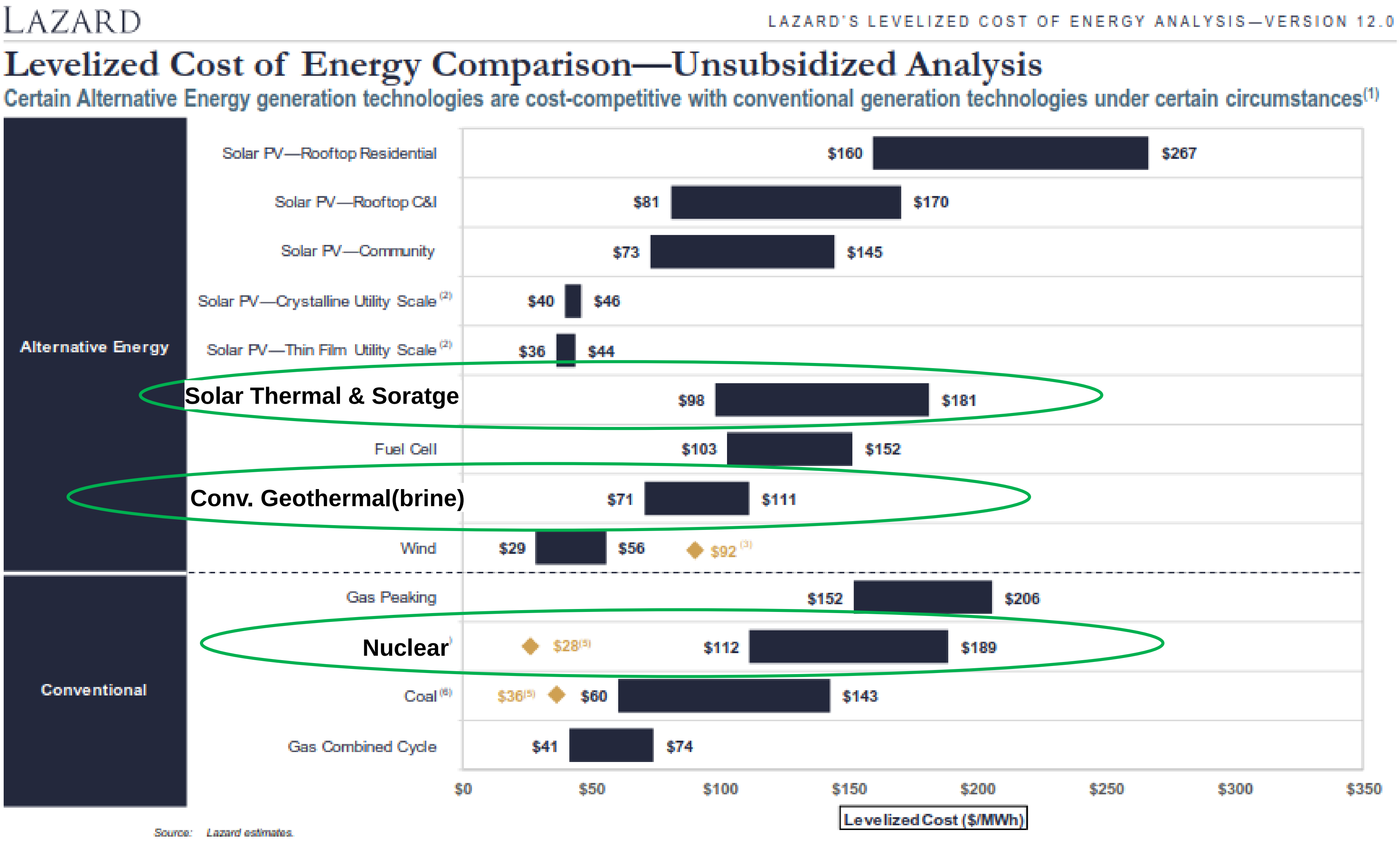
EPA // GETEM [*)]

Lazard's Analysis

- Corporate tax rate
- Interest rates
- Cost escalation
- Depreciation schedule
- Etc.

Levelized Cost of Electricity (LCOE)

*) EPA: United States Environmental Protection Agency, 2008
GETEM: Geothermal Electricity Technology Evaluation Model


LAZARD

LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 12.0

Levelized Cost of Energy Comparison—Unsubsidized Analysis

Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances(1)

Source: *Lazard estimates.*


Levelized Cost of Energy and Levelized Cost of Storage 2018

Lazard's Levelized Cost of Energy Analysis, Version 12.0

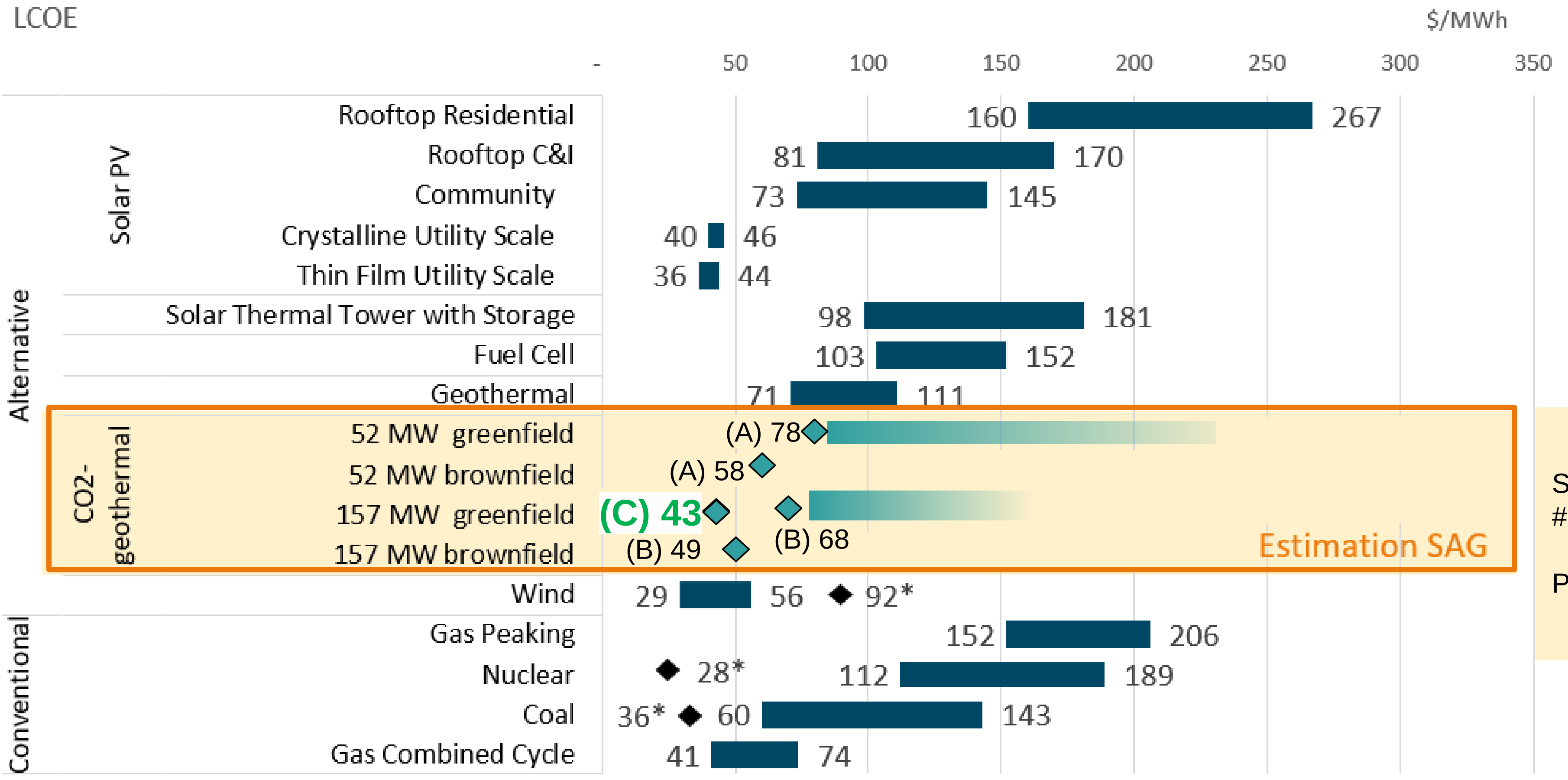
Lazard's Levelized Cost of Storage Analysis, Version 4.0

https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf

Emission free full dispatchable technologies

Levelized Cost of Electricity (LCOE) – first results
NGP system compared to other technologies



Wind: offshore

◆ Nuclear/ Coal: fully depreciated facilities

	(A)	(B)	(C)
Surface size:	2x2km	3x3km	5x5km
# of wells:	15	25	61
depth:	4km	4 km	5km
Permeability:		100mD	

600MW

Source LCOE other technologies: Lazard (2018): Levelized Cost of Energy Analysis, Version 12.0

- ➢ Estimated LCOE for 160 MW power plant within range of conventional technologies
- ➢ Focus on geologically more favorable locations can almost quarter costs

Summary

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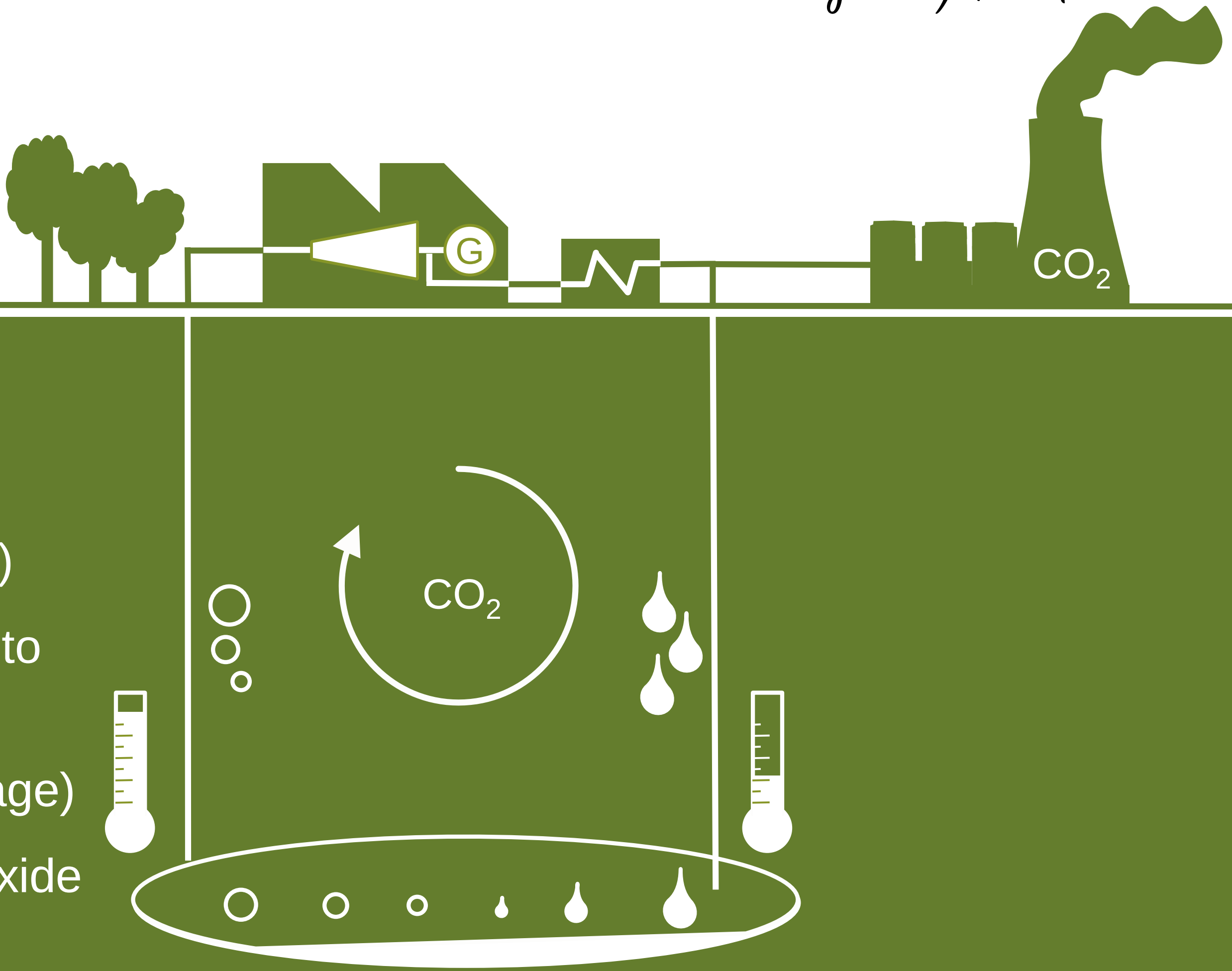
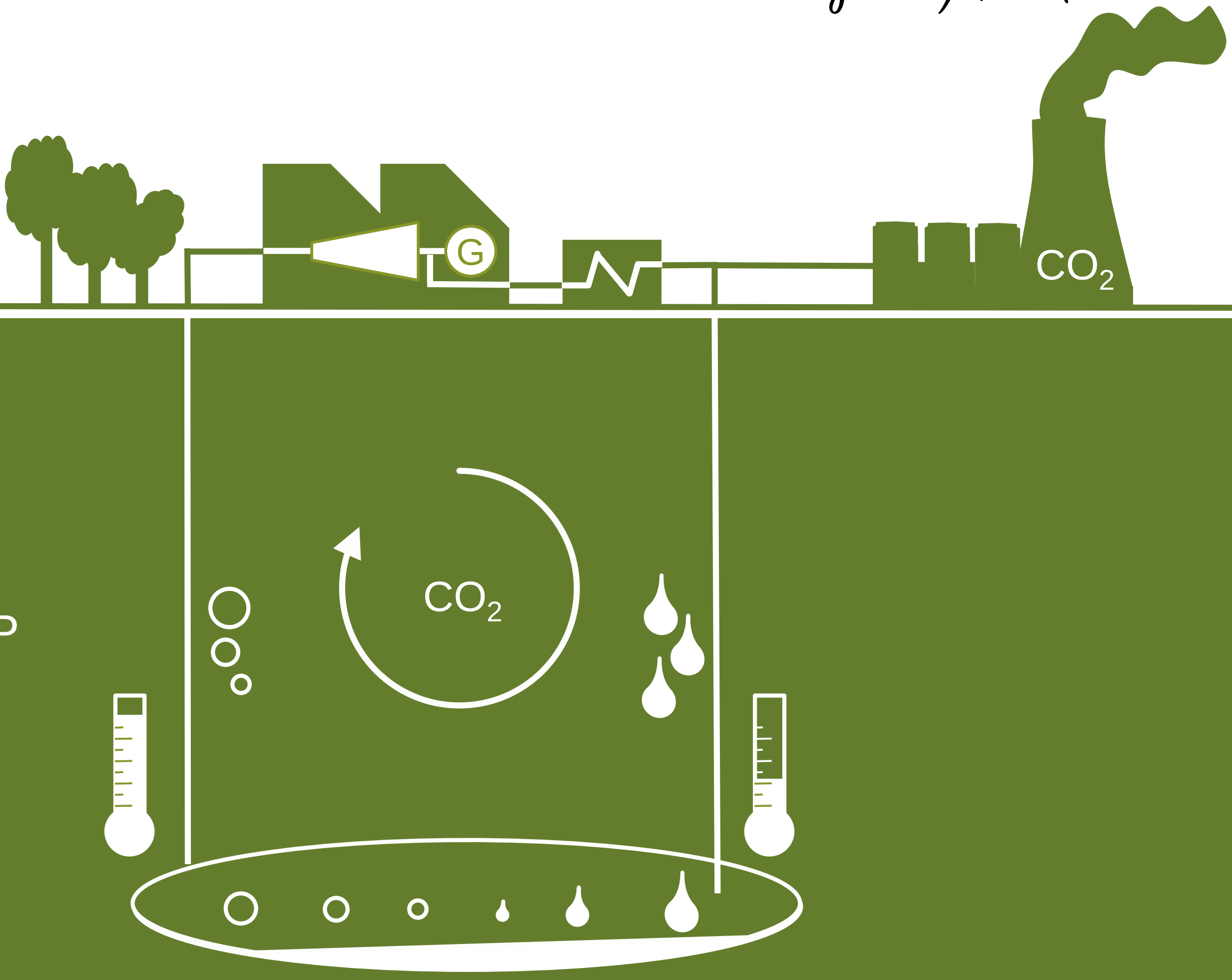


- Agreement of thermodynamic simulations of NGP systems with published data
- Significant more power (than conventional technology)
- Surface power plant layout less complex with respect to equipment
- Cost competitive (compared to solar energy with storage)
- NGP can push the profitability of capturing carbon dioxide and transform CCS to CCU

Outlook



- Identification of partner for subsurface portion and project development
- Accelrate R&D / Proof of concept / Realization of NGP demonstrator
- Realization of commercial projects

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CO2POWER
MAKE CO2 WORK

Spinoff ETH zürich

Assessment of performance and costs of CO_2 based Next Gen Geothermal Power (NGP) systems

Thank you for your attention !

3rd European sCO_2 conference, Paris, September 2019
Dr. Stefan Glos, Siemens AG

Backup

LCOE Calculation
Different financial boundary conditions

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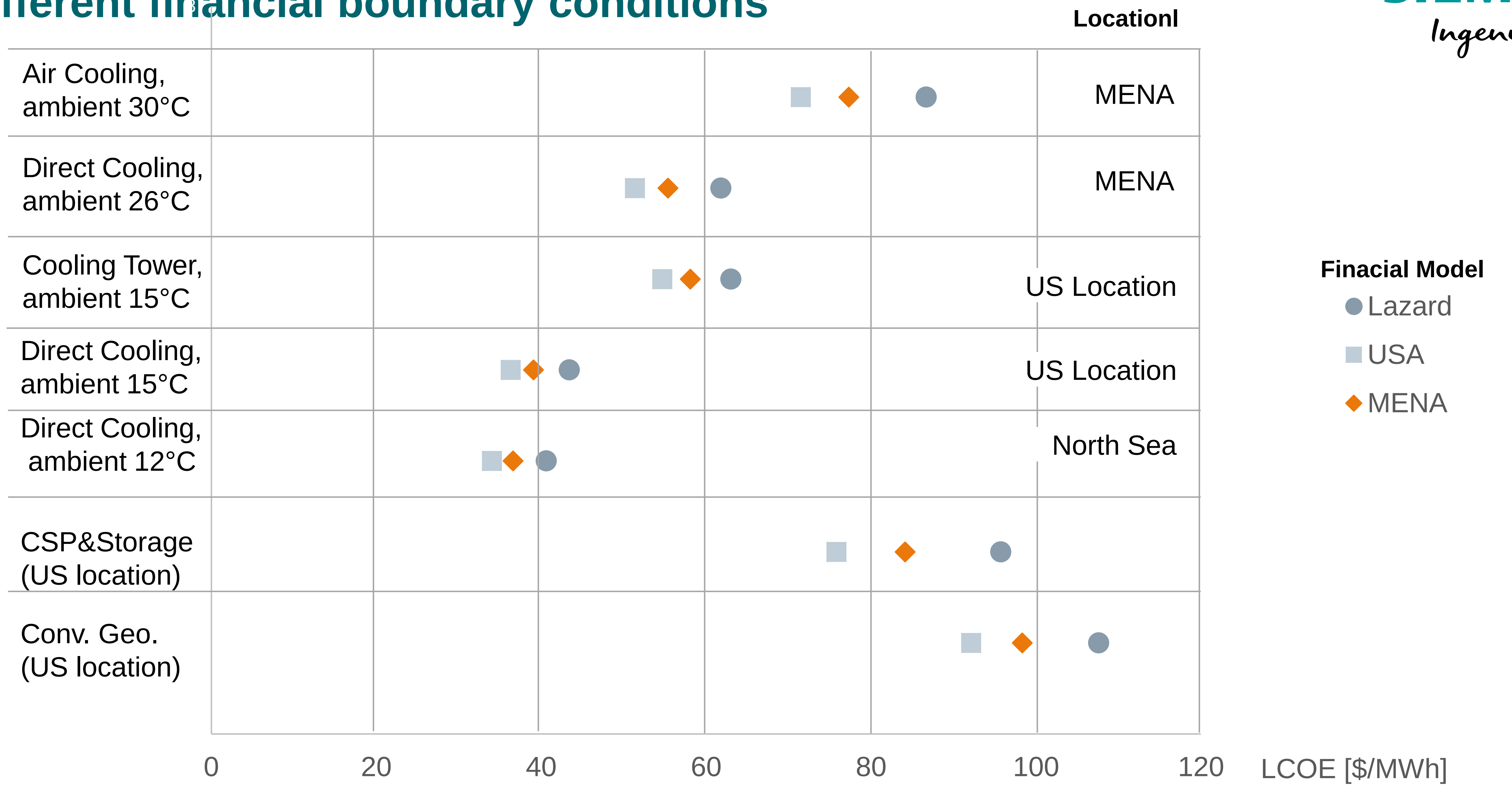

- For the same location and the same financial model LCO 40% lower
- Even for MENA region with Air Cooling LCOE lower than CSP + Storage

LCOE Calculation
Different financial approaches - Assumptions

Assumption	**Lazard**	**USA** (Siemens assumptions)	**MENA** (Siemens assumptions)	**your boundaries**
Cost of Debt	8%	2,6%	3,2%	
Combined Tax Rate	40%	23%	5%	
Depreciation schedule	MACRS 5-years	MACRS 5-years	Declining Balance (20%)	