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# Flexible DRI operation with high-temperature electrolysis for cost-effective iron decarbonization

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# Introduction

## Promising technologies for decarbonizing iron production

- Hydrogen-based direct reduced iron (**H<sub>2</sub>-DRI**)
- Natural gas-based DRI with carbon capture and storage (**NG-DRI-CCS**)

**Competitiveness of H<sub>2</sub>-DRI** requires green hydrogen costs as low as 1–2 \$/kg<sub>H<sub>2</sub></sub><sup>1</sup>

- Lower electricity costs
- High-efficiency electrolysis

## High-temperature solid oxide electrolysis

- Operating temperature of **600-800°C**
- Reduces electricity consumption from >50 (e.g. Alkaline, PEM) to **~35 kWh<sub>e</sub>/kgH<sub>2</sub>** (>**90% LHV**)
- Achievable if steam generated with already available **waste heat sources**

▶ **Attractive integration with iron & steel production**

<sup>1</sup>Rosner et al., "Green steel: design and cost analysis of hydrogen-based direct iron reduction", *Energy Environ. Sci.*, 2023.

# Objectives

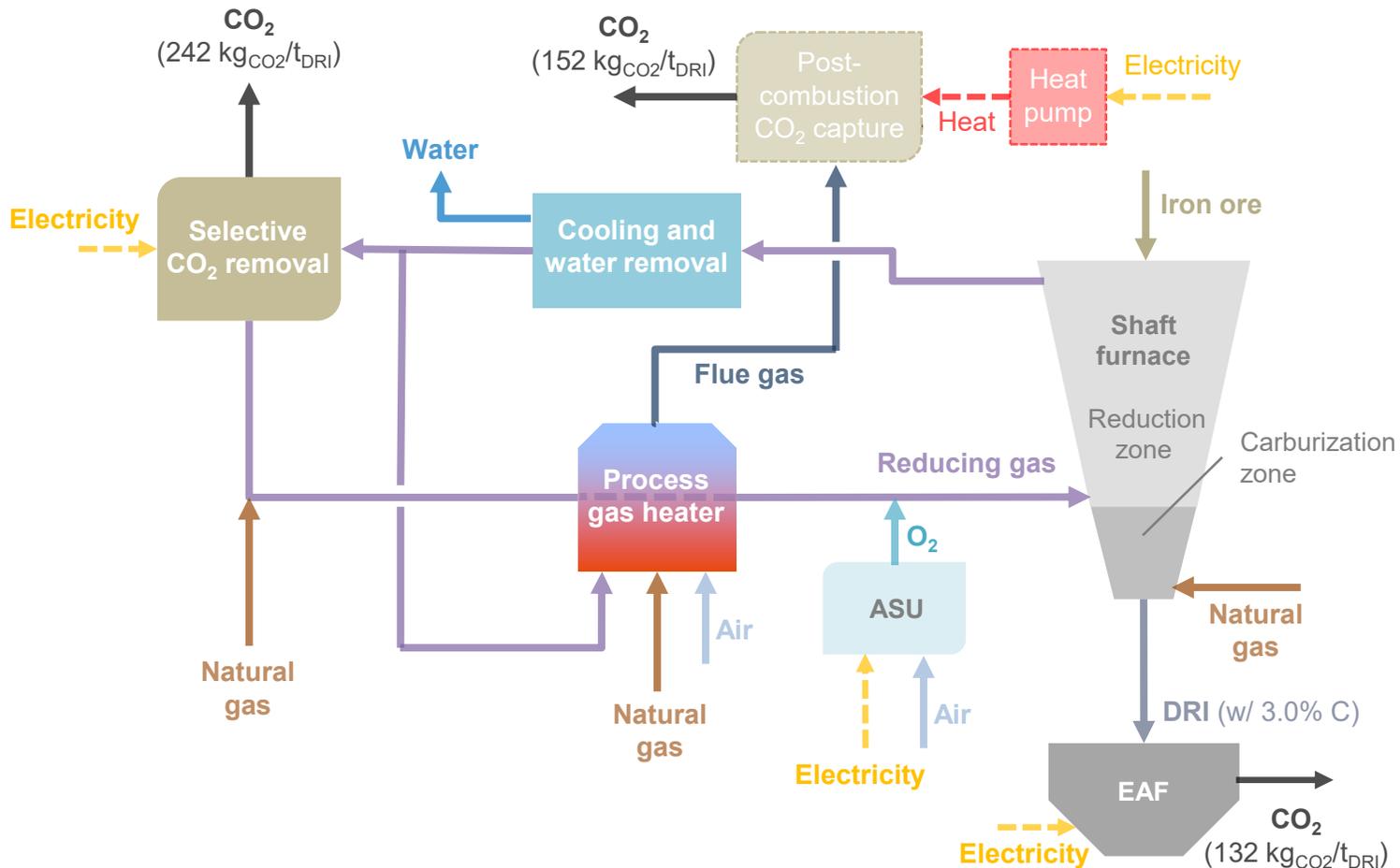
## I. **Process analysis of a SOEC-based H<sub>2</sub>-DRI plant (SOEC-DRI)**

- Evaluation of integration options between SOEC and DRI
- Off-design operations (flexible DRI operation, natural gas in reducing loop)

## II. **Techno-economic optimization**

- Optimizes SOEC-DRI integration with PV, wind, and storage units
- Short- and long-term cost scenarios
- Locations: Cleveland, OH (USA), Pilbara (Australia)
- Cost performance and CO<sub>2</sub> emissions benchmarked against NG-DRI and NG-DRI-CCS plants

## Reference: NG-DRI and NG-DRI-CCS

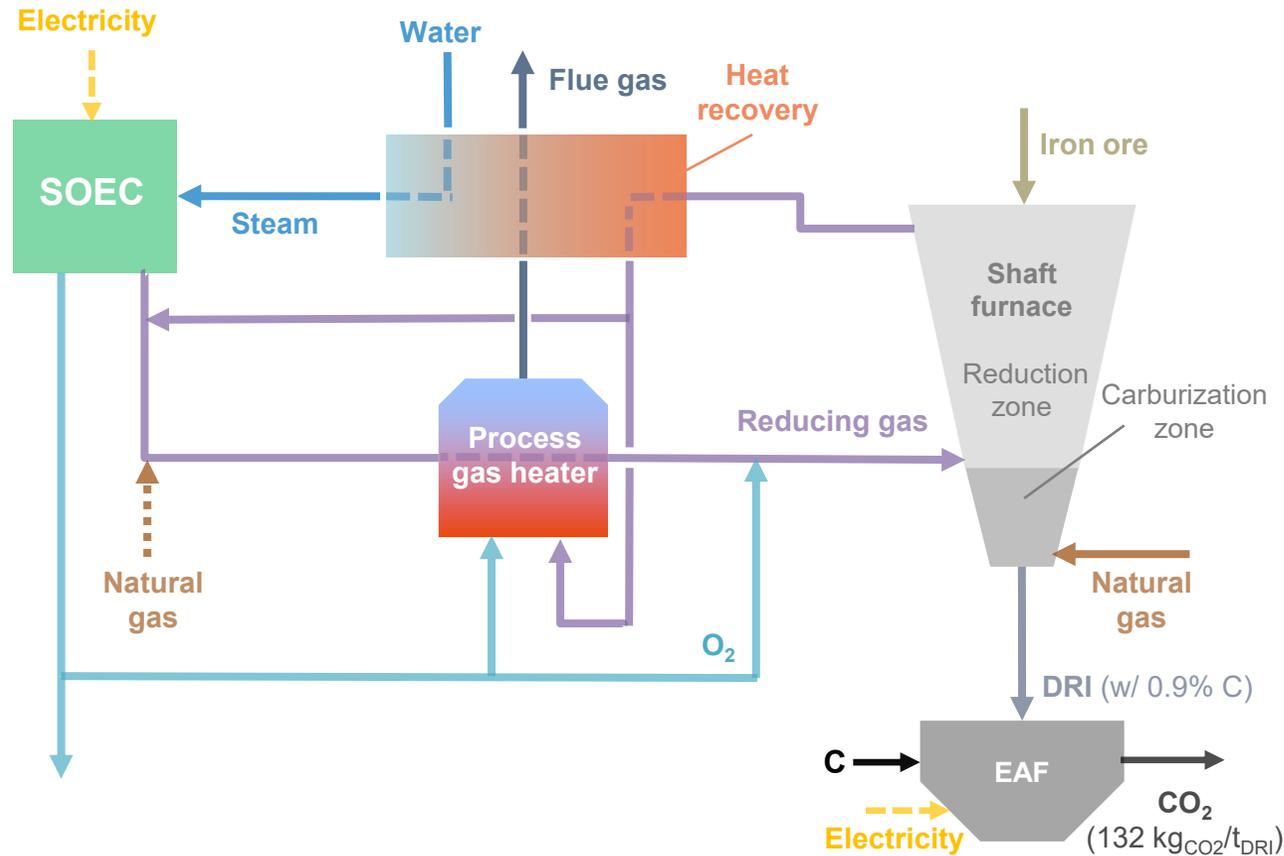


- Based on **ENERGIRON ZR®**
- Natural gas used as reductant and fuel
- 3.0%<sub>wt</sub> carbon content in DRI product
- **CO<sub>2</sub> emissions** from selective removal, flue gas, and downstream carbon oxidation
- NG-DRI-CCS: **CO<sub>2</sub> selective removal** and **post-combustion CO<sub>2</sub> capture**

### ► Net energy consumption: 9.4 GJ/t<sub>DRI</sub>

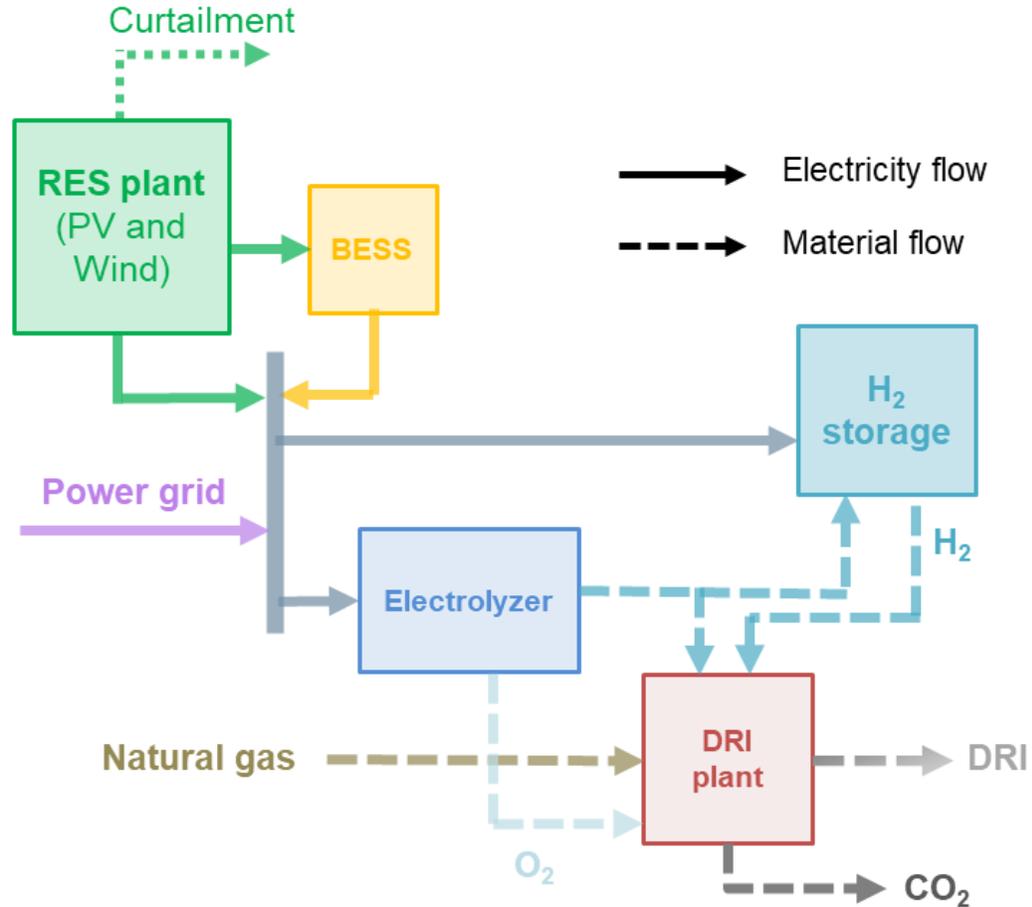
- 10 GJ/t<sub>DRI</sub> of natural gas
- 0.4 GJ/t<sub>DRI</sub> of electricity
- -1.0 GJ/t<sub>DRI</sub> from DRI C oxidation

# Thermally integrated SOEC-DRI



- Reducing gas: H<sub>2</sub>-rich mixture (10% H<sub>2</sub>O)
- **Thermal integration** → Steam generation exploiting DRI shaft hot top-gas
- Part of top-gas (H<sub>2</sub>-rich) burned to complete steam generation
- **0.9%<sub>wt</sub>** carbon content in DRI product
- **Assumption: Carbon addition** in EAF to have equal downstream CO<sub>2</sub> emissions with respect to NG-DRI
- ▶ **Net energy consumption: 8.1 GJ/t<sub>DRI</sub>**
  - 0.9 GJ/t<sub>DRI</sub> of natural gas
  - 7.6 GJ/t<sub>DRI</sub> of electricity
  - -0.3 GJ/t<sub>DRI</sub> from DRI C oxidation

# Techno-economic optimization



➤ **Mixed-Integer Linear Programming (MILP)**



➤ One year with 1-hour resolution



➤ Minimize the **total annual cost (TAC)**



➤ Energy and material balances from system process analysis  
 ➤ **Flexible DRI shaft furnace and possible NG co-feeding**  
 ➤ Fixed DRI production of 2 Mt/y



➤ **Short- and long-term** cost scenarios  
 ➤ Renewable energy source profiles of **Cleveland** and **Pilbara**

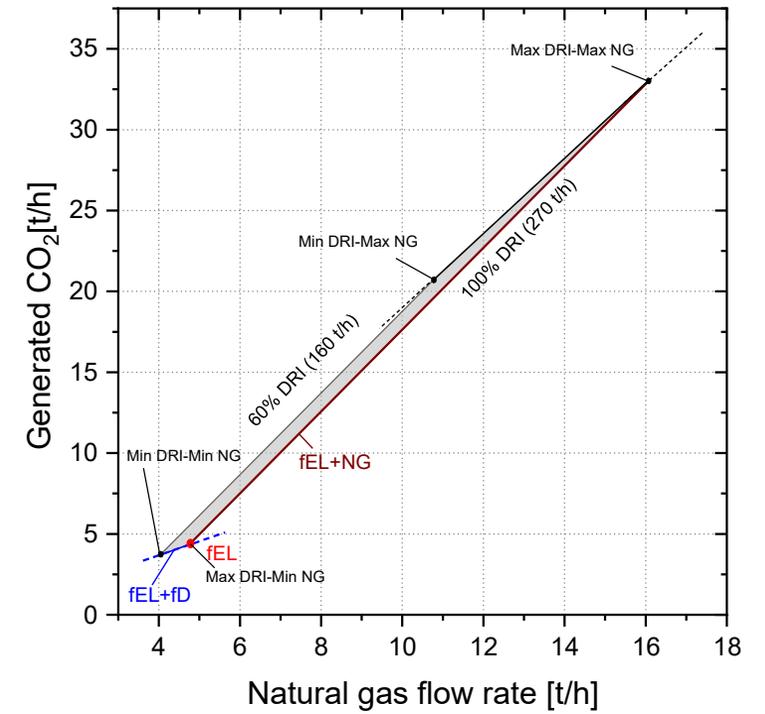
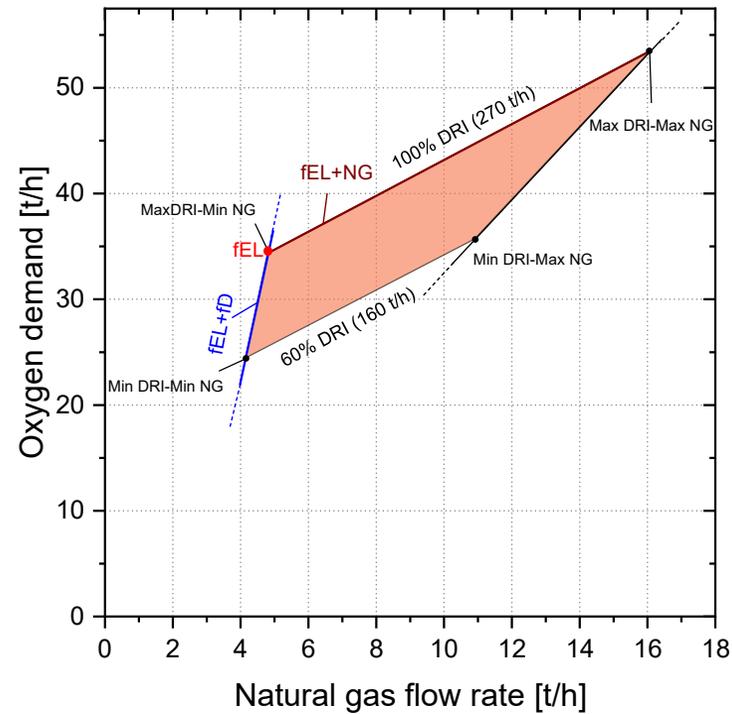
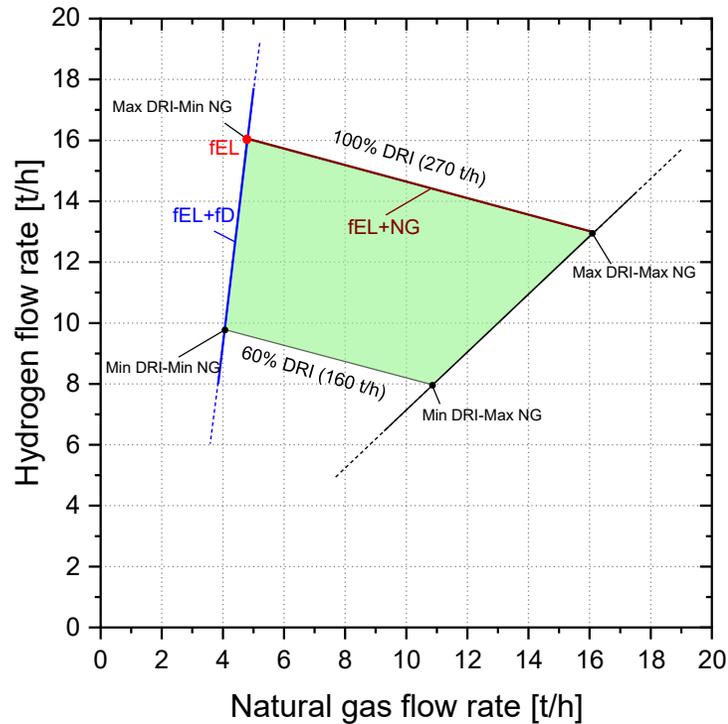


Benchmarked with:

➤ Natural gas based DRI (**NG-DRI**)  
 ➤ Natural gas based DRI with  $CO_2$  capture (**NG-DRI-CCS**)

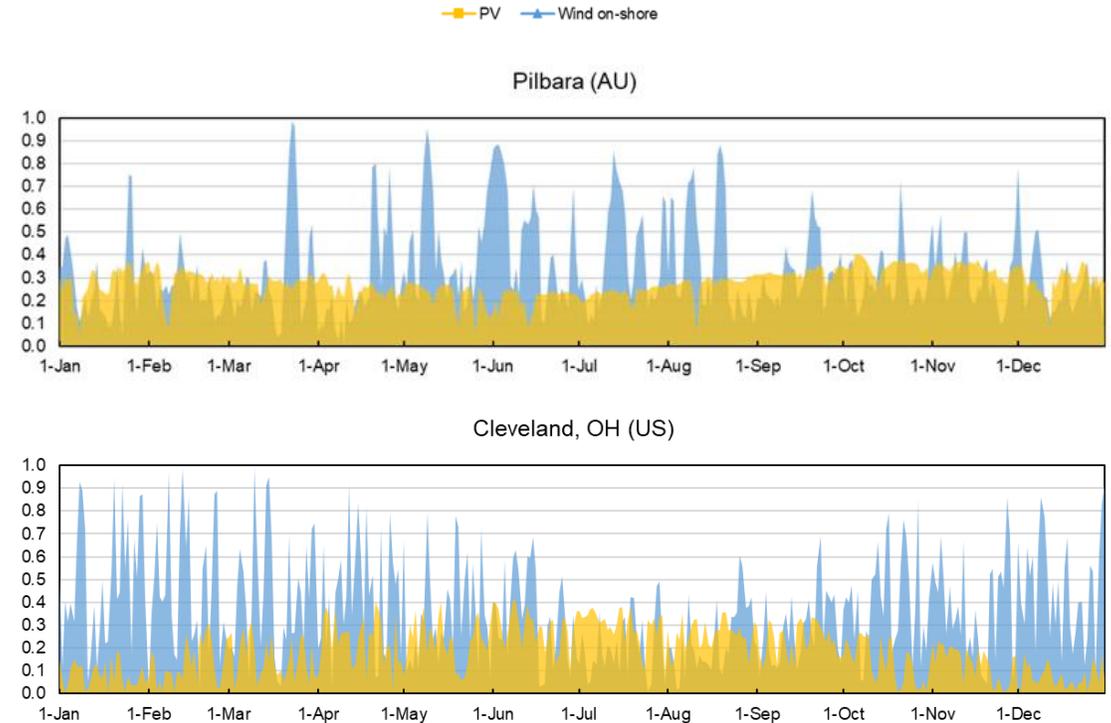
# Operational maps

- Derived from off-design process analyses
- Describe flexible operation of DRI shaft furnace with possibility of NG-H<sub>2</sub> co-feeding

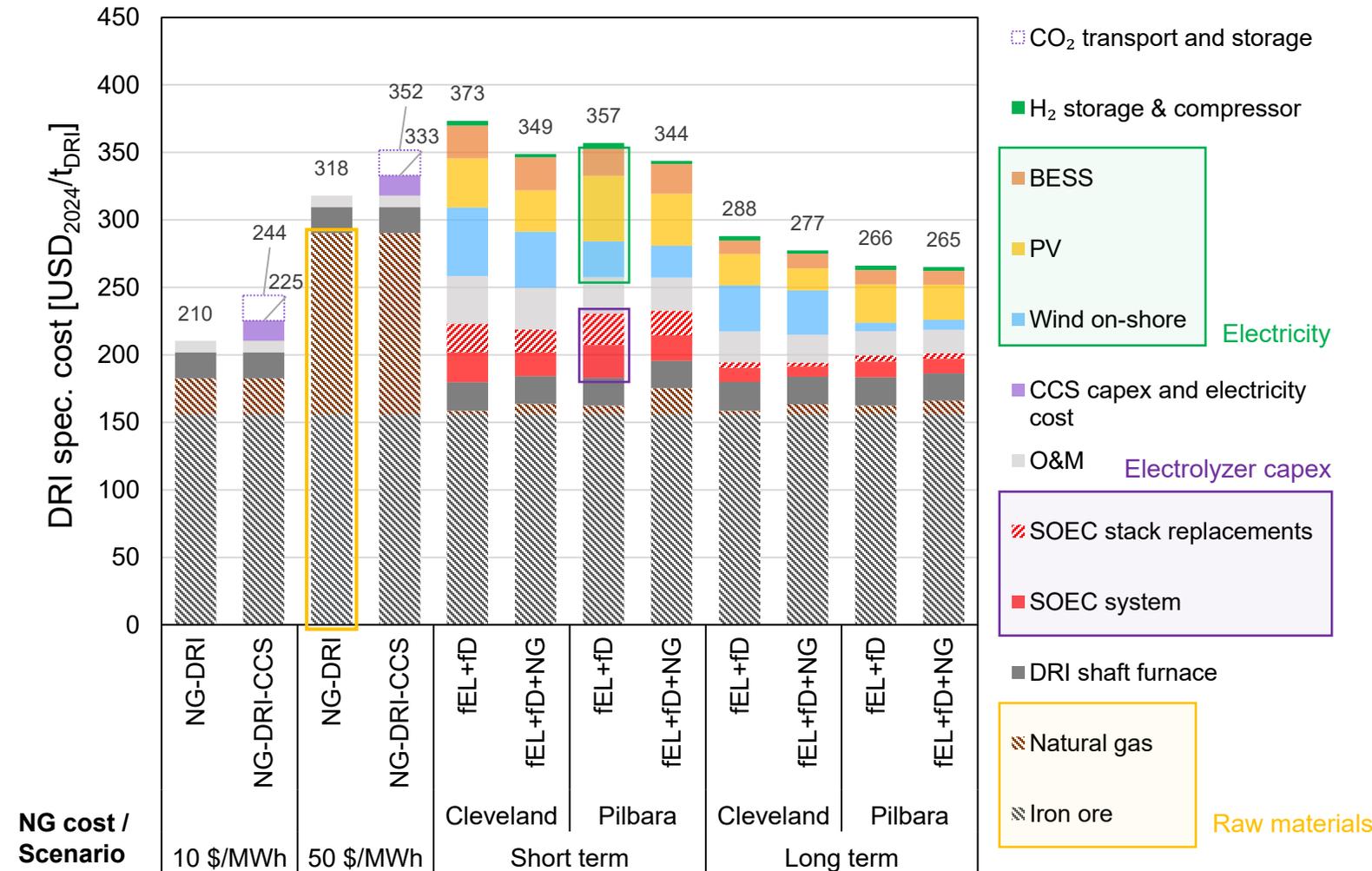


# Techno-economic assumptions

Case	Short term	Long term
PV Capex	760 \$/kW	330 \$/kW
Onshore wind Capex	1160 \$/kW	1080 \$/kW
BESS Capex	270 \$/kWh	130 \$/kWh
H <sub>2</sub> storage Capex	1.65 \$/kWh (55 \$/kg)	
SOEC Capex	650 \$/kW	260 \$/kW
PV embedded CO <sub>2</sub>	800 kg <sub>CO2</sub> /kW	
Onshore wind embedded CO <sub>2</sub>	560 kg <sub>CO2</sub> /kW	
BESS embedded CO <sub>2</sub>	70 kg <sub>CO2</sub> /kW	
Weighted average cost of capital (WACC)	8 %	



# Economic results



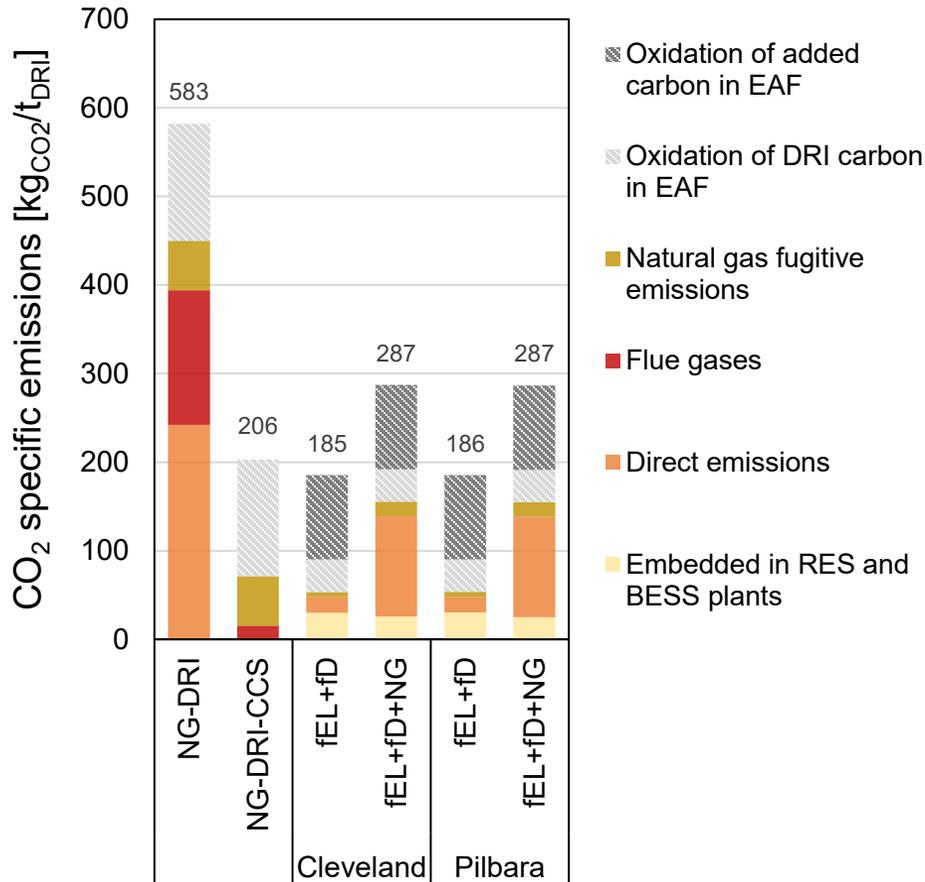
## NG-DRI and NG-DRI-CCS

- Cost highly dependent on feedstock
- NG-DRI-CCS achieves limited cost increase: +15-34 \$/t<sub>DRI</sub>

## SOEC-DRI

- Electricity main cost driver
- Co-feeding of NG and H<sub>2</sub> yields limited cost reduction (- 3-6%)
- Short-term: competitive vs. NG-DRI / NG-DRI-CCS only at high NG price (50 \$/MWh)
- Long-term: competitive in favorable sites (abundant PV) with higher reference NG price (e.g. Pilbara)

# CO<sub>2</sub> emissions and cost of CO<sub>2</sub> avoided



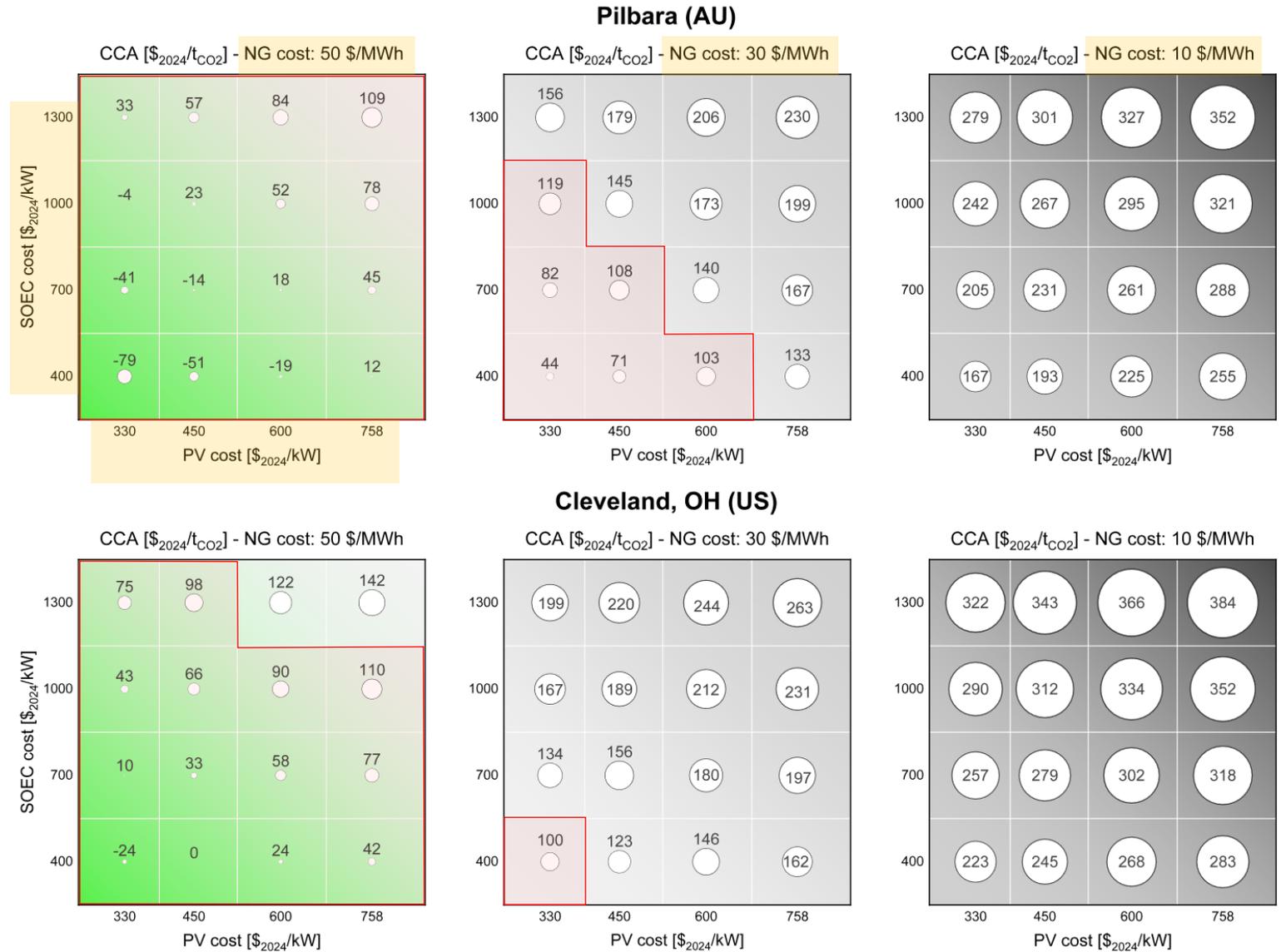
**Cost of CO<sub>2</sub> avoided:** required carbon tax such that low-carbon plants are cost-competitive with reference plants

$$CCA = \frac{cost_{DRI,LC} - cost_{DRI,NG-DRI}}{e_{CO_2,NG-DRI} - e_{CO_2,LC}} \quad * LC = Low-carbon$$

- NG-DRI-CCS and SOEC-DRI achieve comparable CO<sub>2</sub> emissions reduction
- Co-feeding of NG and H<sub>2</sub> does not justify limited cost benefit
- Cost of CO<sub>2</sub> avoided (CCA) highly dependent on reference NG price

	NG ref. price	Short term	Long term
<b>NG-DRI-CCS</b>		<b>50-100 \$/t<sub>CO2</sub></b>	
<b>SOEC-DRI - Cleveland (US)</b>	10 \$/MWh	<b>381 \$/t<sub>CO2</sub></b>	<b>192 \$/t<sub>CO2</sub></b>
<b>SOEC-DRI - Pilbara (AU)</b>	25 \$/MWh	<b>204 \$/t<sub>CO2</sub></b>	<b>3 \$/t<sub>CO2</sub></b>

# Bonus: Cross-sensitivity on PV, SOEC and NG costs



Competitive with NG-DRI-CCS  
CCA  $\approx$  50-100  $\$/t_{CO_2}$

# Conclusions

## Configurations net energy consumption

- NG-DRI: **9.4 GJ/t<sub>DRI</sub>**
- Thermally integrated SOEC-DRI: **8.1 GJ/t<sub>DRI</sub>**

## *How does this translate into costs and CO<sub>2</sub> emissions?*

### NG-DRI-CCS vs. NG-DRI

- CO<sub>2</sub> emissions reduced from 583 → **206 kg<sub>CO2</sub>/t<sub>DRI</sub> (-65%)**
- **Limited** cost increase: **+15-34 \$/t<sub>DRI</sub>**
- Cost of CO<sub>2</sub> avoided: **50-100 \$/t<sub>CO2</sub>**

### SOEC-DRI vs. NG-DRI-CCS

- Further CO<sub>2</sub> emissions reduction to **~185 kg<sub>CO2</sub>/t<sub>DRI</sub>**
- **Electricity cost** is the **main driver**, more than electrolyzer CAPEX/stack replacement
- **Short-term**: competitive with NG-DRI-CCS **only if NG ≥50 \$/MWh**
- **Long-term**: competitive at **natural gas prices ≥30 \$/MWh** and in **favorable locations** (e.g. Pilbara)



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# Thank for your attention

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