SOFC with CCS: The Optimal Path to Carbon-Free Electricity from Carbon-Based Fuels

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Clean energy
starts with Ceres

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Contents

1. Introduction

The transition to carbon-free electricity generation is a pressing global imperative. While renewable energy sources have gained significant traction, carbon-based fuels still (and will continue to) play a crucial role in the current energy landscape providing firm, reliable and low-cost electricity from natural gas and similar biofuels. To address this challenge, the integration of solid oxide fuel cell ("SOFC") technology with carbon capture and storage ("CCS") offers an effective pathway towards decarbonising electricity generation. In this whitepaper, we will explore why SOFC with CCS represents the lowest total cost approach to carbon-free electricity from carbon-based fuels.

2. Emerging global drivers and large markets for carbon capture

The need to curb greenhouse gas emissions has spurred the emergence of global drivers and large markets for carbon capture technologies. There are a number of mechanisms for valuing carbon capture, including the passing of the US Inflation Reduction Act ("IRA/Q45")[1] which directly calls for carbon capture technologies and explicitly values the carbon captured at an index linked USD$85/tonne. There are a number of emissions trading schemes around the world that have similar though more volatile pricing structures and, increasingly, carbon border adjustment mechanisms will apply to more goods and services, driving manufacturers to further lower the embedded carbon in their products to protect competitiveness. Such incentives and trading schemes aim to support the Net Zero Emissions 2050 Scenario (NZE), a pathway for the global energy sector to achieve net zero carbon dioxide ("CO_2") emissions by 2050. Figure 1 below highlights how large scale CO_2 capture projects compare against the NZE objective.

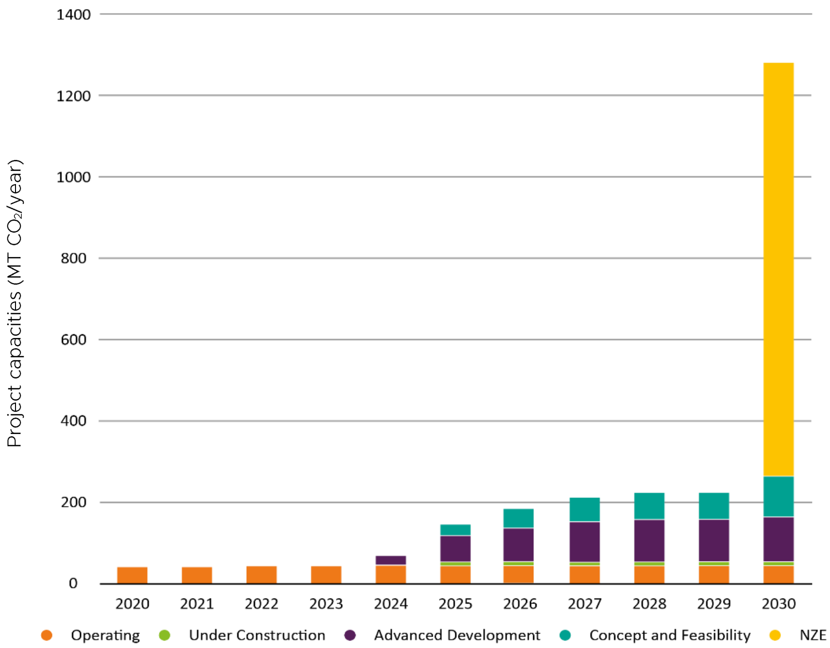

Figure 1: Capacity of large-scale CO_2 capture project capacities (MT CO_2/year), current and planned vs the Net Zero Scenario, 2020–2030 from IEA[2].

[1] IEA. (n.d.). Inflation Reduction Act 2022: Sec. 13104 Extension and Modification of Credit for Carbon Oxide Sequestration – Policies. [online] Available at: https://www.iea.org/policies/16255-inflation-reduction-act-2022-sec-13104-extension-and-modification-of-credit-for-carbon-oxide-sequestration.

[2] IEA. (n.d.). Capacity of current and planned large-scale CO2 capture projects vs. the Net Zero Scenario, 2020-2030 – Charts – Data & Statistics. [online] Available at: https://www.iea.org/data-and-statistics/charts/capacity-of-current-and-planned-large-scale-co2-capture-projects-vs-the-net-zero-scenario-2020-2030, Paris. Licence: CC BY 4.0.

Minimising the NZE gap shown in Figure 1 above and achieving net zero is critical to reducing emissions contributing to global warming, a key motivation to invest in carbon capture with high efficiency power generation solutions such as SOFC. Another way to think about the value of an SOFC system with CCS is to consider the net present value of revenue from the carbon trading schemes to be a "green premium", which could be applied to the upfront cost of the product compared to the cost of the baseline SOFC technology. Figure 2 below highlights the product premium opportunity for both the Q45 and EU trading incentives. With a fixed carbon capture incentive, the Q45 would offer a reliable premium. Conversely, the EU scheme would fluctuate based on current pricing structure but could offer significantly higher returns.

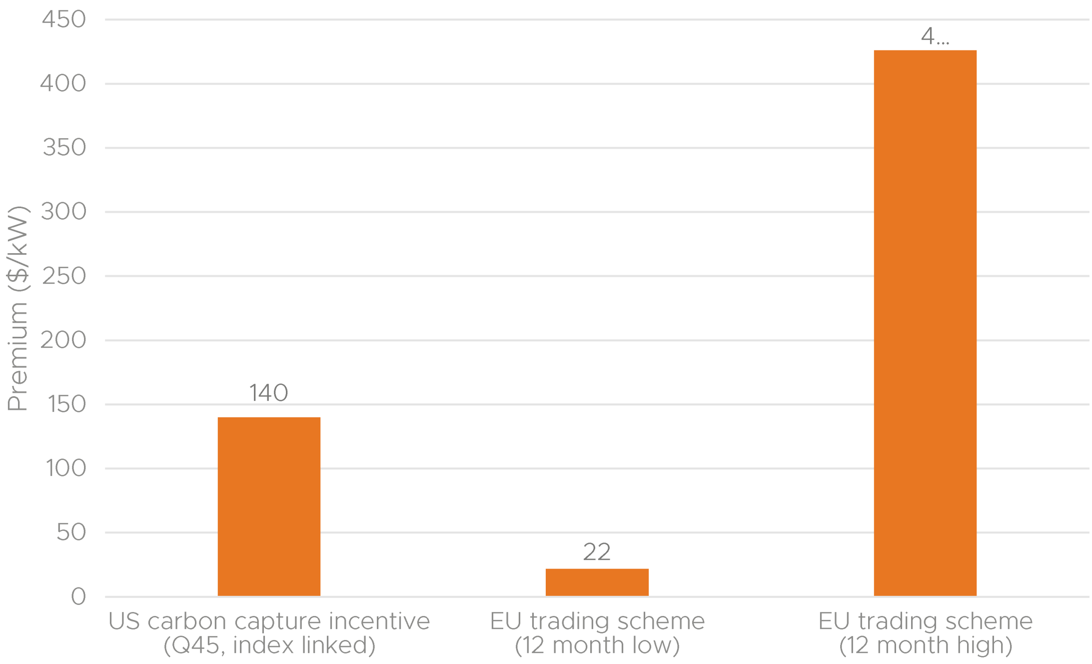

Figure 2: Premium ($/kW) for Q45 and EU trading incentives.

3. *Application of commercially available mature CCS technology*

The key requirement for any effective CCS technology is to produce a relatively pure stream of CO_2 at an acceptable cost. The following table outlines a range of mature and emerging carbon capture solutions that are applicable for integration with SOFC technology.

Technology	Tech maturity	Feed pressure	Min. feed CO_2 conc.	CO_2 purity	Effectiveness	Applicability to SOFC
Absorption (Chemical/physical)	Commercially deployed at scale	Atm (chemical)/ 30 bar (physical)	10–20 mol%	95–99%	85–95%	High for chemical absorption
Adsorption (Temperature/ pressure/vacuum swing)	In commercial demonstration	Atm/low/ 60 bar	>20 mol%	90–95%	85–95%	High-medium for temperature swing
Cryogenic (Distillation/ solid separation)	Under development	Atm	>40 mol%	>99%	95–99%	Solid separation is promising future tech due to low energy requirements
Membrane	Under development	20–60 bar	>20 mol%	95%	90–95%	Low due to feed pressure requirements
Advanced combustion (Oxy-fuel/chemical looping)	Under development	Atm	0	>95% (dry)	>95%	Chemical looping is promising future tech. Ability to replace off-gas oxidation

Table 1: Comparison of carbon capture solutions.

4. *The physics of CCS are simply better with SOFC*

The unique characteristics of SOFC technology enable the physics behind efficient CCS. The fundamental difference in approach with SOFC leads to a lower cost carbon capture solution for the following reasons:

1. OPEX – most CO_2 capture technologies work by having two steps – capture and release. The energy, and associated cost, penalty for capturing and recovering the CO_2 is lower if the stream is more concentrated.
2. OPEX – less CO_2 is produced per unit of electricity so less cost is associated with the capture step.
3. CAPEX – because the streams of exhaust gases produced are much smaller (by around half), the capture system capital cost is reduced through smaller pipes and other components.

Fuel cells are a highly efficient converter of fuel to power. There is an immediate carbon capture cost benefit from the efficiency advantage of SOFC – less CO_2 produced per unit of useful electricity – between 45% and 75% depending on the comparative technology such as traditional coal power plants and gas turbines, highlighted in Figure 3 below.

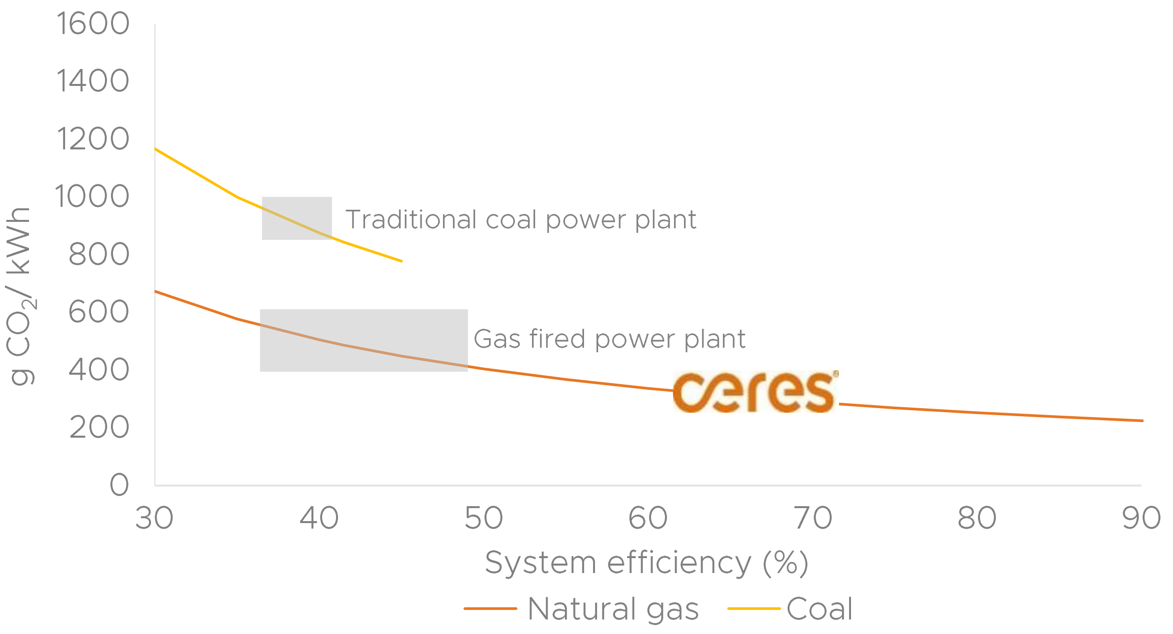

Figure 3: Carbon Intensity comparison of different carbon based fuels and power production technologies.

Beyond efficiency alone, there is a more fundamental difference – CO_2 is more concentrated at the point it is available for capture. This makes the separation process more cost effective for a number of reasons. In a fuel cell there are two steps to the reaction. First, oxygen is removed from the bulk air stream and passed through the conductive ceramic membrane. Second, this oxygen reacts with incoming fuel to produce CO_2 and water. Compare this to a typical combustion process where fuel is added to the air with nitrogen diluting the combustion product, summarised by the diagram in Figure 4 below.

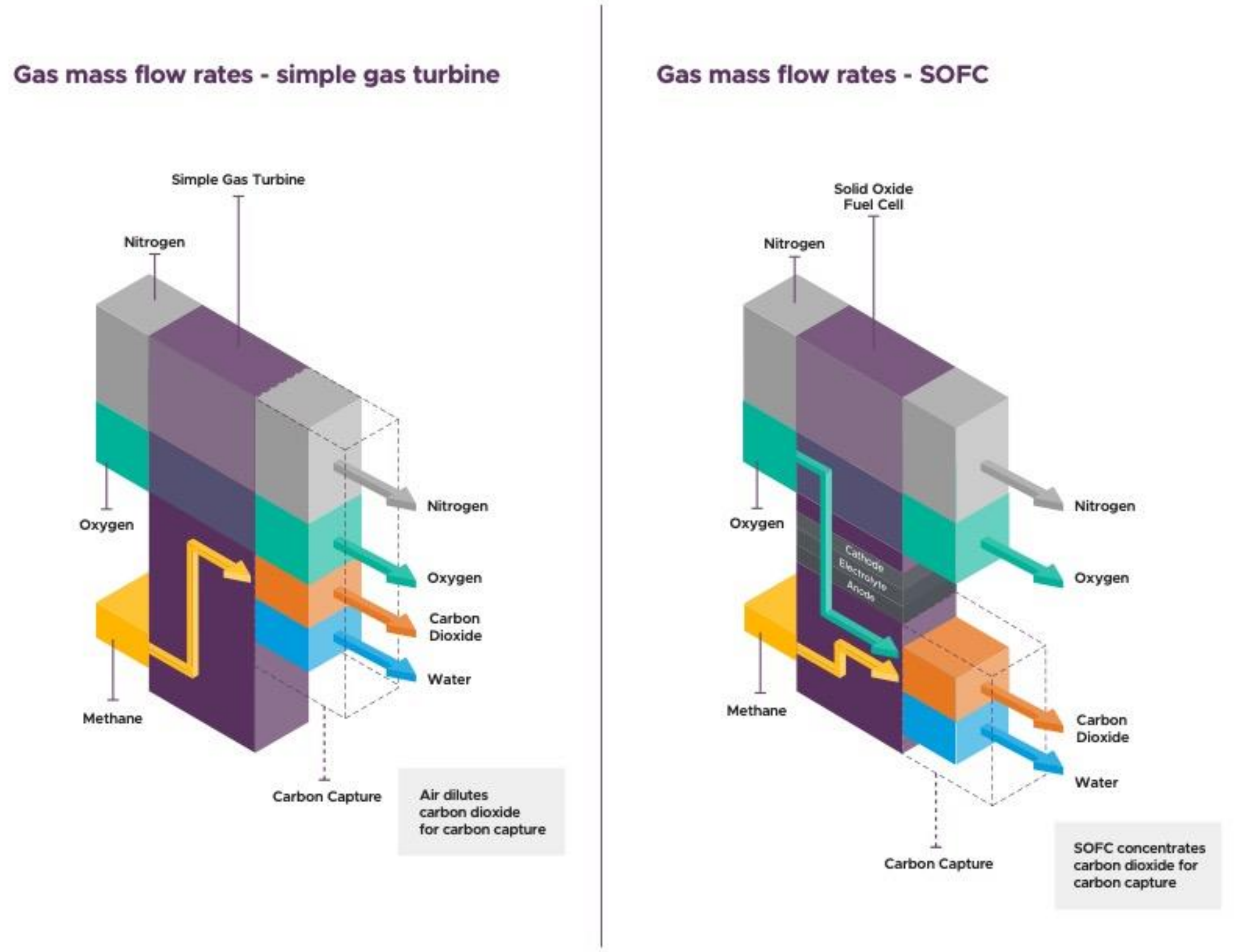

Figure 4: Visualisation of how typical combustion technologies (left image) dilute the CO_2 produced with air whilst SOFC concentrates (right image) through oxygen separation.

This dilution of the CO_2 in traditional power generation leads to a doubling of the energy required to capture the CO_2 compared to SOFC, highlighted in Figure 5 below.

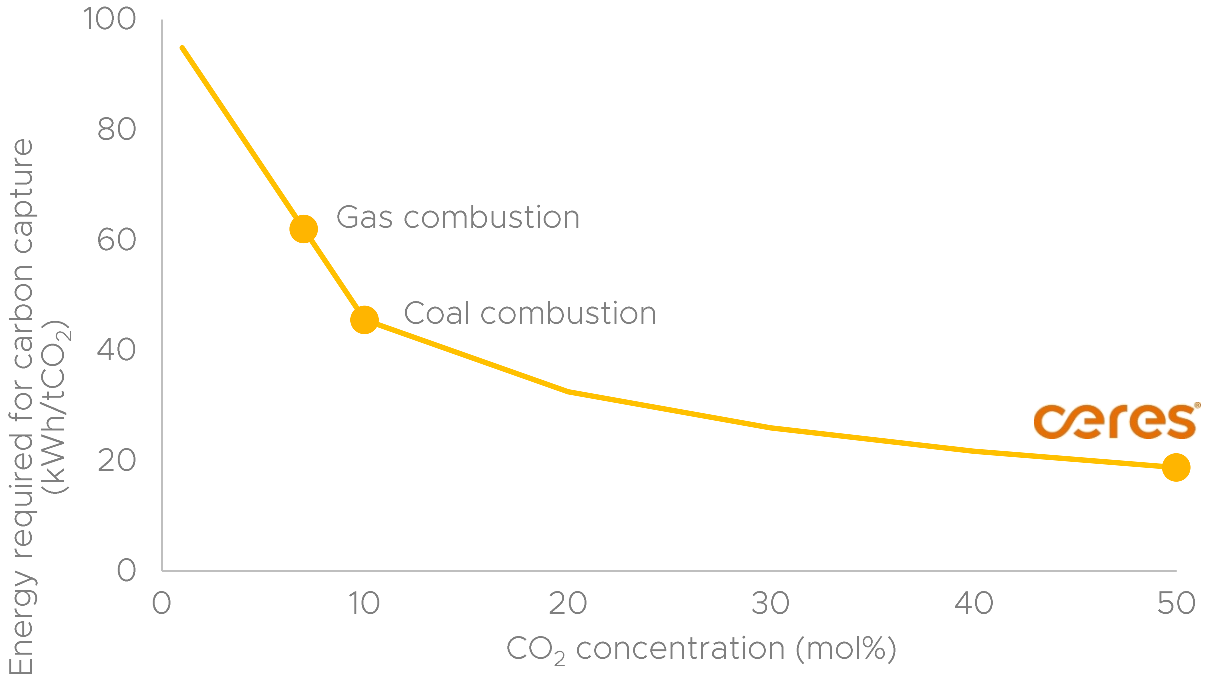

Figure 5: Energy consumption requirement to capture CO_2 at different flue gas concentrations.

5. *Efficiency and lower CO_2 emissions: advantages of SOFC with CCS*

The integration of SOFC with CCS not only facilitates carbon capture but also leads to higher overall efficiency and lower CO_2 emissions, for example through a reduction in primary energy consumption. Due to the concentration of CO_2 in the flue gas, the capture process becomes more efficient, resulting in a lower levelised cost of electricity ("LCOE") compared to traditional carbon-based power generation technologies. Figure 6 below illustrates how efficient carbon capture and tax incentives create cost competitive SOFC systems when coupled with CCS, reducing the LCOE beyond that without carbon capture.

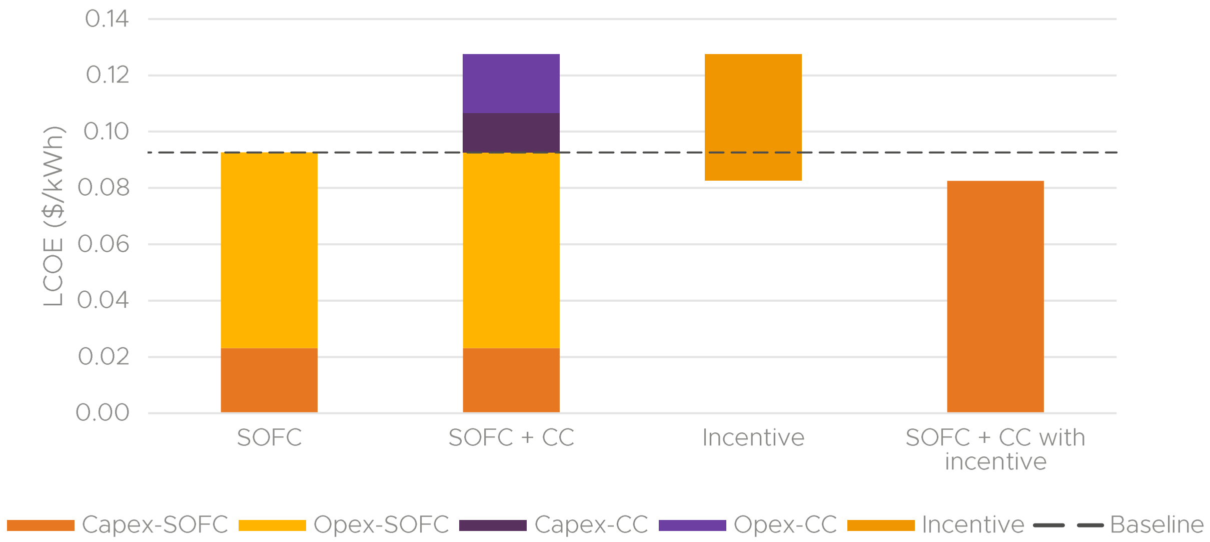

Figure 6: LCOE for SOFC without and with carbon capture assuming IRA tax credits for a 30 MW SOFC system, generating a premium compared to no carbon capture.

6. Conclusion: advancing SOFC with CCS technology

Ceres, a leader in energy innovation, offers a compelling technology solution that combines SOFC with CCS. Its system seamlessly integrates with commercially available carbon capture solution necessary for efficient carbon capture and storage, enabling clean and reliable electricity generation, and in the case of biofuels, a carbon negative solution.

As the world strives to achieve a carbon-free future, SOFC with CCS emerges as the most cost-effective approach to generating carbon-free electricity from carbon-based fuels. The integration of mature CCS technology with the unique properties of SOFC enables efficient carbon capture, leading to lower emissions and reduced costs. With emerging global drivers and substantial markets for carbon capture, the time is ripe to leverage the potential of SOFC with CCS to pave the way for a sustainable energy transition. Companies like Ceres are at the forefront of this innovation, offering advanced technology solutions that hold immense promise for a cleaner and greener future.

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