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Carbon capture and storage: where from and where to?

A paper by Kelly (Kailai) Thambimuthu, titled as referenced above, was published in the Progress in Energy Journal in April 2024. This paper examined the subtleties of addressing climate change by highlighting the need to maintain a clear perspective on the implications of our technological choices. Kelly warned that it is critical to remain aware of a significant overarching issue: the push for worldwide deployment of renewable energy technologies will inevitably lead to a significant reduction in the conversion efficiencies of global energy systems.

The dynamic between the scale of a plant and its energy conversion efficiency is crucial when considering the deployment of clean energy technologies like photovoltaic solar and wind. These technologies, while beneficial in reducing carbon emissions, often require significantly larger areas to deliver the same energy output (MWh) as a plant with high conversion efficiency. The paper underscores the importance of considering both the technological capabilities and the practical implications of large-scale implementation, including the spatial and resource demands of energy projects. Such considerations are essential to ensure that the transition to low-carbon energy does not inadvertently lead to new environmental or logistical issues, thereby complicating the path to achieving net zero emissions.

Kelly's paper opens by highlighting the humble beginnings of carbon capture and storage (CCS), a response to seminal events in the 1980s and early 1990s. By the end of 2023, a global stocktake of projects reported 41 fully operational CCS facilities removing a total of 49 million tonnes per annum of CO_2 across a diverse range of sectors, including cement, steel, hydrogen, and power generation.

The future direction for CCS is intricately linked to achieving net-zero greenhouse gas (GHG) emissions, as outlined in projections developed by integrated assessment models (IAMs). In IAMs, CCS is frequently modelled with a CO_2 capture rate of 90% for direct emissions from plants, although there is no legitimate justification for this standard. The 2019 IEAGHG study led by Paul Feron at CSIRO[1] demonstrates that CO_2 capture rates can reach up to 99.7% through specific plant designs or by co-firing with sustainable biomass. These enhancements can effectively render direct emissions from plants like ultra-supercritical pulverized coal-fired CCS plants (USC PCC-CCS) and natural gas combined cycle plants with CCS (NGCC-CCS) CO_2 neutral relative to the incoming combustion air. While increasing CO_2 capture rates to near-total levels significantly reduces emissions, it does come with cost implications that appear to be marginal.

Despite these cost increases, such enhancements in CO_2 capture efficiency offer a substantial benefit by aligning more closely with the goals of achieving net-zero emissions by 2050 and reducing reliance on Carbon Dioxide Removal (CDR) methods like Direct Air Carbon Capture and Storage (DACCS) that are much more energy intensive compared to CO2 removal from biomass or fossil-fuelled process streams. Ultimately, this approach supports a strategy of emission prevention, potentially making CDR methods like BECCS more cost-competitive if needed later. This is a critical area for further evaluation as sustainable climate strategies in terms of land and other resource use continue to evolve.

The perception that CCS is prohibitively costly has significantly hindered its deployment, largely due to misunderstandings about the true nature of its costs. An accurate cost assessment for CCS at a project level highly depends on specific factors, such as plant location and the logistical requirements of the plant's operations. This includes the direct operational costs and infrastructure for fuel and feedstock delivery, waste removal and treatment, CO_2 compression and delivery at pressures suitable

[1] Towards zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass, IEAGHG Technical Report 2019-02, March 2019.

for transportation, and energy export especially in remote locations. These factors contribute to the levelized cost of electricity (LCOE).

To ensure a fair comparison across different energy technologies, it is crucial that all options, including wind and solar, are assessed under comparable boundary parameters. This includes accounting for the additional capacity needed to achieve the same MWh output when energy conversion efficiencies are lower, energy storage to compensate for intermittent operations, and the necessary transmission lines. Additionally, the assessment should include unique requirements such as monitoring, compliance, and decommissioning costs, especially for nuclear power projects.

The IEA has introduced the concept of VALCOE (Value-Adjusted Levelized Cost of Electricity) to better reflect the true costs and benefits of different generation technologies. VALCOE considers not just LCOE but also the value of energy, capacity, and flexibility values of generation technology. For CCS-equipped plants, VALCOE can be significantly lower than LCOE, demonstrating the economic feasibility of CCS. This raises the question of whether the assumptions regarding the cost and performance of energy technologies used in IAMs are robust enough and truly reflect a level playing field.

What are the impacts of deploying low-carbon energy technologies to meet the net zero targets? To decipher this, Kelly employed a plot of fractional time averaged efficiency (a product of primary energy conversion to electricity and plant operation time) versus a scale factor representing the size of the plant required for electricity generation.

The findings affirm that for a plant to operate continuously at 100% time-averaged efficiency to produce a fixed quantum of electricity in MWh, an energy technology operating at a time-averaged efficiency of 50% due to suboptimal primary energy conversion efficiency and/or mandated downtime would require a plant with twice the capacity (MW) to deliver the same quantum of electrical output (MWh) to the grid. Further, if a plant with 50% primary energy conversion efficiency could only operate 50% of the time due to intermittent supply of primary energy or fuel, a plant four times larger in capacity (MW) would be necessary to produce the same amount of electricity in MWh. This contextualises the issues relating to the scale of operation of much-touted renewables like solar PV and wind energy that apply to both electricity and hydrogen production using these energy forms.

CCS-abated energy systems, biomass, hydro and nuclear seem to be the best placed, lowest in deployed scale and most energy efficient options, followed by wind (when at near peak capacity factors). The influence of average plant efficiencies on the required plant scale is markedly more pronounced for hydrogen production, particularly from nuclear and various renewable energy sources, although this is not the case for biomass. For biomass, coal, and natural gas with CCS, the scaling factors necessary for plant output are considerably smaller than those needed for equivalent electricity generation plants. These variances stem from the specific sources and methods of hydrogen production.

In conclusion, the land or aerial footprint of energy plants correlates with the plant scale factor or size. Plants that harness dispersed energy sources like solar, wind, hydro (water reservoirs), and biomass (areas for sustainable growth) require significantly more surface area compared to those using denser energy sources such as nuclear or fossil fuels. Nuclear and fossil fuel plants are more energy efficient, which further reduces their required physical footprint. Conversely, plants equipped with CCS see an increase in net surface coverage due to the additional infrastructure needed for CO_2 capture, transport, and storage.

Kelly’s closing statement was ‘unless we deploy a diverse portfolio of primary energy resources that include CCS (where required) which address efficiency and cost, climate, energy security and broader sustainable development goals, we are doomed to stumble into yet another unintended existential threat!’

IEAGHG is currently conducting a study aimed at analysing the impact of net energy conversion efficiencies, costs, and scale of deployment of net-zero energy technologies producing 10 TWh of electricity or the equivalent in hydrogen. Expected to yield comprehensive insights, this study will systematically examine and document the intricate relationships and trade-offs between efficiency, cost, and scalability within the framework of sustainable energy production. The findings are anticipated to contribute significantly to the strategic planning of future energy systems, and they will provide valuable technical insights for policymakers and industry leaders aiming to optimize the balance between energy sustainability and technical pragmatism.

The paper 'Carbon capture and storage: where from and where to?' can be accessed via the link provided below.

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