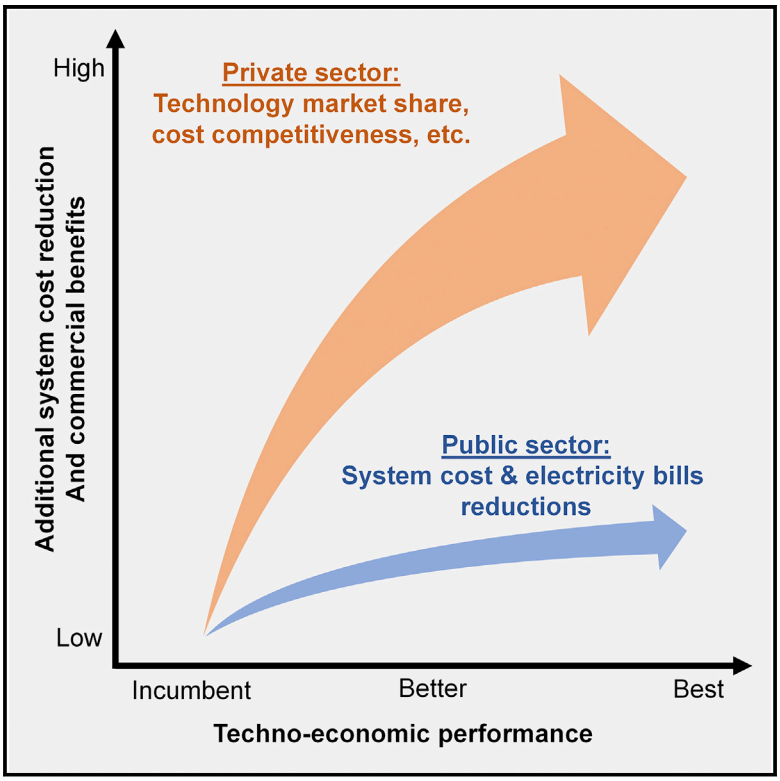
One Earth

Article

Carbon capture and storage investment: Fiddling while the planet burns

Graphical abstract



Highlights

- Public funding to support CCS has been primarily spent on the technology RD&D
- Values of existing and advanced CCS in electricity systems are comparable
- CCS improvements are commercially beneficial for private sectors
- Public spending should focus on efforts to accelerate CCS commercialization

Authors

Yoga Wienda Pratama,
Niall Mac Dowell

Correspondence

niall@imperial.ac.uk

In brief

Carbon capture and storage (CCS) can provide value to the public by significantly reducing the cost of electricity systems decarbonization. However, owing to the perceived high cost of technology, CCS deployment at scale has been hindered, and public resources have been mainly spent on technology improvements. Here, we use an electricity systems optimization model to show that the public sector needs to refocus its efforts to accelerate commercialization of CCS to encourage the private sector to continue technology improvements.

Pratama & Mac Dowell, 2022, One Earth 5, 434–442
April 15, 2022 © 2022 Elsevier Inc.
https://doi.org/10.1016/j.oneear.2022.03.008

CellPress

CellPress

One Earth

Article

Carbon capture and storage investment: Fiddling while the planet burns

Yoga Wienda Pratama[1,2] and Niall Mac Dowell[1,2,3,*]
[1]Centre for Environmental Policy, Imperial College London, London SW7 1NE, UK
[2]Centre for Process Systems Engineering, Imperial College London, London SW7 2AZ, UK
[3]Lead contact
*Correspondence: niall@imperial.ac.uk
https://doi.org/10.1016/j.oneear.2022.03.008

SCIENCE FOR SOCIETY Despite the recognized value of carbon capture and storage (CCS) to the net-zero transition, cost reduction of CCS technology continues to be seen as a prerequisite to its deployment at scale. Thus, governmental support has been limited to research, development, and demonstration (RD&D), and this has essentially prohibited investment in CO_2 transport and storage (T&S) infrastructure, which is critical to CCS commercial deployment. While reduced cost is *prima facie* desirable, the extent to which this is material at the system level remains opaque. In this work, we quantify the value of CCS RD&D in the electricity systems from public and private perspectives in different national contexts. We found that existing CCS technologies are already cost-effective to provide substantial value at the system level and that technology improvements are primarily beneficial for private sectors. Thus, public spending should focus on CO_2 T&S infrastructure deployment to accelerate CCS commercialization.

SUMMARY

Carbon capture and storage (CCS) has been recognized as a key technology in energy systems decarbonization. However, numerous attempts to deploy CCS failed, and the technology is still viewed as pre-commercial. Consequently, public investment in CCS has been largely limited to research, development, and demonstration (RD&D) in capture technology. While it is understood that private investment will typically focus on the development of intellectual property aimed at delivering a commercial advantage, there is a lack of evidence that public investment in CCS RD&D can deliver commercial viability. Here, we show that, while improved CCS technology in the electricity systems will deliver larger market shares to the technology developers, the benefit on overall system cost is negligible. Thus, public sector efforts should focus primarily on overcoming commercialization failures, such as the absence of CO_2 transport and storage infrastructures and other deployment barriers, leaving the development of intellectual property to the private sector.

INTRODUCTION

In 2004, Pacala and Socolow proposed that technologies required for climate change mitigation are currently available.[1] Since then, there has been an increasing appreciation of the value of carbon capture and storage (CCS) in delivering affordable and reliable decarbonization of the economy. While there is abundant evidence, such as that of the Intergovernmental Panel on Climate Change (IPCC),[2] showing that decarbonization without CCS will be uncertain and far more costly, support for the deployment of CCS at scale has been inconsistent.[3,4] One of the key rationales for this hesitation is the perceived high cost of CCS technology, leading to a preferential focus of public funding on research, development, and demonstration (RD&D) as opposed to deployment.[3–5] As a result, the majority of CCS plants currently in operation are used for gas processing or enhanced oil recovery.[4,6] In contrast, CCS applications for industrial and electricity sectors are very limited, in which the latter is understood to be critical to enable decarbonization for other sectors via electrification.

Although support for CCS has been, once again, increasing since the Paris Agreement,[3,4] the preoccupation with technology cost reduction persists.[7,8] To illustrate, most countries that extensively mentioned CCS as a key for their net-zero strategies ahead and after the COP26 in Glasgow also emphasized the need to improve CCS techno-economic performance for large-scale deployment.[9–15] Consequently, the drive to find a "unicorn" CCS technology—that is a CCS technology with very low capital cost and high efficiency and flexibility—continues, funded by not only the private sector but also governments

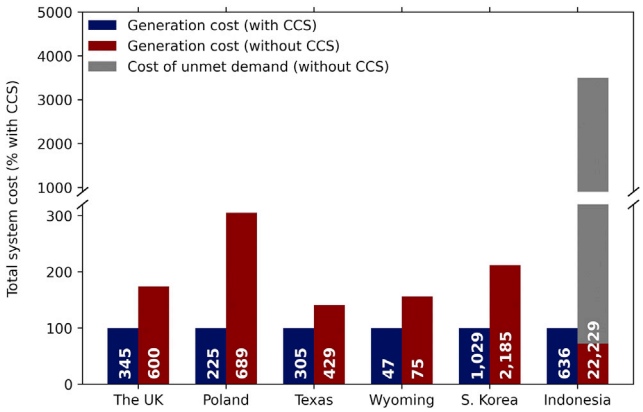


Figure 1. Total system costs of net-zero emissions systems in the United Kingdom, Poland, Texas, Wyoming, South Korea, and Indonesia

Data labels inside bars show total system costs in billion £. Total system cost in this study includes generation cost and cost of unmet demand. Here we observe that, regardless of national context, the exclusion of CCS as a technology is observed to significantly increase the costs of achieving a net-zero emissions paradigm, with the magnitude of the value proposition varying by the grid. Without CCS, total system cost in Indonesia is 35 times the cost with CCS due to the value of lost load not meeting 80% of the demand in 2050.

through public funding for CCS RD&D. It has been estimated that, from 2010 to 2019, the US, UK, and EEA governments have invested approximately £3.8 billion in CCS RD&D,[16,17] with the global total estimated at £6.2 billion.[18] For context, the global public RD&D budget for renewable energy between 2010 and 2020 was approximately £32 billion.[19] Importantly, while the impact of the government's investment on CCS infrastructure is understood to be critical in enabling the commercialization of CCS,[20] the extent to which this has been achieved to date is minimal. Therefore, given the limited public budget for additional spending of any kind, particularly at the time of writing, it is imperative that there is a clear understanding of where the investment of public money in CCS will deliver the greatest value: ought this be in improved capture technologies or in the deployment of transport and storage (T&S) infrastructure?

In the context of CCS RD&D, the value of techno-economic improvement is primarily investigated at the technology level[21–25] to illustrate its impact on CCS competitiveness against other technologies. Thus, CCS innovations are consistently portrayed as being critical to deployment. However, there is a distinct lack of discussions on the value of CCS innovations from the whole system perspective. In 2012, Lohwasser and Madlener showed that capital cost reduction and efficiency improvement not only increases the deployment of CCS but also significantly reduces the system cost in Europe by up to 35%.[26] In agreement with Lohwasser and Madlener's work, Heuberger and Mac Dowell[27] also showed that cheaper technology with higher flexibility and efficiency can reduce the UK's system cost by approximately 20%. However, these studies were performed based on an assumption that emissions reduction alone would be sufficient to stabilize the global average temperature, in which the role and capacity uptake of the technology might be substantially different. From the RD&D perspective, developing a unicorn CCS technology remains a challenging task, given that the features of such a technology may be region specific, depending on the unique characteristics and challenges of a given national context. For example, the interplay between the value propositions of reduced capital costs, improved efficiency, fuel price volatility, flexibility, demand patterns and projections, and the abundance of renewable energy remains complex and opaque. Together, there is a lack of evidence as to the significance of benefits the public may gain from further investment in CCS RD&D.

Here, we aimed to address this knowledge gap by developing an electricity systems optimization model to quantify the potential value of disruptive CCS technology in the net-zero transitions of the power sector from the technological and systems points of view. Moreover, we also aimed to provide insight as to whom CCS RD&D benefit accrues and, if any, on which element of the technology the efforts should be focused. In this study, we used the United Kingdom, Poland, Texas, Wyoming, South Korea, and Indonesia as case studies to take into account the impact of different system characteristics on CCS RD&D's value and priorities. Our findings show that improvements in CCS technologies can significantly increase market share of CCS and allow CCS to catch a broader range of demand levels in the systems, which are therefore significantly valuable for the private sector that develops and utilizes the technology to generate more revenue. However, improved CCS technologies cannot significantly reduce system costs further than that an incumbent CCS technology can deliver to the system. The evidence we presented here suggests that the public sector needs to reallocate its resources for efforts to accelerate commercialization of CCS, such as deployment of CO_2 T&S infrastructure to de-risk private sector's investment in CCS deployment, which, in turn, encourages the private sector to continue its RD&D efforts to advance CCS technology.

RESULTS AND DISCUSSION

Competitiveness of novel technologies against incumbent options

Similar to the IPCC,[2] we find that CCS provides substantial value for energy system transitions across a wide range of system characteristics. As may be observed from Figure 1, total system costs of systems without CCS are consistently more expensive than those where CCS technology is available, with total system costs, in the United Kingdom, Poland, Texas, Wyoming, and South Korea, increasing by between 40% and 200%. For example, owing to the considerable potential of renewable energy and existing nuclear capacity, decarbonizing the Texas power system without CCS is observed to be more than 40% more costly relative to the scenario where CCS is available. In contrast, the costs of transitioning the Polish electricity system to a net-zero paradigm without CCS are found to be around 200% more costly than in the counterfactual; the challenges associated with decarbonizing the Polish energy system have been observed previously and are discussed extensively elsewhere.[28] In other contexts, such as Indonesia, the challenge is in meeting both expectations of rapid growth in electricity demand, owing to economic growth and development, and also deep decarbonization. As illustrated below, despite the assumption of a consistently supportive energy policy environment, a

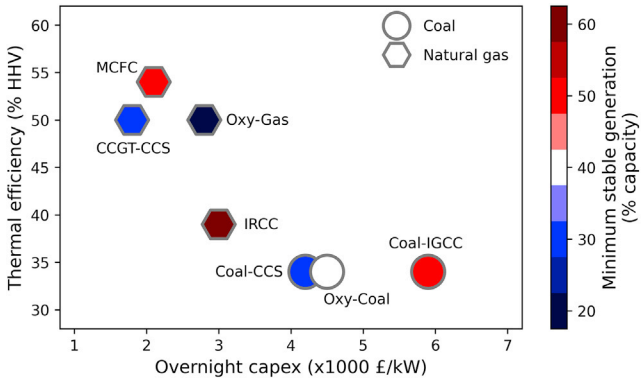


Figure 2. Key techno-economic parameters of various CCS technologies

Technologies presented here provide comprehensive coverage of the existing and emerging portfolio of CCS technologies. It can be observed that they span an appreciable range of techno-economic features,[29–36] namely capital costs, thermal efficiencies, and flexibilities (characterized by the minimum stable generation parameter).

very substantial quantity of power demand may well go unserved, leading to substantial costs in the form of unmet demand. Thus, the key point of this analysis is that, while CCS appears to have a consistently positive value proposition, the magnitude of this value and the specific services expected on the technology will vary according to the national context.

At the time of writing, CCS remains commercially immature, with a predominant focus on technology development. There is currently a plethora of alternative technology concepts in the R&D stage. They can broadly be considered to fall into liquid solvent-, solid sorbent-, membrane-, cryogenic-, or hybrid-based approaches. Strictly speaking, the market remains too nascent to identify an incumbent technology. However, solvent-based post-combustion capture technologies generally seem to be a preferred benchmark in most analyses, with commercial offerings from several vendors, e.g., Shell, MHI, GE, and so forth. Thus combined cycle gas turbine with post-combustion CCS (CCGT-CCS) is identified as an incumbent option, with some key emerging technology options being projected in terms of their capital cost, HHV efficiency, and minimum stable generation, including (1) CCGT with molten carbonate fuel cell with post-combustion CCS (MCFC), (2) oxy-fired supercritical gas power generation, often referred to as the Allam cycle (Oxy-Gas), (3) integrated reforming combined cycle gas power plant with pre-combustion CCS (IRCC), (4) coal with post-combustion CCS (Coal-CCS), (5) coal with oxy-combustion CCS (Oxy-Coal), and (6) coal integrated gasification combined cycle with pre-combustion CCS (Coal-IGCC),[29–36] as shown in Figure 2.

It is therefore instructive to consider how these various alternative technology options compare in terms of deployment and cost reduction when made available in each area, i.e., the United Kingdom, Poland, Texas, Wyoming, South Korea, and Indonesia. In performing these calculations, Electricity Systems Optimization (ESO) was used to identify the cost-optimal transition to a 2050 net-zero emissions paradigm for each electricity system. For each grid, a given unicorn technology was made available with a capital cost (£/kW) and HHV efficiency in the range of 0–10,000 £/kW and 30%–80%$_{HHV}$, respectively, in order to fully bind the feasible operating envelope. Here, techno-economic performance of the unicorn technology is assumed constant at the time the technology is made available in the system. The results of this investigation are presented in Figure 3.

From this figure, a number of conclusions emerge. First, it would appear that it is very difficult, if not impossible, for a new CCS technology to improve to an extent sufficient to make a material and definitive difference to the total system costs, regardless of national context.

Second, it would appear that the incumbent technology—CCGT with post-combustion CCS—is, in all cases, very tough to beat, although the MCFC option is close. In term of efficiency, the MCFC has a 4%$_{HHV}$ efficiency advantage over CCGT-CCS. However, this efficiency gain comes at the cost of an increased capital intensity; a difference of approximately £300/kW. Consequently, the advantage of a higher efficiency over CCGT-CCS is outweighed by the increased capital cost. Similarly, while the efficiency of Oxy-Gas is comparable with that of CCGT-CCS and MCFC, the capital cost needs to be further reduced to be competitive against the two technologies. In contrast, with an efficiency of only ~37%, IRCC-CCS is greatly disadvantaged against other gas-based CCS technologies, particularly in a country with relatively expensive natural gas prices such as Poland.

Finally, the competing roles of coal and gas CCS technologies are drawn out. Although the capital intensity on a £/kW basis of coal-based CCS is greater than that of CCGT options, the fuel is generally cheaper. Accordingly, the comparison with their natural gas-based counterparts is carried out using 2050's variable cost-adjusted efficiencies to consider the benefit of the cheaper fuel cost of coal. In this study, we define variable cost-adjusted efficiency as thermal efficiency the incumbent technology needs to have so that its variable cost matches the cost of coal-based CCS technologies. This adjustment accounts for variable, OPEX, fuel, and CO_2 T&S costs, but it excludes the total system cost increase for CO_2 removal expenses through negative emissions technology. As illustrated in Figure 3, even after the efficiencies are adjusted, the techno-economic performance of coal-based technologies in the United Kingdom, Texas, Wyoming, and Indonesia is behind that of CCGT-CCS, MCFC, and Oxy-Gas. However, it is important to note that this analysis has been performed on a least-cost basis, i.e., we are minimizing the cost of electricity generation. This does not consider the impact of policy instruments, such as a CO_2 price, e.g., the UK and EU ETS, which will further privilege gas over coal, or payment for CO_2 sequestration, e.g., the 45Q tax credit in the United States.

Ultimately, if a unicorn CCS with overnight Capex as low as unabated CCGT and efficiency equal to oxy-CCS theoretical limit[37] is available, the total system cost (TSC) will decrease by only 3%–9%, which, given the uncertainty inherent in this kind of analysis, is negligible, thus emphasizing the importance of expediting the deployment of incumbent CCS technologies.[2,38]

System value of disruptive innovations

Based on the foregoing discussion, it appears that there is a limited public value, i.e., reduction in TSC, associated with the development of new CCS technologies. Does that, then, imply

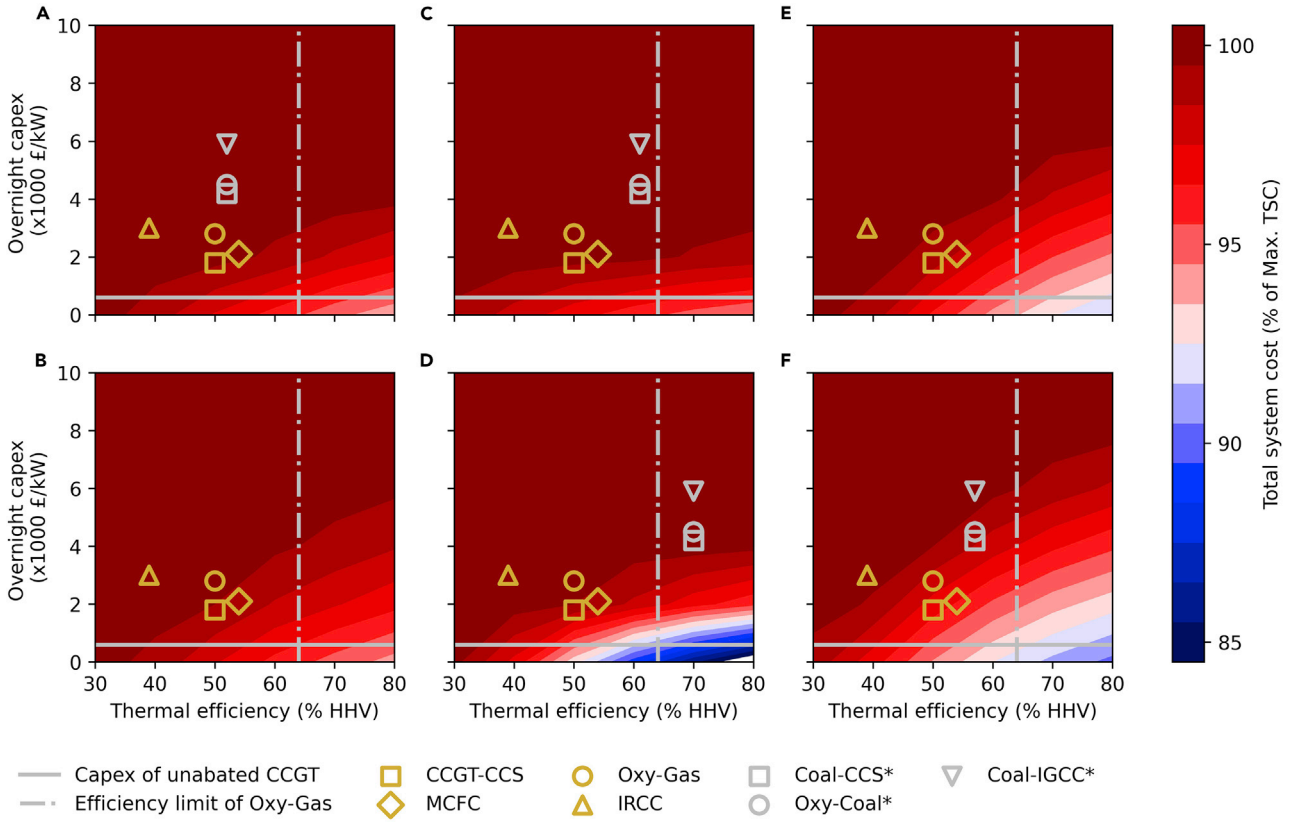


Figure 3. Techno-economic characteristics comparison between novel and incumbent technologies and their potential values for the systems

(A–F) Values of incumbent and novel technologies under development in (A) the United Kingdom, (B) Poland, (C) Texas, (D) Wyoming, (E) South Korea, and (F) Indonesia are compared with the values of unicorns under different levels of capital cost and efficiency. As can be seen, incumbent technology is ahead of other technologies in terms of techno-economic performance. Other technologies that might compete include MCFC and Oxy-Gas. This figure also illustrates that even for unicorn as cheap as unabated CCGT with an efficiency of equal to the maximum theoretical efficiency of an abated CCGT,[37] the system value of the technology is limited. In this figure, efficiencies of coal-based technologies are variable cost adjusted based on efficiencies needed by CCGT-CCS to match coal's variable costs. Accordingly, the adjusted efficiencies of coal-based technologies in countries with cheap coal and expensive gas, such as Poland and South Korea, appear to be very high (i.e., significantly greater than 80%) so are not included in the plot.

that there is no value at all in the development of improved technologies? And if there is, to whom does this value accrue? To address these questions, we now pivot from the public perspective to that of the private sector and consider the extent to which disruptive CCS technologies might be deployed.

As can be observed from Figure 4, our defined maximum technological improvements, i.e., CCS with a capital cost of unabated CCGT and efficiency of CCGT-CCS' theoretical limit, can deliver between 25% and 35% of grid capacity in the United Kingdom, Poland, Texas, South Korea, and Indonesia, and as much as 64% in Wyoming. Thus, even though technology improvements have a minimal effect on TSCs, the potential to capture a material market share is significant, thus emphasizing the importance of continuing the private development of new intellectual property in this area.

At this point, the importance of grid-specific characteristics becomes evident. For example, regions with highly seasonal load profiles and abundant renewable energy resources, such as the United Kingdom and Texas, inherently require different dispatch patterns to meet demand at different points in time, e.g., baseload, load following, and peak load capacity. In these grid archetypes, reducing capital cost and increasing flexibility of all this technology to capture the greatest portion of the market are beneficial. Conversely, grids like Wyoming, which have a flat load profile and relatively limited natural endowment of renewable energy, favor improved efficiency and obviously reduced capital cost. Thus, as the electricity grid evolves, the importance of reducing capital cost is ubiquitous, but there is a trade-off between the value of efficiency improvements and that of increased flexibility.

Market share of the unicorn technology

The impact of flexibility on the competitiveness of unicorn is minor compared to that of cost reduction and efficiency improvement. As seen in Figure 5, the impact of improving flexibility by reducing the minimum stable generation from 70% to 20% is generally marginal, but in cases when the values of unicorn and incumbent are critical, it can increase the share of the unicorn in total CCS capacity by up to 42%. In contrast, a marginal reduction in capital cost and increase in efficiency can greatly

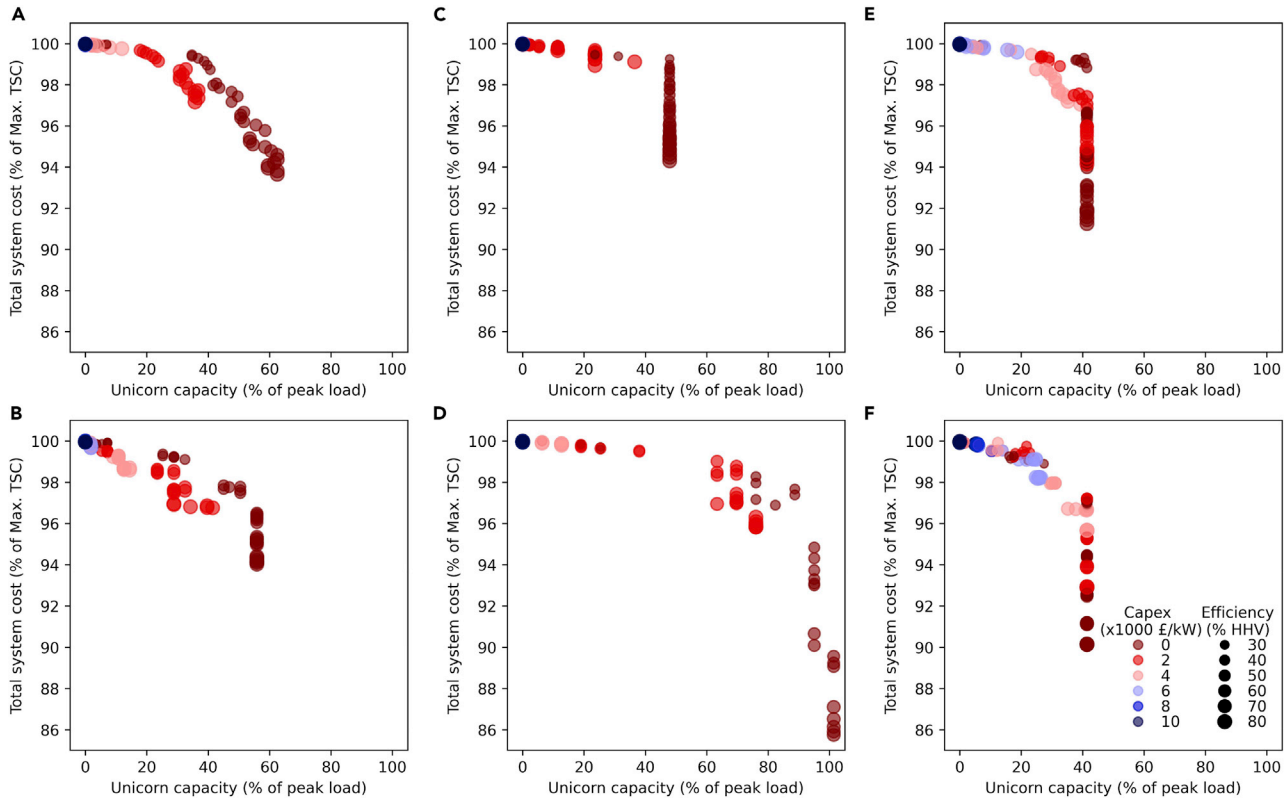


Figure 4. The impacts of unicorn's techno-economic characteristics on total system cost and the capacity of the unicorn

(A–F) The figure shows impacts of unicorn's techno-economic characteristics on total system cost and the capacity of the unicorn in (A) the United Kingdom, (B) Poland, (C) Texas, (D) Wyoming, (E) South Korea, and (F) Indonesia. As can be seen, capital cost and efficiency may have a significant impact on the competitiveness of unicorns in the system. However, the value of such techno-economic advantages to the total system cost tends to be limited.

affect the share of CCS in the systems. Accordingly, while it is understood that flexibility adds value to the technology, compromising the cost or efficiency to improve the feature is consistently disadvantageous in all cases.

These results show that a marginal techno-economic advantage of the unicorn over the incumbent technology can greatly improve its competitiveness in a given market. Interestingly, the results for Indonesia show that CCS technology with inferior efficiency and technology cost compared to the incumbent can gain a sizable market share in the system; this shows that increasing the deployment of low carbon firm capacity technologies is more valuable than chasing unicorn technologies if a system with rapidly increasing demand is to meet the net-zero target.

Although the insights are market-specific, *ceteris paribus*, any reduction in capital cost leads to an increase in market share. Using the United Kingdom as an example, a capital cost reduction of £100/kW relative to the incumbent option results in a 4% increase in market share, with the converse holding true. Moreover, the relationship between increased capital cost being offset by improved efficiency is non-monotonic in all markets and varies qualitatively even then: a key lesson being that efficiency improvements may not always deliver good value and should thus be carefully evaluated. Thus, while significant improvements in efficiency are potentially achievable,[39–41] it should be recalled that the associated benefits will primarily accrue to the private sector.

These results suggest that the urgent deployment of incumbent technologies is a greater priority for the public sector than the development of new technology concepts. Moreover, the cost reduction and efficiency improvement impact of market-making via technology deployment should not be under-estimated as it allows the private sector to gain higher margins. Thus, it is clear that the deployment of the incumbent technology can maximize the welfare of both the public and private sectors.

CONCLUSION

CCS is widely recognized as being uniquely valuable to meeting climate goals.[2] However, while this is emphasized via scenarios, with the recent IEA Net Zero by 2050 report noting that CCS needs to increase from 40 Mt worldwide today to 1.6 Gt by 2030,[42] there is a marked absence of meaningful initiatives to deploy the critical enabling CO_2 T&S infrastructure to facilitate the deployment of CCS technology.[43] Instead, the focus is primarily directed at the research and innovation levels,[9–15,21–23] which, while important, cannot translate into avoided CO_2 emissions, regardless of how advanced the technology becomes. Using the United Kingdom, Poland, Texas, Wyoming, South Korea, and Indonesia as archetypal electricity systems, characterized by a range of energy prices, demand profiles and growth, renewables availability, and existing technology compositions, we have shown that incumbent CCS technology

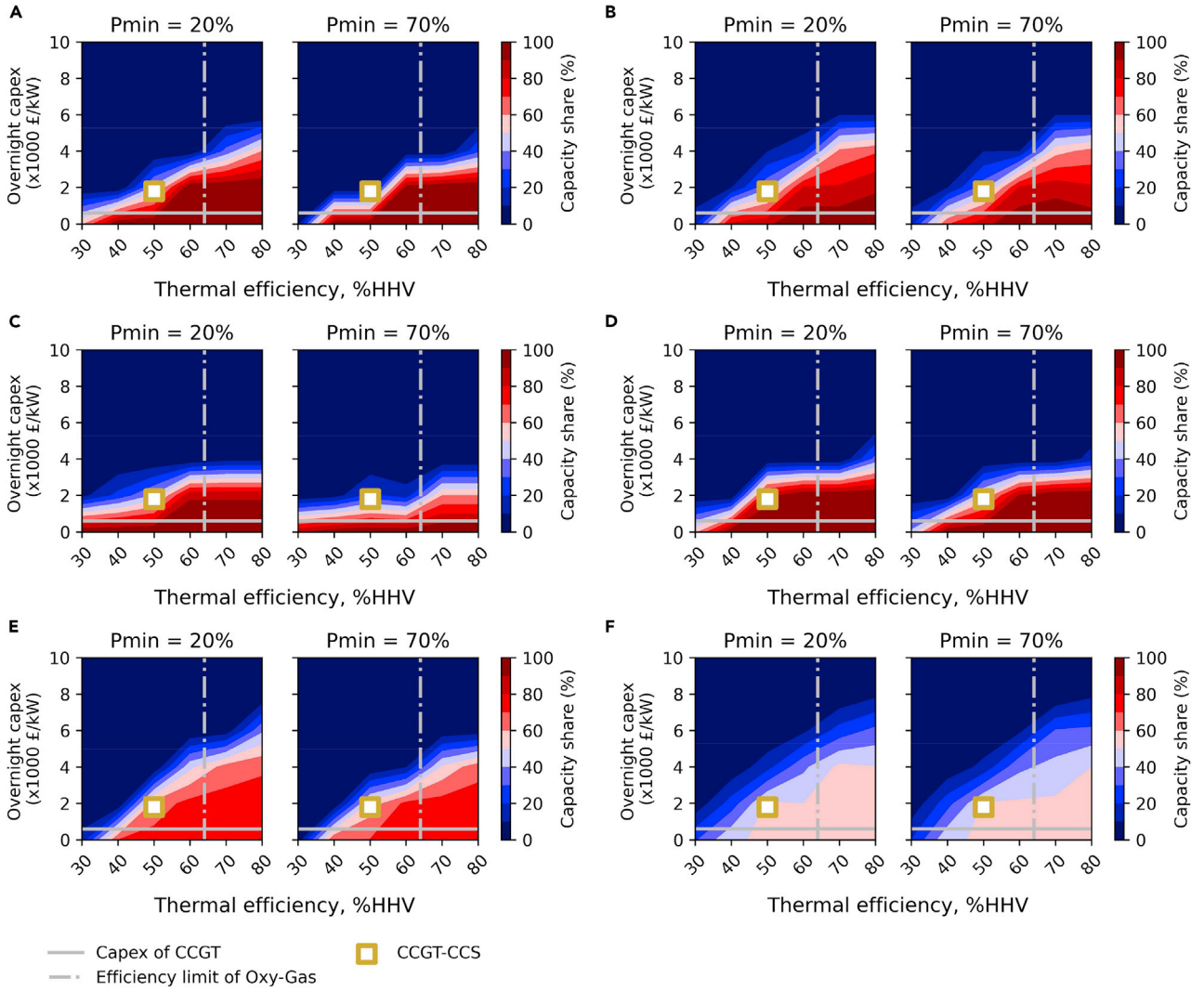


Figure 5. The share of unicorn technology in total CCS capacity

(A–F) As can be seen, the impact of Capex reduction, efficiency, and flexibility improvements on the competitiveness of unicorn against the incumbent in (A) the United Kingdom, (B) Poland, (C) Texas, (D) Wyoming, (E) South Korea, and (F) Indonesia vary as a function of market. This analysis indicates that there is no single correct answer for the development of breakthrough technologies; the value of individual technical parameters varies as a function of market. In general, minimizing capital cost is of first-order importance, while the value of improving efficiency is strongly linked to prevailing fuel prices, whereas flexibility is somewhat more subtle and linked to a combination of qualitative shape of the load duration curve and the availability of renewable energy. As previously, the gray lines correspond to the proposed limits of thermodynamic efficiency and minimum capital cost.

for electricity systems is already sufficiently cost-effective and efficient and thus cost optimally deployed in all cases explored here in the period to 2050. This finding is built upon an assumption that the electricity system is a stand-alone system, and therefore, the impact of improvements and integration with other systems was not explored and may need to be considered for future works.

Despite its value, the market share of the incumbent market can be significantly reduced by the availability of unicorn technology, providing an opportunity for technology developers to increase their market share by advancing CCS technology. From the plant owner's perspective, technology with lower cost and higher efficiency allows power producers to become more competitive in the capacity and wholesale electricity market auctions. In addition to this, if the technology can operate more flexibly, this grants the owner capability to capture a broader range of demand levels to increase its revenue, particularly in the grid with highly seasonal demand. If compared to the incumbent, however, the majority of emerging CCS technologies appear not to be competitive with incumbent technologies when set in the context of actual market requirements. While some options, such as MCFC and Oxy-CCS, might appear comparable with the incumbent in terms of thermal efficiency, one advantage that incumbent technologies will have is the ability to provide a performance guarantee, which is essentially a prerequisite for commercial deployment.

Notwithstanding this, while having a cheaper, more efficient, and flexible technology is undoubtedly beneficial, this study

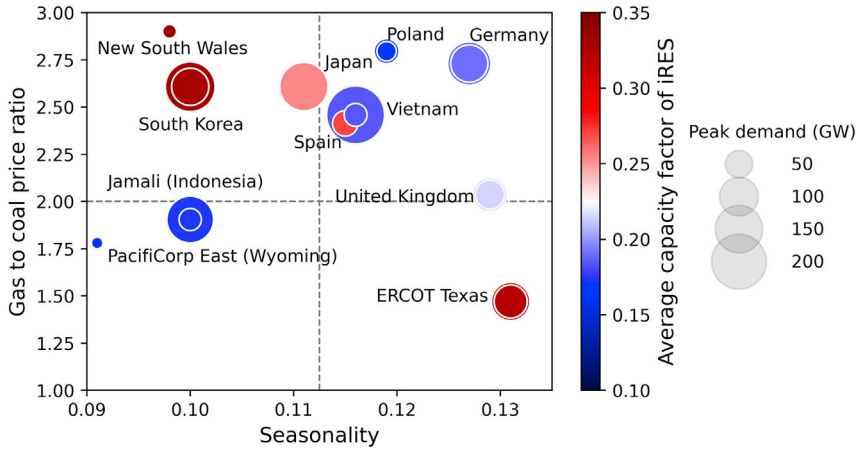


Figure 6. Illustration of key characteristics of various power systems

As can be seen, the fuel price and demand profile are shown as gas-to-coal price ratio and seasonality, which is defined as the standard deviation of the normalized hourly load. Here, the 2020 and projected 2050 peak load demand are presented as the size of the inner and outer circles, respectively. It can be observed that in some regions, such as the United Kingdom, Germany, or Japan, power demand is projected to increase only slightly, if at all, whereas other regions, such as Indonesia or Vietnam, anticipate very significant increased power demand by 2050. These projections come to bear in the context of the capability of supply chains to deliver the requisite generation capacity to meet this demand. Finally, the average capacity factor of renewable energy sources, i.e., solar PV, onshore wind, and offshore wind, illustrates the potential of renewable energy in each system.

has demonstrated that the value of such unicorn technologies is marginal from the public perspective, in terms of further reduction on system costs (or energy bills) compared to what would be achieved by the incumbent alone. This is not to say that there are no other reasons why a new technology may not outperform an incumbent from the public sector's point of view. For example, solutions that use non-volatile solvents, solid sorbents, or membrane technologies will avoid potential issues associated with potential fugitive emissions of volatile organic compounds to the environment.[44–46] Similarly, oxy-combustion concepts both avoid the requirement for an upstream supply chain of solids, liquids, or membranes and the associated potential for carbon leakage and may also provide an energy storage service.[47] There is also the potential for deriving additional revenue from the other product gases arising from the air separation process.[48]

In light of this conclusion, while private efforts to advance CCS technology improvement are welcomed, there is cause to reconsider public funding for CCS RD&D at the technology level. The public sector ought to focus its resources on efforts that can overcome market barriers for the commercial deployment of CCS. These efforts might need to include the development of market mechanisms to ensure reliable and fair revenue streams for CCS, such as improving capacity[49] and ancillary services[50] payments, in which CCS is expected to play a critical role to provide these services for the grid.[51,52] In providing these services, however, CCS might directly compete with its unabated counterpart. Accordingly, fairer mechanisms that allow CCS to be dispatched ahead of unabated plants, such as carbon pricing,[53–55] are key. Moreover, increasing the public sector involvement in the development of CO_2 T&S infrastructure may also greatly benefit CCS commercialization by not only derisking the CCS plant investment but also potentially significantly reducing CO_2 T&S tariffs compared to if the efforts are purely from the private sector.[20] Most importantly, consistent policy support[3,4] for the technology is needed to derisk the investment further, which, in turn, reduces the cost of capital of CCS deployment.[56] Finally, future research on CCS may also need to explore further the integration of the technology and systems levels knowledge to investigate approaches that may support these commercialization efforts, such as pricing mechanisms and CCS infrastructure or network designs.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Niall Mac Dowell (niall@imperial.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

This study did not generate original code. Analysis was carried out using existing ESO framework, in which all the original code has been deposited at Zenodo: https://doi.org/10.5281/zenodo.1048943 and is publicly available. Experimental procedures and ESO modifications required to reproduce this study are available in this paper's supplemental information. All data have been deposited at Zenodo Data: https://doi.org/10.5281/zenodo.6373257 and are publicly available.

Research framework

In this study, we employed the ESO framework[38,51,57] to quantify the value of CCS RD&D in the electricity system from the technological and system perspectives. ESO is a mixed-integer linear programming model that describes the whole electricity system via a hybrid capacity expansion, unit commitment, and economic dispatch formulation. Importantly, ESO explicitly includes key grid constraints on the availability of adequate reserve capacity and ancillary services such as inertia. Decarbonization is driven via emissions targets as appropriate for a given scenario. For this study, we extended the original model to allow early retirement for all technologies and also the retrofit of post-combustion CCS technologies for biomass-, gas-, and coal-fired power plants. In ESO, the number of units of each power generation or storage technology that can be built every 5-year period is constrained to capture how quickly the system can deploy the technology using the historical maximum build rate. While the assumptions might be true for mature technologies, new technologies are understood to have an increasing build rate owing to the increasing adoption. Accordingly, we revised the build rate formulation in the model to allow build rates of potentially disruptive new technologies to exponentially increase. This is particularly important in the context of relatively new technologies, such as renewable energy and CCS, which are still at a relatively low level of deployment and represent a comparatively small fraction of total installed capacity. Modifications in ESO framework required for these extensions are discussed in more detail in supplemental experimental procedures in the supplemental information. Model workflow implemented in this study is illustrated in Figure S1 in the supplemental experimental procedures.

In order to minimize the computational complexity of this study, several assumptions and simplification are implemented in the model:

1. Perfect foresight and the fact that there is no uncertainty are taken into account
2. The demand-side response is not included, assuming the hourly demand is inelastic to the cost of electricity.
3. Similarly, other prices, such as fuel prices and technology costs, are set as exogenous parameters.
4. The model is monopolistic, so the system is optimized according to the system's perspective without considering potential competitions between technologies and between actors in the system.
5 The model assumes the electricity system is a standalone system without considering potential integration with other sectors, such as industrial, heating, residential, and commercial sectors. Thus, conclusions are drawn exclusively from the electricity system's point of view.

It is understood that key technology characteristics are capital cost, efficiency, and flexibility.[58] In this study, we represent flexibility via the minimum stable generation level (*Pmin*) of that technology. Rigorously defining a maximum efficiency for power generation is relatively straightforward. Following Cabral and Mac Dowell,[37] we calculate the maximum theoretical efficiency attainable by a CCGT power plant and then reduce this by the minimum work required to capture the CO_2 from the exhaust gas. However, defining a minimum capital cost is much less straightforward, at least on a theoretical basis. Thus, we propose that the capital cost of an unabated CCGT represents a reasonable lower bound as developing a technology that delivers low carbon power for the price of an unabated CCGT technology is deemed extremely challenging. This provides us with some limits with which to bound our analysis.

We then use ESO to evaluate the extent to which a new CCS technology might be expected to be deployed in a given system, focusing on both absolute capacity deployment and also the displacement of the incumbent technology (CCGT-CCS). In evaluating the value of the new technology, we also consider the impact it has on TSCs, thus providing some insight as to whom the value accrues. This gives rise to three possible outcomes:

1. The technology is not deployed so creates no value.
2. The technology is deployed but does not reduce TSC.
3. The technology is deployed and does reduce TSC.

It is important to note that only one of these outcomes justifies the continued spending of public money, i.e., outcome 3, where the new technology is deployed and reduces system costs, thus returning a benefit to society. Option 2 implies a benefit only to the private sector, and option 1 implies no benefit to anyone.

System characteristics such as load duration curve, demand growth, availability of renewable energy, and prevailing fuel prices will impact the role and value of technology in a given system. Thus, a system with an abundance of renewable capacity, a high level of seasonality in electricity demand, and high fuel costs may well have distinct requirements to systems with limited renewable potential, year-round constant demand for energy, and low fuel costs. These variations are illustrated for a range of nations in Figure 6. In addition to these characteristics, existing capacity may also significantly affect the system transitions. Existing power generation capacity and hourly electricity demand for each system are illustrated in Figures S2 and S3 in the supplemental information. In this study, we performed our search for a unicorn technology in the context of six distinct electricity systems, the United Kingdom, Poland, Texas, Wyoming, South Korea, and Indonesia (represented by the Java-Madura-Bali/JAMALI system), to capture the impact of these system characteristics on the value of CCS innovations. The broad context for all the thought experiments presented here is one where the incumbent system transitions to a net-zero paradigm by 2050, in line with existing legislation in the United Kingdom and European Union, and with an eye on the emerging landscape in the United States and the Asia Pacific regions.

Finally, we use cost data from the UK government's Department of Business Energy and Industrial Strategy (BEIS)[29,30,59] with details of emerging CCS technologies taken from Wood Group's work in this area.[31] This is not meant to imply a particular endorsement of these data; rather they are used as they are internally consistent and are not subject to proponent bias. To calculate the cost of unmet demand, system-specific value of lost load (VoLL) is used. Data of VoLL for each system and techno-economic performance of each technology are outlined in Tables S1–S3 in the supplemental information.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.03.008.

ACKNOWLEDGMENTS

Y.W.P. thanks the Indonesia Endowment Fund for Education (LPDP) for the full funding provided for his study (201711220111875). Y.W.P. also thanks Caroline Ganzer from Center for Environmental Policy for helpful discussions on S-curve formulations used in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, Y.W.P. and N.M.D.; investigation, Y.W.P.; original draft, Y.W.P.; review & editing, Y.W.P. and N.M.D.; supervision, N.M.D.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: August 9, 2021
Revised: October 11, 2021
Accepted: March 22, 2022
Published: April 15, 2022

REFERENCES

1. Pacala, S., and Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science *305*, 968–972.
2. IPCC (2014). In Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Core Writing Team, R.K. Pachauri and L.A. Meyer, eds. (Intergovernmental Panel on Climate Change (IPCC)).
3. A.T. Kearney Energy Transition Institute (2016). Low Carbon Energy Technologies - FactBook Update: Carbon Capture and Storage at a Crossroads (A.T. Kearney Energy Transition Institute).
4. IEA (2016). 20 Years of Carbon Capture and Storage: Accelerating Future Deployment.
5. Reiner, D.M. (2016). Learning through a portfolio of carbon capture and storage demonstration projects. Nat. Energy *1*, 1–7.
6. Global CCS Institute (2019). Global Status of CCS 2020.
7. BEIS (2018). Clean Growth: The UK Carbon Capture Usage and Storage Deployment Pathway (An Action Plan).
8. Campbell, L., Solsbery, L., Hudson, V., and Crawford, M. (2018). Role of CCS in the Energy Transition.
9. (2018). UNFCCC Communication of long-term strategies. https://unfccc.int/process/the-paris-agreement/long-term-strategies.
10. US Department of State (2021). The Long Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 (US Department of State and and the US Executive Office of the President).
11. BEIS (2021). Net Zero Strategy: Build Back Greener (UK Department of Business, Energy & Industrial Strategy).
12. The Government of Japan (2021). The Long-Term Strategy under the Paris Agreement.
13. The Danish Government (2020). Climate Programme 2020 (Danish Ministry of Climate, Energy and Utilities).
14. Government of Canada (2016). Canada's Mid-Century Long-Term Low-GHG Development Strategy.

15. Australian Government (2021). Australia's Long-Term Emissions Reduction Plan: A Whole-Of-Economy Plan to Achieve Net Zero Emissions by 2050 (Australian Government Department of Industry, Science, Energy and Resources).
16. Fiorini, A., Pasimeni, F., Georgakaki, A., and Tzimas, E. (2017). Analysis of the European CCS research and innovation landscape. Energy Proced. *114*, 7651–7658.
17. Folger, P. (2018). FY2019 funding for CCS and other DOE fossil energy R&D. Congressional Research Service.
18. IEA (2017). Tracking Clean Energy Progress 2017.
19. IEA (2021). Energy Technology RD&D Budgets: Overview.
20. Edwards, R.W.J., and Celia, M.A. (2018). Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. Proc. Natl. Acad. Sci. U. S. A. *115*, E8815–E8824.
21. Hughes, G. (2017). The Economics of Carbon Capture and Storage (The Global Warming Policy Foundation).
22. Durmaz, T. (2018). The economics of CCS : why have CCS technologies not had an international breakthrough. Renew. Sustain. Energy Rev. *95*, 328–340.
23. Fichera, A., and Volpe, R. (2020). Investigating the competitiveness of Carbon Capture and Storage in Italian power plants under different investment scenarios. Int. J. Greenh. Gas Control *93*, 102859.
24. Zhou, W., Zhu, B., Fuss, S., Szolgayová, J., Obersteiner, M., and Fei, W. (2010). Uncertainty modeling of CCS investment strategy in China's power sector. Appl. Energy *87*, 2392–2400.
25. Koelbl, B.S., van den Broek, M.A., van Ruijven, B.J., Faaij, A.P.C., and van Vuuren, D.P. (2014). Uncertainty in the deployment of Carbon Capture and Storage (CCS): a sensitivity analysis to techno-economic parameter uncertainty. Int. J. Greenh. Gas Control *27*, 81–102.
26. Lohwasser, R., and Madlener, R. (2012). Economics of CCS for coal plants : impact of investment costs and efficiency on market diffusion in Europe. Energy Econ. *34*, 850–863.
27. Heuberger, C.F., Staffell, I., Shah, N., and Mac Dowell, N. (2017). Valuing Flexibility in CCS Power Plants (IEA Greenhouse Gas R&D Programme (IEAGHG)).
28. Patrizio, P., Pratama, Y.W., and Mac Dowell, N. (2020). Socially equitable energy system transitions. Joule *4*, 1700–1713.
29. BEIS (2016). BEIS Electricity Generation Costs.
30. Leigh Fisher and Jacobs (2016). Electricity Generation Costs and Hurdle Rates.
31. Wood (Amec Foster Wheeler Group Limited) (2018). Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology: Benchmarking State-Of-The-Art and Next Generation Technologies.
32. Ferrari, N., Mancuso, L., and Cotone, P. (2012). Operating Flexibility of Power Plants with CCS.
33. Domenichini, R., Mancuso, L., Ferrari, N., and Davison, J. (2013). Operating flexibility of power plants with carbon capture and storage (CCS). Energy Proced. *37*, 2727–2737.
34. Nord, L.O., and Bolland, O. (2011). Plant flexibility of a pre-combustion CO2 capture cycle. Energy Proced. *4*, 2556–2563.
35. Zaryab, S.A., Scaccabarozzi, R., and Martelli, E. (2020). Advanced part-load control strategies for the Allam cycle. Appl. Therm. Eng. *168*, 114822.
36. McLarty, D., Brouwer, J., and Samuelsen, S. (2014). Fuel cell-gas turbine hybrid system design part II: dynamics and control. J. Power Sourc. *254*, 126–136.
37. Cabral, R.P., and Mac Dowell, N. (2017). A novel methodological approach for achieving £/MWh cost reduction of CO2 capture and storage (CCS) processes. Appl. Energy *205*, 529–539.
38. Heuberger, C.F., Staffell, I., Shah, N., and Mac Dowell, N. (2018). Impact of myopic decision-making and disruptive events in power systems planning. Nat. Energy *3*, 634–640.
39. Kaneko, S. (2016). Integrated coal gasification combined cycle: a reality, not a dream. J. Energy Eng. *142*. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000312.
40. van Biert, L., Woudstra, T., Godjevac, M., Visser, K., and Aravind, P.V. (2018). A thermodynamic comparison of solid oxide fuel cell-combined cycles. J. Power Sourc. *397*, 382–396.
41. Kobayashi, Y., Ando, Y., Kabata, T., Nishiura, M., Tomida, K., and Matake, N. (2011). Extremely high-efficiency thermal power system-solid oxide fuel cell (SOFC) triple combined-cycle system. Mitsubishi Heavy Ind. Tech. Rev. *48*, 9–15.
42. Bouckaert, S., Araceli Fernandez, P., McGlade, C., Remme, U., and Wanner, B. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector (International Energy Agency (IEA)).
43. Turan, G., Zapantis, A., Kearns, D., Tamme, E., Staib, C., Zhang, T., Burrows, J., Gillespie, A., Havercroft, I., Rassool, D., et al. (2021). Global Status of CCS 2021: CCS Accelerating to Net Zero.
44. Strube, R., Pellegrini, G., and Manfrida, G. (2011). The environmental impact of post-combustion CO2 capture with MEA, with aqueous ammonia, and with an aqueous ammonia-ethanol mixture for a coal-fired power plant. Energy *36*, 3763–3770.
45. Kimura, H., Kubo, T., Shimada, M., Kitamura, H., Fujita, K., Suzuki, K., Yamamoto, K., and Akai, M. (2017). Environmental risk assessment of MEA and its degradation products from post-combustion CO2 capture pilot plant: drafting technical guidelines. Energy Proced. *114*, 6490–6500.
46. Thong, D., Dave, N., Feron, P., and Azzi, M. (2012). Environmental Impacts of Amine-Based CO2 Post Cobustion Capture (PCC) Process.
47. Perrin, N., Dubettier, R., Lockwood, F., Tranier, J.P., Bourhy-Weber, C., and Terrien, P. (2015). Oxycombustion for coal power plants: advantages, solutions and projects. Appl. Therm. Eng. *74*, 75–82.
48. Mancuso, L., Ferrari, N., Chiesa, P., Martelli, E., and Romano, M. (2015). Oxy-Combustion Turbine Power Plants.
49. Tennbakk, B., Lafitte, J.-B., Capros, P., Dekis, C., Tasios, N., Zabara, M., Noreng, C.H., Skalund, A.B., and Jenssen, A. (2013). Capacity Mechanisms in Individual Markets within the IEM.
50. Zhou, Z., Levin, T., and Conzelmann, G. (2016). Survey of U.S. Ancillary Services Markets.
51. Heuberger, C.F., Staffell, I., Shah, N., and Mac Dowell, N. (2017). A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks. Comput. Chem. Eng. *107*, 247–256.
52. Pratama, Y.W., and Mac Dowell, N. (2020). Beyond LCOE: Value of Technologies in Different Generation and Grid Scenarios.
53. Renner, M. (2014). Carbon prices and CCS investment: a comparative study between the European Union and China. Energy Policy *75*, 327–340.
54. Wu, N., Parsons, J.E., and Polenske, K.R. (2013). The impact of future carbon prices on CCS investment for power generation in China. Energy Policy *54*, 160–172.
55. Khan, J., and Johansson, B. (2022). Adoption, implementation and design of carbon pricing policy instruments. Energy Strategy Rev. *40*. https://doi.org/10.1016/j.esr.2022.100801.
56. Rubin, E.S. (2012). Understanding the pitfalls of CCS cost estimates. Int. J. Greenh. Gas Control. *10*, 181–190.
57. Heuberger, C.F., Rubin, E.S., Staffell, I., Shah, N., and Mac Dowell, N. (2017). Power capacity expansion planning considering endogenous technology cost learning. Appl. Energy *204*, 831–845.
58. Schnellmann, M.A., Heuberger, C.F., Scott, S.A., Dennis, J.S., and Mac Dowell, N. (2018). Quantifying the role and value of chemical looping combustion in future electricity systems via a retrosynthetic approach. Int. J. Greenh. Gas Control. *73*, 1–15.
59. ARUP (2016). Review of Renewable Electricity Generation Cost and Technical Assumptions.