Decarbonizing gas turbines through carbon capture

A pathway to lower CO_2

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Executive Summary

In order to combat man-made climate change, carbon capture, utilization, and sequestration is a necessity

In 2019, global CO_2 emissions from fossil fuels amounted to 33 gigatons, with 41 percent of that coming from the power generation sector, and the remainder from the transportation and industrial sectors. There is a lot of work to be done and time is against us. According to the IPCC's 2018 special report "Global Warming of 1.5 °C," we had 580 gigatons of CO_2 in our remaining carbon budget if the globe were to have a 50–50 chance of keeping global warming to 1.5 °C compared to pre-industrial levels. Bring that forward from 2018 to 2020, and if we continue on our current path of emissions, we have only 15 years left before the budget runs out. The good news is that there are solutions available today to enable the power sector's rapid reduction in carbon intensity.

Carbon Capture, Utilization, and Storage (CCUS) is one of these solutions and will play an integral role across multiple sectors on the journey to lower carbon.

As governments, countries, and companies establish their charters for achieving carbon reduction goals, CCUS should be part of the pathway. The International Energy Agency's Sustainable Development Scenario (SDS), emphasizes the contribution CCUS will play in reducing cumulative CO_2 emissions, indicating **CCUS will account for one sixth of the needed cumulative CO_2 reduction. However, in order for CCUS to fulfill its role, policies and regulations are needed to both accelerate the speed of adoption and to de-risk public concerns around the technology.**

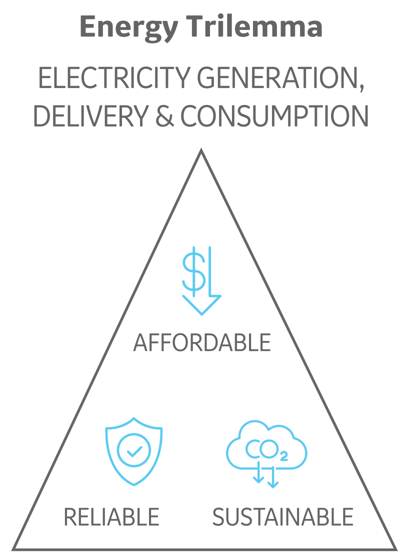


FIGURE 1: The energy trilemma is the challenge of providing affordable, reliable and sustainable energy.

Planning for sustainability in the power sector is one of three corners in the Energy Trilemma: the need to balance affordable energy, maintain reliable power supply, and improve sustainability. See Figure 1. Each country is at a different point in its decarbonization* journey and will prioritize the elements of the trilemma differently, but the most effective way is a mix of generation resources that complement one another.

Based on our extensive analysis and experience across the breadth of the global power industry, GE believes that the accelerated and strategic deployment of renewables and gas power can change the near-term trajectory for climate change, enabling substantive reductions in emissions quickly, while in parallel continuing to advance the technologies for near zero-carbon power generation.

**Decarbonization in this paper is intended to mean the reduction of carbon emissions on a kilogram per megawatt hour basis.*

GE believes that the accelerated and strategic deployment of CCUS and gas power can change the trajectory for climate change

Introduction

As of 2020 there were ~1.6 TW of gas turbines installed globally, and despite the effects of COVID-19 on power demand gas generation accounted for ~22 percent of generation globally. There are two ways to systematically approach the task of turning high efficiency gas generation into a zero or near zero-carbon resource: pre and post-combustion. See Figure 2. Pre-combustion refers to the systems and processes upstream of the gas turbine. The most common approach today to tackle pre-combustion decarbonization is simple: change the fuel. The vast majority of gas turbines burn natural gas, or methane (CH_4), to release energy which ultimately produces the electricity we use at home and for industry. An advantage of gas turbines is that they are able to operate on many other fuels besides natural gas. Some of these fuels, such as hydrogen (H_2), do not contain carbon in the first place, and will therefore not emit CO_2 when combusted. Furthermore, H_2 can be introduced to new gas turbines and existing gas turbines alike, reinforcing the concept that solutions are available today to decarbonize assets already in the field and those waiting to be installed. The possibility of burning hydrogen in a gas turbine avoids the potential "lock-in" of CO_2 emissions for the entire life of the power plant.

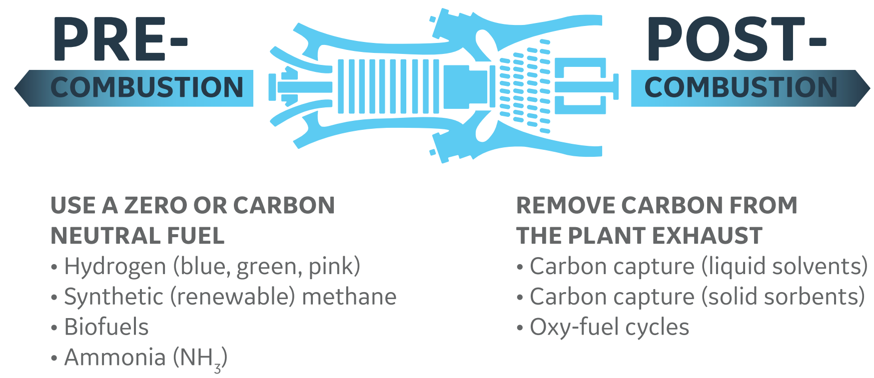


FIGURE 2: Means of decarbonizing a gas turbine

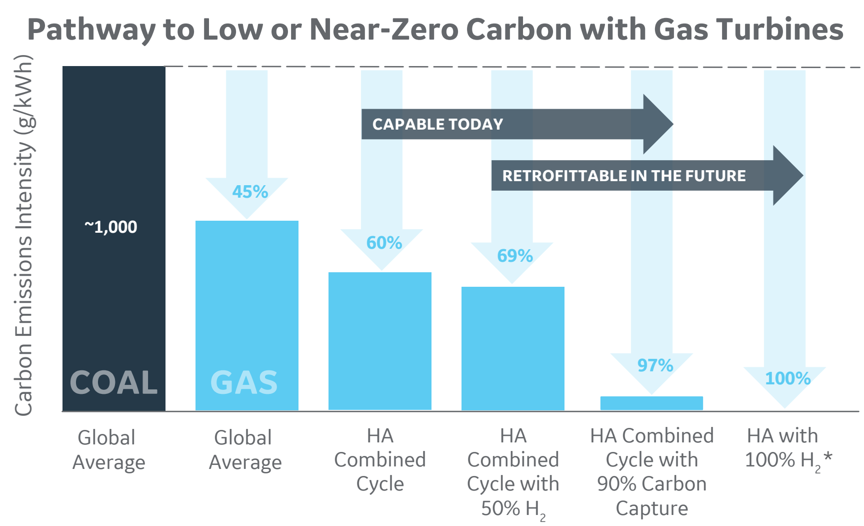


FIGURE 3: Gas turbine decarbonization opportunity

**The atmosphere contains approximately 0.06% (by mass) CO_2. Therefore, a gas turbine on 100% H_2 will still emit a small amount of CO_2 due to the ambient air composition.*

On the other side of the gas turbine, or post-combustion, there is a tool chest of different technologies that can remove CO_2 from the flue gases in a process that is commonly referred to as carbon capture. The general concept of carbon capture involves introducing into the plant exhaust stack a specialized chemical which has an engineered affinity to carbon. Once the CO_2 and the agent bond, the CO_2 and specialized chemical are processed, the CO_2 is separated, and taken to a compression tank as pure CO_2. This CO_2 is then transported to either a geologic formation deep underground for permanent sequestration, or re-used in industrial process, thus completing the process of Carbon Capture and Utilization or Sequestration (CCUS). Similar to introducing hydrogen to a plant, CCUS can be applied to both new and existing gas power plants, again avoiding lock-in of CO_2 emissions for the life of the power plant.

GE believes that in order for the power sector to rapidly decarbonize while maintaining high levels of reliability, both pre and post-combustion decarbonization options for gas turbines are viable tools available today. Both hydrogen and CCUS have their own merits and ideal areas of application. This paper will discuss the merits and limitations specific to carbon capture. See Figure 3.

WHO NEEDS CCUS?

Anthropogenic (man-made) sources of greenhouse gases (GHG) are certainly not limited to the power generation sector. In fact, one of the most compelling arguments for the deployment of CCUS as a tool to reduce CO_2 emissions is that it is not limited to applications in just one sector. In fact, we should think about four different value streams for CCUS to make an impact. Those sectors are power generation, industry, transportation fuels (blue H_2 via steam methane reforming), and direct air capture. In the IEA's Sustainable Development Scenario (SDS), their hypothetical scenario that keeps global average temperatures well below 2° C with efforts to limit it to 1.5° C, aligned with the goal of the Paris Agreement, over the next 50 years the power generation, transportation, and industrial sectors will play a major role in the aggregation and sequestration of CO_2 (Figure 4).

Expanding on the other sectors where CCUS will play a role, the industrial sector is a rather expansive term. Drilling down and identifying industrial operations which are considered "hard to abate" will bring us to the iron & steel, cement, chemical, oil & gas, pulp & paper sectors. These industries rely on manufacturing processes in which it is difficult to replace current fuels with electricity, which is often referred to as electrification. In the case of transportation, and primarily long-distance transportation, limitations in battery duration and limited infrastructure to support low carbon fuels make it a difficult sector to tackle emissions, but not impossible. One low carbon fuel option today is hydrogen. Hydrogen as it's made today generally goes through an industrial process know as steam methane reforming (SMR), which breaks up a standard methane molecule (CH_4), separating the carbon from the hydrogen, and emitting the carbon into the atmosphere as CO_2. Based on a recent study, CO_2 emissions from SMR hydrogen production is ~9 Kg CO_2 per Kg H_2 produced.[1] For many, an ideal state to create hydrogen is instead using an electrolyzer powered from renewable energy to crack a water molecule (H_2O), making "green" hydrogen. However, green hydrogen may be a few decades away before it becomes more economical and scalable. Thus, in order for hydrogen to be effective in the short term as a viable transportation fuel, carbon capture must (and can) be applied to SMR processes. Fortunately, capturing carbon dioxide can be completed in a wide array of applications to fit the industrial, mechanical, and alternative fuel processes (Blue H_2) which produce CO_2 emissions.

CCUS is in fact expected to play a major role in order to reach net-zero emissions, accounting for one-sixth of cumulative emissions reductions, according to the IEA (Figure 5).[2] In order for CCUS to be an effective tool to remove a material amount of carbon from power production and industrial operations, it will need to be deployed on both existing and newly constructed assets.

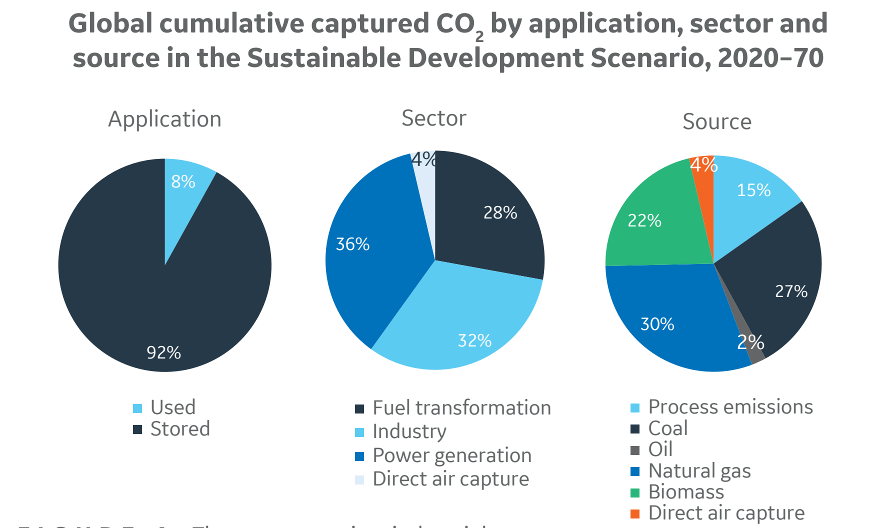


FIGURE 4: The transportation, industrial, and power generation sectors will play a major role when it comes to capturing CO_2.

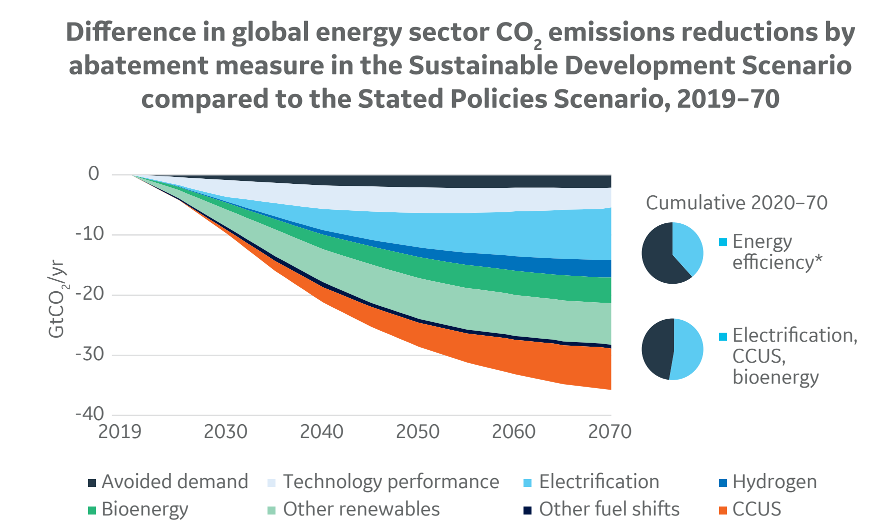


FIGURE 5: Global energy sector CO_2 emissions reductions by measure in the IEA SDS relative to the Stated Policies scenario. Stated Policies scenario represents if the world's current policies where to carry forward on its current track in addition to announced Government intentions.

In addition to the benefit of applying CCUS to existing assets, it can also be deployed as a modular solution, solving for incremental amounts of carbon reduction with each additional module. This translates to greater optionality for plant owners, taking either a phased approach by deploying carbon capture systems over years and spreading out the capital expenses over a longer period, or an immediate approach by building out the carbon capture system to full capacity in one go. By 2050, retrofits to both the power and heavy industry assets are expected to contribute more than 2 gigatons in annual carbon reduction according to the IEA's SDS. In fact, carbon capture retrofits are expected to account for 50 percent of all CO_2 capture projects by 2050 in their scenario (Figure 6).

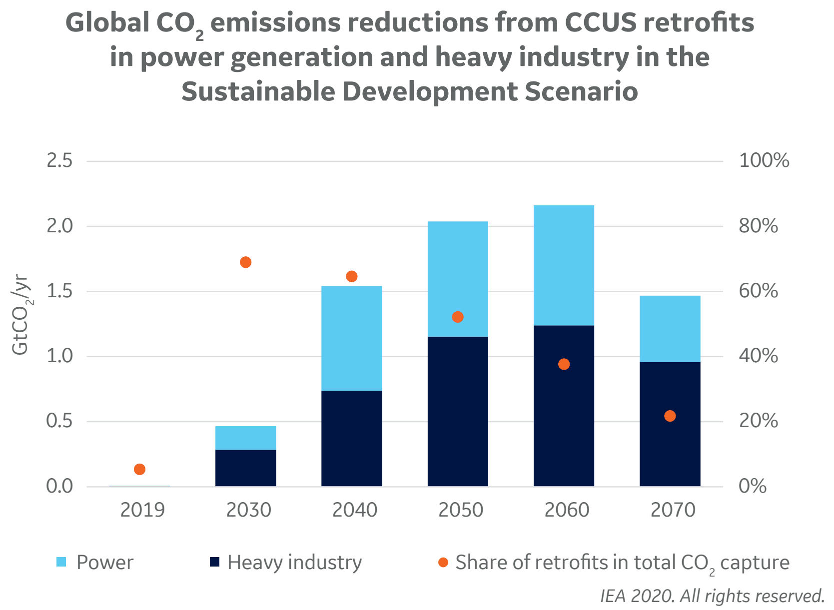


FIGURE 6: Global CO_2 emission reduction from CCUS retrofits in power generation and heavy industry in IEA's 2020 SDS

Post-combustion carbon capture can be installed on both new and existing assets

WHAT IS CCUS AND HOW DOES IT WORK?

In its simplest sense carbon capture and sequestration is the process of removing CO_2 from the waste gas from industrial or power generation processes. It has four central components: (i) capture, (ii) compression, (iii) transport, and (iv) storage or use. There is a portfolio of options to tackle this challenge, using liquid solvents or solid sorbents which have an affinity towards acidic gases. Once captured, the CO_2 is compressed on site, and injected into a pipeline for transportation to a well-head for injection deep into the earth, or to an industrial site for use. The repurposing of carbon is generally directed to the production of synthetic fuels, chemicals, and building materials. However, the majority of captured CO_2 will be destined for sequestration and enhanced oil recovery (EOR), due to the limited volume of CO_2 demanded for utilization.

When it comes to the actual process of capturing CO_2, the most mature option today, and the baseline for all other carbon capture technologies, is a post-combustion technology called Amine Carbon Capture. A special chemical liquid called monoethanolamine (MEA, or Amine for short), is literally rained down through an exhaust stream, absorbing the CO_2 from the exhaust. That CO_2-rich liquid is then moved to a second vessel, where it is heated to drive off pure CO_2. That CO_2 can then be compressed and transported to a sequestration or industrial site.

On a more granular chemical level, MEA is a base that reacts with the acid by forming a complex compound with the CO_2 in the acid gas, effectively removing the acid gas from the original stream (absorbing process). The liquid amine solution with the acidic gas is then heated to recover the amine, resulting in a purified CO_2 stream (desorbing process). The heat forces the CO_2 back to a vapor form, where the now pure CO_2 gas can be compressed for sequestration, and the amine is recycled into the stream. (Figure 8).

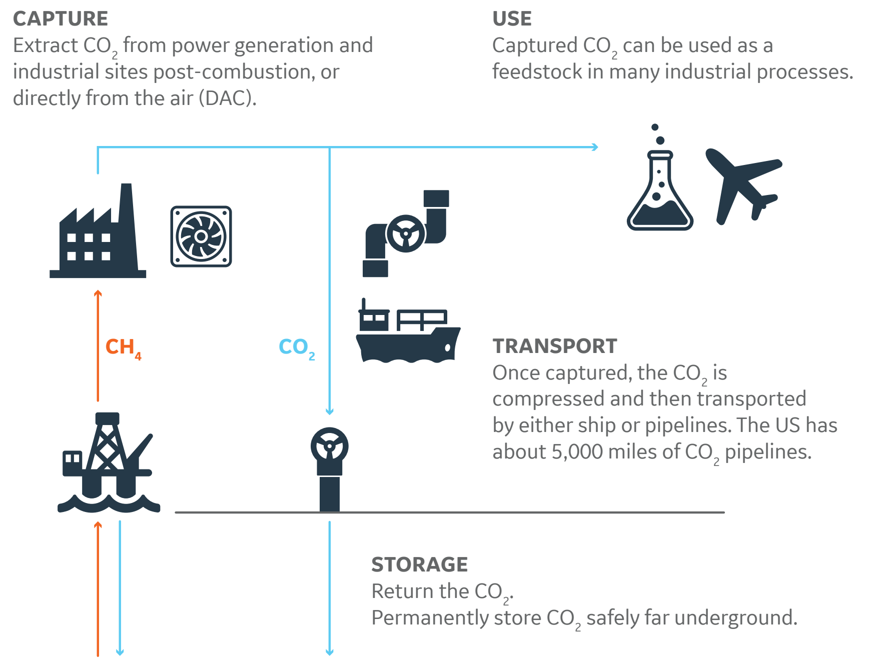


FIGURE 7: Lifecycle of carbon in a CCUS application

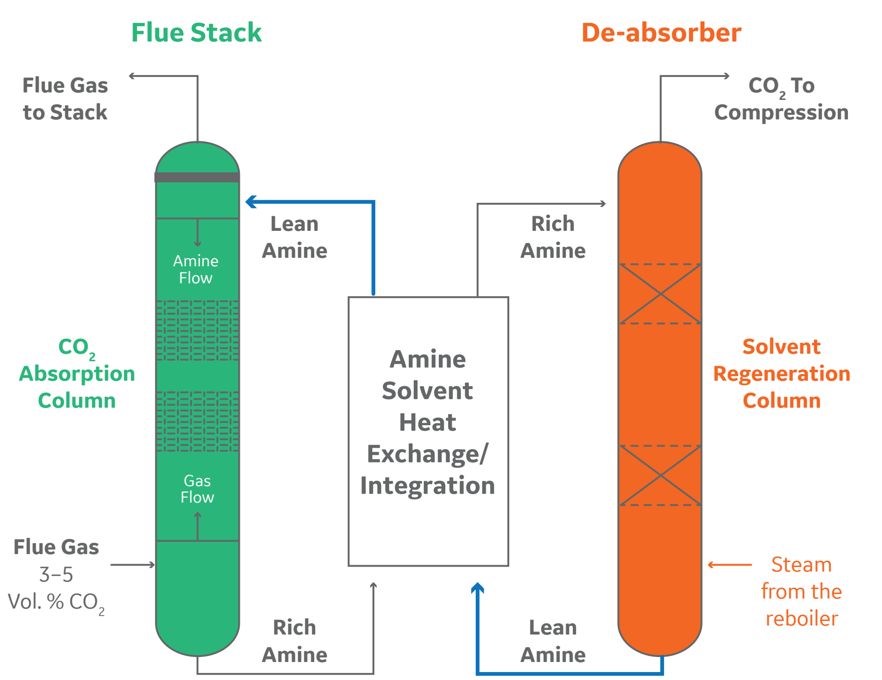


FIGURE 8: Post combustion amine process diagram

Amine-based carbon capture is the most mature technology, though many options exist

The primary components in the basic MEA process are presented below.

ABSORBER

Vessel—also called tower or column—in which the chemical absorption reactions take place. The absorption reaction chain binds the CO_2 to the MEA, in its aqueous solution, separating it from the flue gas. After the amine solution binds with CO_2, it is collected at the bottom of the absorber (CO_2-rich solution) while the scrubbed flue gas is vented through the top of the column. The fraction of flue gas that has been separated from the CO_2 is vented at the top of the absorber. The geometry of an absorber has two main degrees of freedom: diameter and height. These two parameters are tailored to ensure that the unit is not too big, heavy and expensive but at the same time, the velocity of the gas ascending the column is under control. A gas stream that is too fast induces pressure loss along the column and results in the need for high compression power to pressurize the flue gas at the bottom of the tower. The equilibrium reactions inside the column takes place at a rate controlled by the kinetics of the amine chemistry, which means the absorber should be sized according to the time required to ensure a binding reaction occurs between the amines and the CO_2.

HEAT EXCHANGER (ECONOMIZER)

The rich solution carries CO_2 from the absorber to the de-absorber. The de-absorber works optimally when the rich solution temperature is approximately 80° C higher than that at the absorber bottom. Therefore, the rich solution must travel through a heater first and then to the top of the de-absorber tower using a pump. This heater is a heat exchanger also called an "Economizer," that transfers excess energy from the hot and lean solution exiting the regeneration (de-absorber) column to the relatively cold and rich solution exiting the absorption column.

DE-ABSORBER (STRIPPER)

The CO_2-rich amine solution is sprayed down from the top of the de-absorber tower (also known as the solvent regeneration column) while steam generated in the reboiler rises under pressure, from the bottom to the top. This counter-current motion of rich solution through steam creates the right environment for the equilibrium reactions to be shifted towards the release of CO_2 from the amine solution, which becomes "lean", or stripped of the CO_2, and is collected at the bottom of the column. As a result of the reaction and system configuration, the CO_2 migrates to the top of the column while the MEA solution that is now poor in CO_2 is collected at the bottom of the column. The CO_2 is separated from the water vapor that "stripped" it from the rich solution in the condenser/flash tank. At the top of the condenser, the CO_2 can be accumulated or pumped away.

LEAN PUMP AND AMINE MAKEUP

The regenerated "lean" amine solution travels to the heat exchanger by using a lean solution pump where it cools down. A control unit is designed to provide the necessary amine makeup—amine is degraded by the process to compounds that are not effective at binding with CO_2—and set the solution flowrate. The same amine plant can accept a range of flue gas flowrates by regulating the flowrate of amine solution to maintain a balanced ratio between molar flowrate of CO_2 in the flue and molar flowrate of amine in contact with it.

As mentioned before, amines are the most commonly used chemicals, but there are other options which are commercially available. While there are a variety of options, it is important to point out that there are limitations to the process. The most significant of these limitations is the cost associated with achieving more than ~90 percent carbon capture. The relationship between carbon capture percent and capital expense is not linear. To achieve a capture rate greater than 90 percent, the equipment gets larger and larger with small increments in the plant's capture rate. Additionally, there are several developments in new chemical compositions which show promise to increase the effectiveness of CCUS above 90 percent, such as Metal Organic Frameworks (MOF) which may be able to improve on amine's current limitations.

CARBON CAPTURE IN PRACTICE

IMPACTS TO THERMAL PERFORMANCE

As with most things in life, rarely is there any free lunch. The same holds true for the positive benefits that come along with carbon capture systems. As described in the section above, the thermodynamic cycle of the amine system requires thermal energy, which in a combined cycle power plant would be taken from the Heat Recovery Steam generator (HRSG) or the steam turbine, depending on the required conditions. Historically, the associated efficiency penalty has been calculated to be rather high at almost 10 points of combined cycle efficiency. Reassessment of this topic has uncovered the possibility of reducing the penalty by improving the steam and carbon capture processes. As shown in Figure 9,

GE's analysis of a 2 x 1 combined cycle 7HA plant (~1,200 MWs) indicated the efficiency penalty is closer to 6 percent at an 85 percent carbon capture rate.

More work is being done in this area, but there is no avoiding an efficiency penalty nonetheless.

The impact of CCUS on power plant efficiency can be assessed by examining three key pieces of the carbon capture system: 1) de-absorber, 2) CO_2 compressor, and 3) blower. Within the de-absorber is a subcomponent called the steam reboiler, which provides two key functions. First, it keeps steam at the pressure needed in order to force gases to ascend the de-absorber tower and second, it maintains the temperature at which the CO_2 segregates from the rich amine solution, which can be as high as 120º C–140º C. However, when the system is paired with a combined cycle plant, there is no need for a dedicated reboiler, steam is instead drawn directly from the steam cycle. The impact of steam removal causes a reduction in electricity production at the steam turbine shaft and a corresponding reduction in plant efficiency.

The CO_2 compressor is the second largest contributor to the power plant's efficiency loss. The compressor pressurizes the CO_2 collected at the top of the solvent regeneration column as need to prepare the gas for injection into the pipeline system for transport to the storage site. An important factor to keep in mind is that compression operations are volumetric. The higher the CO_2 capture rate, the larger the CO_2 flowrate, and therefore the efficiency loss due to CO_2 compression increases with the carbon capture level.

The third major source of efficiency loss comes from a blower unit, situated upstream of the absorber. In the absorber, lean solution rains down through the ascending column of flue gas. The blower uses electrical power to create the necessary pressure to the flue gas to overcome the pressure losses through the absorber's packing.

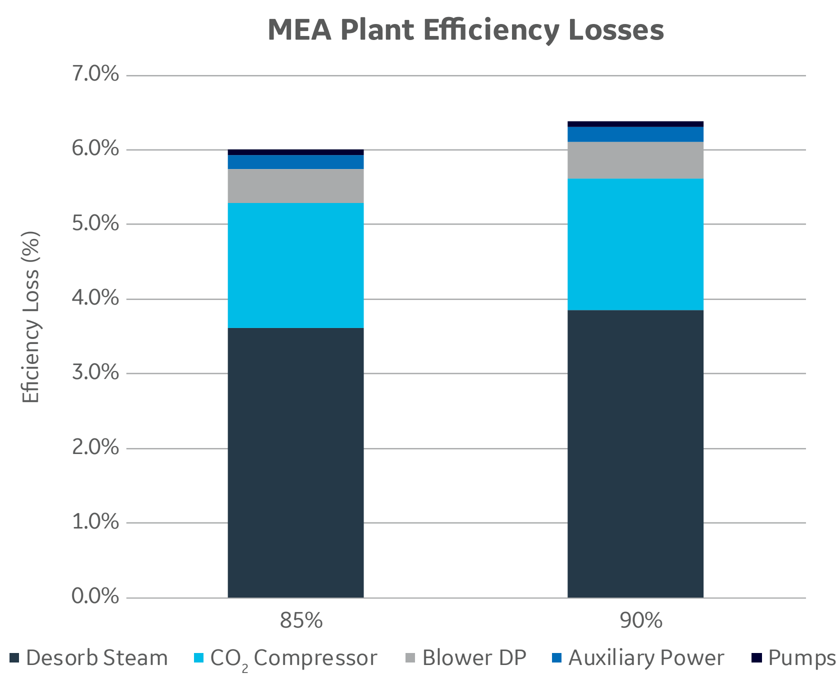


FIGURE 9: Plant efficiency losses for a combined cycle plant at 90 percent and 85 percent carbon capture

Source: GE Gas Power marketing analysis

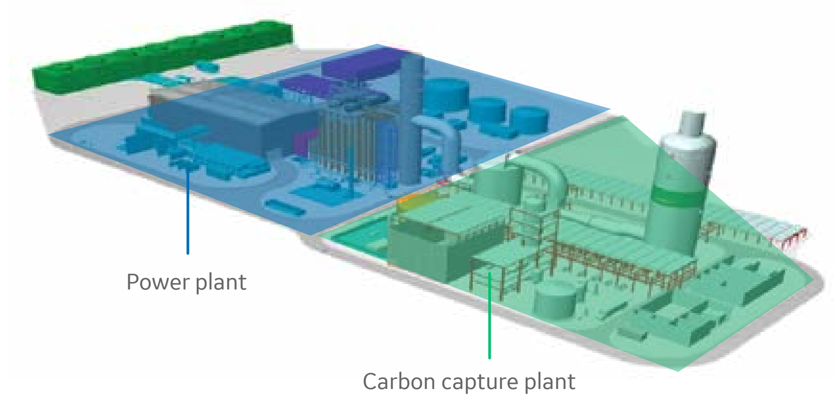


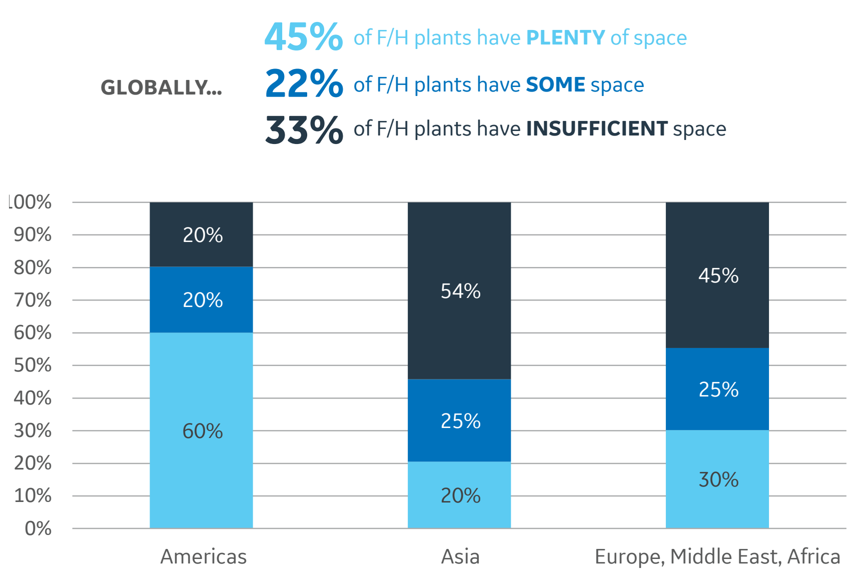
FIGURE 10: Conceptual layout of gas power plant and carbon capture plant

RETROFITS

As discussed earlier, one of the merits of post-combustion carbon capture is that it can be applied to both existing and future CO_2-producing assets. However, it is important to note that not every asset will be considered a good candidate due to multiple factors, including available land, access to geologic storage formations, and lack of policy/regulations to encourage deployment.

Starting with land constraints, it is important to point out that adding a post-combustion system is a considerable expansion in the site's footprint, approximately doubling the size assuming an ~90 percent carbon capture system. For a typical plant this is an additional ~4 acres. In an analysis of hundreds of gas power plants using GE's F/HA class gas turbines around the globe across 48 countries, approximately 45 percent of existing plants had **plenty** of physical space adjacent to the site, 22 percent of plants had **some** space, and 33 percent of sites likely had **insufficient** space.

An added benefit of a retrofit strategy is that it helps de-risk future carbon regulations that impact the decision to build a gas-fired power plant today. Furthermore, retrofits can significantly extend the lifetime of operating assets, extending their economic viability and even deferring incredibly costly decommissioning expenses with forced retirements.



Based on a visual inspection of the sites using Google Earth, assuming carbon capture requires a doubling of current site on at least one adjacent side. Analysis looked only for un-used property, not property ownership.

FIGURE 11: Available space analysis for adding carbon capture systems to a sample of power plants with GE gas turbines

Source: GE Gas Power marketing analysis

ECONOMICS

The cost of adding a carbon capture system to any CO_2-emitting asset has often been labeled as overly expensive and unnecessary. This holds true under circumstances where CO_2 emissions may continue unabated. However, with the transition to a decarbonized future across multiple sectors, this is no longer the case. In fact, given the proper market structures and regulatory frameworks that already exist in certain regions, CCUS is economical today, especially compared to alternatives to decarbonize thermal assets.

An approximate rule of thumb for a 90 percent post-combustion carbon capture system is that it can double the capital expense of the power plant. Nominally, this is certainly a significant investment. But unlike efficiency losses, which are linear to the amount of carbon reduction, it is important to keep in mind that capital expense does not have a linear relationship with the percentage of carbon reduction. Therefore, moving down to an 85 percent carbon capture rate sees a very significant reduction in capital cost. Additionally, costs can be reduced even more so on new power plant builds due to synergies of construction operations, onsite equipment and labor, etc.

Most carbon prices are too low to enable meaningful change

When looking at operational costs, the important buckets include onsite utilities (CO_2 compression, etc.), operating and maintenance labor, CO_2 take-away costs, and raw materials such as the amine, to name a few. Despite the fact that these raw materials degrade over time and need to be replaced, the costs of these materials are incredibly low when looking at the overall operating expense of the entire plant site.

Indeed, when capital costs and operational costs are amortized over a ~20 year plant life, the levelized cost of energy from the asset are highly competitive when compared to other forms of decarbonized thermal assets, and even more so when an added cost of a carbon tax comes into the picture. Placing a price (i.e., a tax) on carbon can be a meaningful way to encourage cleaner forms of power. There are a handful of markets that place a value on CO_2 emissions and mostly take the form of a cap-and-trade system. However, the markets are currently structured in such a manner where the price of carbon remains too low to provide the price signal that is needed to encourage meaningful decarbonization. Looking across a few of the carbon pricing schemes, the European Emissions Trading System (ETS) had a 12 month average of ~€24/MT (Nov '19–Nov '20) reaching a high of ~€30/MT and in the Northeast US, the Regional Greenhouse Gas Initiative's (RGGI) 49th auction cleared at $6.82/ton in September '20. Not only are these prices, among many other schemes, too low to encourage impactful decarbonization to CO_2 emitting sectors, they often lack sustained pricing needed for long-term planning and business certainty. See Figure 12 below for a global sampling of established carbon pricing schemes.

In analysis performed by GE, the trade-off between paying a carbon tax on emissions versus paying to capture and sequester the carbon tips in favor of installing post-combustion carbon capture in certain conditions starting as low as ~$35–~$50 per metric ton of sustained CO_2 pricing. At this rate, a plant's levelized cost of electricity comes down as the asset decarbonizes until it reaches ~90 percent decarbonization. The relationship between carbon capture percent and capital expense is not linear, and in fact, costs begin to increase exponentially above ~90 percent capture.

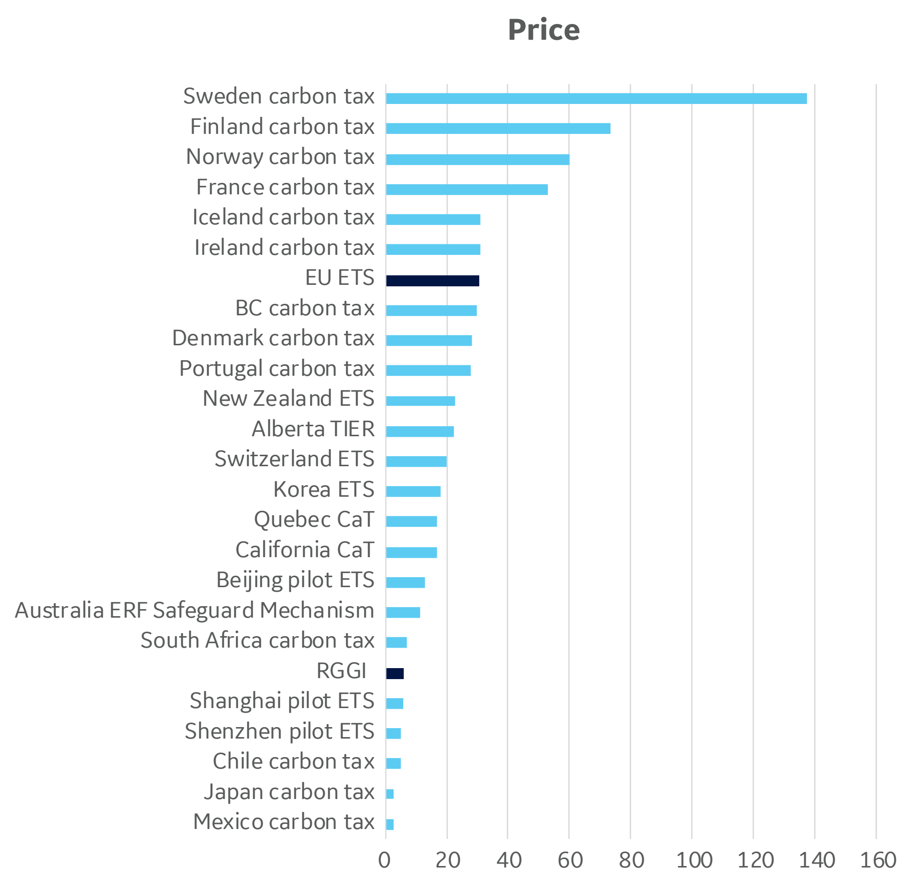


FIGURE 12: Selected CO_2 prices, US$/t$CO_2$e

Source: The World Bank Carbon Pricing Dashboard https://carbonpricingdashboard.worldbank.org

TRANSPORTATION

Once the CO_2 is compressed to the appropriate pressure its ready leave the site and be repurposed or sequestered, there are a few modes to transport it: truck, train, ship, and pipeline.

Pipeline transport is by far the lowest cost option when looking at significant volumes.

The technology for transporting CO_2 via pipelines is fundamentally no different than the technology for transporting natural gas and other gases, and also safely managed in the same ways. Dry CO_2 does not corrode the carbon-manganese steels generally used for pipelines, as long as relative humidity can be controlled.[3]

There are already millions of miles of pipelines carrying hydrocarbons around the globe, with established rights-of-way (routes) the CO_2 pipelines can follow, see Map 1, minimizing the potential construction impact associated with greenfield infrastructure projects. In fact, there are already 5,000 miles (~8,000 km) of CO_2 pipelines globally (compared to ~2,800 miles of H_2 pipelines[5]), with the majority in the United States, see Map 2, used to bring CO_2 to the Permian basin for use in enhanced oil recovery. Some of these pipelines have already demonstrated nearly a half-century worth of safe and reliable operations, going into service as early as the 1970s. However, CO_2 pipelines have a perceived stigma among communities, despite many of these same communities accepting the day-to-day risks brought by existing natural gas infrastructure. With that in mind, it is especially important to ensure the proper regulation, monitoring, and maintenance structures are in place for CO_2 pipelines in sufficient measure to overcome public perception.

While other modes of transportation can be both viable and well suited for different CCUS applications or geographies, pipeline networks are the most cost-effective infrastructure to connect the power generation sector to sequestration sites. Developing CO_2 pipeline infrastructure is a classic chicken and egg dilemma. Because pipelines are suited for moving large, continuous volumes of material, their construction for purposes of moving CO_2 will depend on being able to aggregate clusters of CO_2 suppliers, or creating the hubs for CO_2 collection. This business model has been applied in many of sequestration projects that are currently in development, but not at the scale of the standard long-haul pipeline systems we see today.

The cluster & hub model is one that is likely to be replicated given the multi-regional hurdles that long-haul systems face. In fact, large concentrations of major industrial and power generation operations are within ~300 km of areas that may hold formations ideal for geologic storage.[7] These clusters of stationary emitters are ideal for aggregating sufficient volumes to satisfy a pipeline's capacity, from which a modest pipeline is needed to ship the compressed CO_2 to a nearby geologic resource. This obviously has economic implications for both the developer of the pipeline and the supplier of the CO_2. From a development perspective, it costs on average anywhere from \$80K–\$150K per inch/mile (inch of pipeline diameter per mile of pipeline) to construct a new CO_2 pipeline. From the perspective of the supplier of the CO_2, transportation can become a significant cost if there is a great distance between CO_2 production and storage. In a recent National Petroleum Council study, the transportation costs of CO_2 range from \$2 USD–\$38 per metric tonne.[8]

MAP 1: Natural Gas Infrastructure in US/CAN[4]

MAP 2: Existing CO_2 Pipelines in the US[6]

SEQUESTRATION AND ENHANCED OIL RECOVERY (EOR)

Today, most of the CO_2 that is captured and piped to wellheads is used for a process called EOR. The EOR process is generally implemented at the final extraction phase of a well, after the natural geological pressures have pushed the hydrocarbons into the well. Once these natural forces have done their job, the remaining deposits need a little more help to make it to the surface. One method to do this is to inject gases into the well, which expand and push remaining hydrocarbon deposits into the well stream. Using CO_2 as the agent has been done in the US for decades. Under this scheme, there is actually a value that carbon provides in these operations to improve the productivity of wells which would otherwise be considered "dry."

While EOR will continue to be a viable route for utilization of carbon capture, sequestration without additional hydrocarbon extraction is a necessary activity for CCUS to make its full impact in the energy transition. The techniques, tools, and geologies to do so are well known, and are almost all born out of the oil & gas industry. The questions become, where are these geologic structures, and how safe is it?

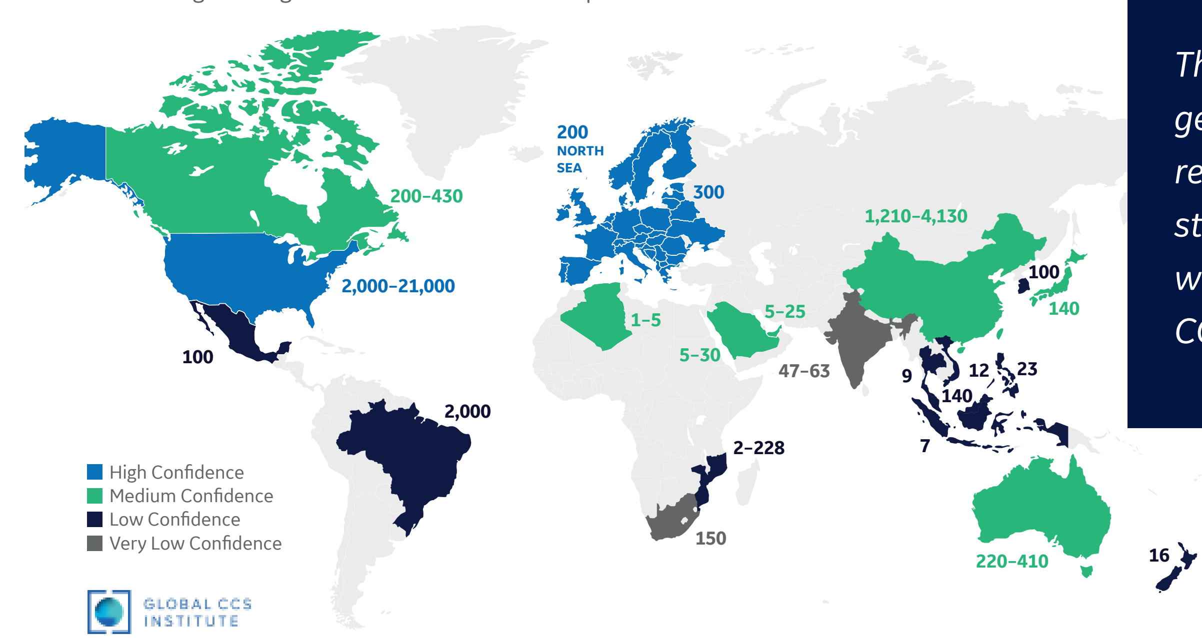
In fact, it is often a misconception that there is not enough capacity deep below the Earth to house a meaningful amount of carbon, or that resources that do exist are far away and hard to access. A study completed by the Global Carbon Capture and Resource Institute indicates there is ample space both onshore and offshore.

Afterall, the majority of the carbon in the atmosphere that we need to capture originated from those same location. Granted, it is not an infinite resource if one considers a millennial time scale, but the magnitude of known resources are more than enough to accommodate centuries of sequestration, making CCUS a viable and necessary tool to achieve net-zero targets. To present this in a more quantifiable manner, anthropogenic CO_2 emissions (excluding land use) in 2019 were ~33 gigatons. On the low end, there are 2,000 gigatons of storage capacity in the US alone, with sizable capacities in many countries across the globe. See Map 3 below.

An additional public misconception is that carbon sequestration is unsafe, and there are fears that the carbon may not stay underground in perpetuity. While there are inevitably risks with these types of operations, proper regulation, monitoring, maintenance, and implementing tools that already exist can safely mitigate these risks. There is very strong evidence that we can safely store the CO_2 underground for hundreds of millions of years, just as hydrocarbons were stored underground before being intentionally extracted by humans.

It's important to point out that leakage can occur, as it does naturally with current hydrocarbon deposits. The best way to explain this phenomenon is the study of the very liquids and gases that humans use to create CO_2: hydrocarbons. Generally, fossil fuels are created when biological matter, mostly dead vegetation, is buried over millennia, and cooked under extreme temperature and pressure. Much of the crust above these cooked deposits is porous and made of materials that are denser than oil and natural gas. As a result, buoyancy naturally wants to drive the hydrocarbons upward through the porous layers. If the Earth's crust was merely made of perfectly cylindrical layers of porous rock, then all of the fossil fuels would have escaped to form pools of oil on the surface of the Earth a long time ago. But this is not the case. Some fossil fuels do make it to the Earth's surface and atmosphere naturally, but the vast majority are trapped underground.

MAP 3: Geologic Storage Reserves: Global Carbon Capture and Resource Institute



There are geologic resources to store centuries worth of CO_2 emissions

The reason for this is that there are also non-porous layers—like granite, or salt. While these layers are not continuous all around the Earth, both porous and non-porous layers undulate in upward and downward slopes. Hydrocarbons and other less dense gases will continue to rise upwards, along the slope of that impermeable strata until reaching a concave section—a dome—where it is then trapped.

In fact, oil and gas geologists are exceptionally good at finding these structures and therefore pockets of oil and gas. Once we understand that the simple geometry of the geology provides natural places for gases and liquids to reside, it's a small step to realizing one other fact: those fossil fuels have been trapped in those domes for millions and millions of years. Re-injecting the carbon back from where it came is nothing short of a "bottle return" concept.

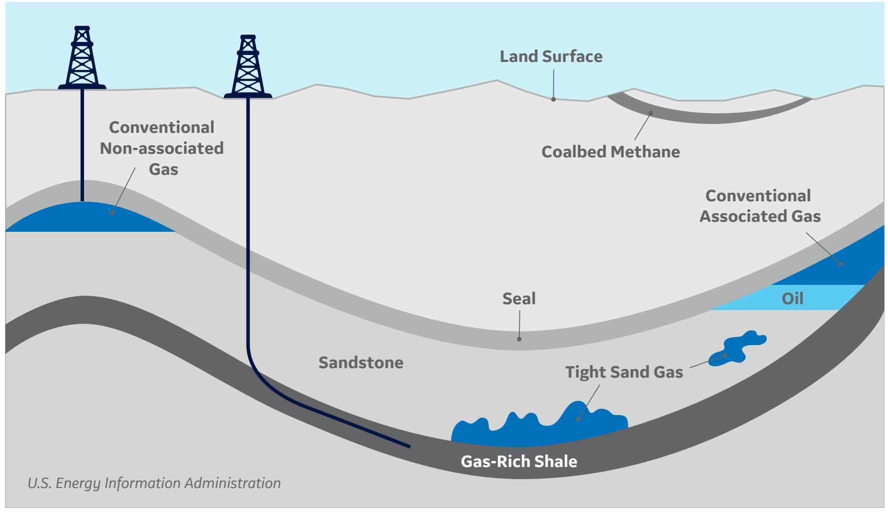


FIGURE 13: Cross-sectional view of geologic formations and drilling activities.

Monitoring remains a very important piece of this puzzle in order to properly manage the risks. Items such as injection rates, well pressures, seismic profiling, and even satellite monitoring are a few of the critical tools that will play a role in monitoring the CO_2 to ensure it does not leak into the atmosphere. It is important to structure international regulatory and monitoring standards in a manner that gains the trust of the public and ensures effective long-term success of CCUS applications.

POLICIES

Policy and regulatory statutes remain somewhat fractured between countries and even their constituent regions when it comes to many of the facets required for successful deployment of CCUS across the full value stream. These facets include a sustained value placed on CO_2, uniform standards and procedures for monitoring and safety, tax incentives, assignment of long-term storage liability, and significant infrastructure development.

An outcome of good and sound policy is that it lays the framework for a structured and safe economic activity, which is needed in order to attract investment capital.

An important part of thoughtful policymaking is to structure regulations and incentives in a manner that decouples the existing economic relationship between EOR and CCUS. That is to say, ensure CCUS is viable without being tied to the price of a barrel of oil. The CO_2 projects that are active today and the corresponding infrastructure and operations are generally stimulated by the commercial opportunity to use the CO_2 for EOR and maximize withdrawal from existing wellheads. This places an inherent vulnerability on the project, as is evidenced by the Petra Nova facility in Texas, which idled starting in March 2020 due to low oil prices.[9] At lower oil prices, EOR is no longer economical, so the CO_2 that would otherwise have been captured and routed to a storage site is emitted into the atmosphere.

It needs to be understood that use of captured CO_2 for EOR is an acceptable and necessary action as long as the world continues to demand fossil fuels, acting as the "bottle return" concept for the hydrocarbon industry. However, if the world is to achieve meaningful decarbonization, policies need to be structured to ensure the long-term viability of projects and infrastructure.

Because CCUS projects have such a long operational life and require significant amounts of investment, billions of dollars worth, policy must bring stability and business certainty to developers and investors alike. Characteristics that will bring about certainty include nation-wide emission reduction targets across all economic sectors, a firm and sustained price on carbon, programs to encourage and fund innovation in CCUS applications, defining long term liabilities for storage, and establishing goals or targets for CCUS deployment in the field. Some regions are more advanced when it comes to providing this certainty, but in most cases, many of these facets have yet to be defined. Many governments are still struggling to provide the right mix of regulations to create the change that is needed in order for CCUS to play its needed role in decarbonization.

Conclusion

In order for the world to avoid the negative impacts that accompany climate change, it must become a global priority and involve all carbon emitting sectors.

Continued investment in a combination of wind, solar, batteries, and gas-fired power is critical to the enablement of coal generation retirements while maintaining grid reliability. In fact, renewables and gas power have the capability to quickly make meaningful and long-lasting reductions to CO_2 emissions in the power sector.

Within the power generation sector, the technologies and capabilities to remove carbon from critical generation equipment already exist, but still face economic headwinds. Increased R&D funding will help with cost declines, efficiency improvements, and will accelerate the deployment of hydrogen and carbon capture solutions for assets that provide the electric grid with the dependable capacity it requires.

Going beyond the power sector, governments must establish impactful Nationally Determined Contributions (NDCs) under the Paris Agreement. In support of these NDCs there needs to be well thought out policies that:

1. incentivize the reduction of carbon emissions
2. foster the creation of new market structures that properly value decarbonized assets
3. provide stability and business certainty for decision makers.

One of the most effective economic mechanisms that support these three outcomes is placing a price on a unit of carbon.

GE as a company is uniquely positioned to play a key role through its scale, breadth, and technological depth. We have been a key player in the power industry since its inception and have a suite of complementary technologies including gas-fired power with hydrogen and CCUS capability, onshore and offshore wind, hydro, small modular reactors, battery storage, hybrids and grid solutions needed for the energy transformation.

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