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Review article

The carbon conundrum: GCC perspectives

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ABSTRACT
The solution to the carbon conundrum does not seem to be within reach in the short or medium term, despite significant advances and knowledge gains in demonstration scale CCS facilities. This stems from the fact that currently carbon management has no binding policies and legal framework. Without this legislation, it is unlikely that international cooperation in carbon trade and management would flourish. The situation is also exacerbated by doubts about the suitability of sites and global capacity to store captured CO_2. Sophisticated cost models have been developed for carbon capture and storage, and these indicate that cost reduction in the complete carbon value chain should be focused on the capture phase as this is the most energy intensive. However, there are uncertainties about properly costing carbon storage as this should involve search for suitable site location costs. The GCC states have characteristics that make them one of the largest consumers of fresh water and energy in the world, and by default emitters of CO_2 per capita. There are currently no demonstration or commercial scale CCS facilities in the GCC and in the short term, it is unlikely to be the case given that current carbon capture technologies favor coal rather than natural gas as fuel in power plants. It is also unlikely that underground carbon storage be considered in the short term, given the risk of CO_2 plume migration that may displace brine in saline formations into strata containing hydrocarbon resources or potable. It is therefore imperative that substantial research be conducted to identify storage sites, reduce energy consumption in carbon capture and develop alternatives to CCS in the form of carbon conversion into useful products or minerals with low environmental impact. The GCC have tremendous opportunities to lead the world in carbon management given their strong experience in hydrocarbon processing. However, this may only be successful if agreed policies and legal frameworks are in place to facilitate a robust carbon pricing.

Keywords: carbon management, GCC perspectives in CCS, hydrocarbon economy, liability and risk, economics of CCS

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INTRODUCTION

The GCC states are characterized by a number of unique features that make them quite distinct compared to other countries in the Middles East and North Africa (MENA) and indeed any other parts of the world. These features may be broadly defined as permanent and non-permanent. The permanent features include hot climate, fresh water scarcity and arid land and poor soil nutrients. The non-permanent features include vast hydrocarbon reserves and carbon based economies.

Over the next twenty years the countries of the GCC are likely to experience some of the fastest economic and energy-consumption growth rates anywhere in the world [1].

The GCC energy consumption has grown 74 percent since 2000, and is projected to nearly double its current levels by 2020 [2]. The current sources of energy mix for electricity generation is shown in Table 1.

Table 1. Sources of energy for domestic [1] consumption in the GCC.

State	Natural gas	Oil
Bahrain	84.2%	15.8%
Kuwait	37.4%	62.6%
Oman	69.3%	30.7%
Qatar	75.3%	24.7%
K.S.A	37.6%	62.4%
U.A.E	82.4%	17.6%

[1] For electricity generation
[2] Source: International Energy Agency (2008)

Despite the Middle East and North Africa (MENA) region seeming energy-rich and holding 56% of the world proven oil reserves, it is on a downward trend in terms of energy security. MENA countries are approximately 60% more energy-intensive than OECD countries. Environmental degradation, resource depletion, limited conversion capacities and unbalanced regional distribution of fossil fuel resources, have had strong constraining effects on MENA economies. This has been exacerbated with the region's fresh water supply because of heavy reliance on desalination, in turn, imposing increasingly tough choices on resource allocation [3].

Despite an increase in population in the GCC states (made up of a significant expatriate manpower to drive the booming economies), the carbon emissions per capita are amongst the highest in the world. Tables 2 and 3 show recent trends in carbon emissions arising from energy consumption.

Table 2. Per capita carbon dioxide emissions from the consumption of energy (metric tons of carbon dioxide per person).

State/Year	2005	2006	2007	2008	2009
Bahrain	36	40	41	43	43
Kuwait	33	32	30	31	31
Oman	12	13	14	16	17
Qatar	67	70	72	74	76
K.S.A	17	17	16	17	17
U.A.E	34	36	39	42	41

Source: US energy information administration (2010)

Table 3. Total carbon dioxide emissions from the consumption of energy (million metric tons).

State/Year	2005	2006	2007	2008	2009
Bahrain	25	28	29	31	31
Kuwait	77	77	75	79	84
Oman	31	36	38	44	49
Qatar	52	56	59	61	64
K.S.A	405	406	396	426	438
U.A.E	140	155	172	196	194

Source: US energy information administration (2010)

The energy intensity of the GCC states includes a significant contribution from desalination plants that are typically coupled with power generation. When water consumption increases (which is currently the case), demand for power also increases and the carbon emissions naturally follow. It is instructive to notice that a great deal of the fresh water produced in the GCC is used for agricultural purposes.

The GCC nations became well aware of the challenges facing them as a result of the unique permanent and non-permanent features highlighted above and embarked on ambitious sustainability exercises. The best known examples of these were articulated in the Qatar National Development Strategy 2011–2016 and the Qatar National Vision 2030, where rational use of hydrocarbon resources and environmental protection constituted essential ingredients. Amongst these, carbon emission reduction is given particular attention. The global carbon conundrum is perhaps more complex in the GCC region given its excessive dependency on hydrocarbons to drive the economy and provide essential power for fresh water supplies and air conditioning during the hot months of the year. This paper attempts to highlight and explain the current outstanding issues preventing the full deployment of carbon capture and storage, and the GCC specific barriers and opportunities.

CARBON CAPTURE AND STORAGE: STATE OF THE ART AND GLOBAL HORIZONS

State of the art in carbon capture

There has been significant progress in technology development and costing models for carbon capture for power plants ahead of full deployment in the future, pending similar progress being made in underground storage and legal frameworks. The carbon capture technologies explored include post-combustion, pre-combustion and oxyfuel combustion. Sophisticated cost models were developed depending on the type of fossil fuel used and the degree of carbon capture integration within the plant. This progress has been largely led by industry given its vast experience in power plant systems and gas processing [4]. In summary, economics of carbon capture favor coal fueled power plants because more carbon is emitted from such facilities compared to gas driven power plants. It has been suggested that the capture and transport cost of CO_2 from coal fired plants would be around 50 USD compared to 100 USD for natural gas [4]. Obviously this cost range needs regional adjustments. The cost of the full carbon value chain seems to be dominated by the cost of capture and compression accounting for as much as 80% of the total carbon capture and storage (CCS) cost despite uncertainties in the cost of underground storage. Extensive details of such models, as well as comprehensive details of the state of the art in carbon capture technologies, may be found in [4]. In general, it is the lack of carbon capture and storage (CCS) policy that makes it difficult to "price" accurately CO_2 in the market place. It is well known that international money markets are very sensitive to policies and regulations.

Carbon storage state of the art

The inter-governmental panel on climate change (IPCC) produced several useful documents aimed at helping decision makers on carbon matters. An important report by the IPCC includes a survey on global potential underground storage capacity for captured CO_2 [5]. It can be seen from Fig. 1 that promising storage sites (shown as dark areas) are not uniformly distributed, that these sedimentary basins are not always close to power plants (usually located at close proximity to large metropoles). Figure 1 shows that many parts of the globe completely lack suitable or even potential carbon storage sites, making it hard for the international community to exert any form of pressure on them to store CO_2 from power plants, simply because they do not have such facility. The absence of policies and legal frameworks makes it practically impossible to reach agreements with countries that do have storage capacity.

In underground reservoirs, CO_2 can be stored in porous rocks at a depth of more than 800 m in supercritical form under an impermeable caprock, in the top part of a water-filled reservoir. According to the international energy agency, deep saline aquifers offer potentially decades or hundreds of years' worth of storage capacity with estimated 1,000-10,000 Gt of capacity available. This is currently the single most important underground storage potential. Around 920 Gt of CO_2 could be stored in depleted oil and gas fields. Small leakages of CO_2 may occur over an extended period of time, which may reduce the effectiveness of CCS as an emission mitigation option. This so-called 'permanence problem' is currently dealt with through field tests and through modeling studies. Depleted oil and gas fields have contained hydrocarbons for millions of years and this makes them a relatively safe place to store CO_2 provided exploration work did not entail excessive fracturing and

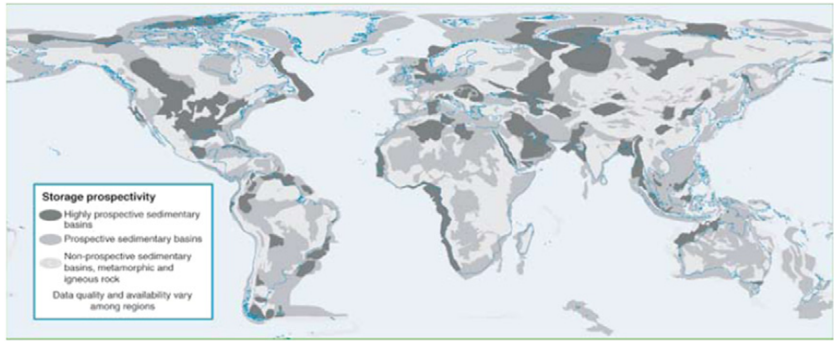

Figure 1. Global prospectivity for captured CO_2 storage [5].

other forceful forms of enhancing hydrocarbons extraction. The problem for such reservoirs is therefore if the extraction activity has created leakage pathways, and if abandoned boreholes can be plugged properly so the CO_2 cannot escape. Many projects for natural gas storage and acid gas storage have worked well. Progress in modeling allows increasingly accurate forecasts of the long-term fate of the CO_2, which cannot be tested in practice.

Several natural phenomena, such as CO_2 dissolution in the aquifer water, will reduce the long-term risk of leakage. The understanding of these phenomena is improving gradually, especially after successful operations of commercial scale facilities (in Salah, Algeria; Sleipner, Norway) and demonstration scale facilities (Frio, USA; Ketzin, Germany and Nagaoka, Japan).

CCS economics: not such a bright short term prospect

Constraints for the full deployment of CCS remain. CCS for power generation has yet to reach the stage of commercialization, and is a long-term prospect rather than a short-term option. This is especially true for CCS from natural gas power generation; nearly all existing or planned CCS power plants worldwide are coal-fired. Moreover, because natural gas generation is 50 percent less carbon intensive than electricity from coal, there is less carbon to be captured from natural gas power plants. Assuming a carbon price that provides an incentive for capture, the economic returns of carbon capture from natural gas plants, the predominant means of power generation in the GCC, are limited in comparison with those from coal power plants elsewhere. Anyhow, even in those markets that do have a price on carbon, the financial incentive is currently nowhere near adequate to justify investment in CCS for power-generation facilities.

One of the most significant uncertainties to the cost of CCS on a project level is the cost of CO_2 storage. This is naturally due to the uncertainties associated with finding and appraising a suitable site to prove that CO_2 can be safely stored in the required quantities. As experience in the oil and gas industry has shown, these activities can incur significant costs with no guarantees of reaching injection targets. In the same manner, for CO_2 storage, significant investments can be made in finding and appraising a potential storage site only to find that it is unsuitable for any number of reasons, not limited to technical unsuitability. The costs associated with finding and appraising potential storage sites, whether they are successful or not, is referred to as the "finding cost", parallel with the "exploration and appraisal costs" for an oil and gas exploration venture.

These "finding costs" are site specific, and will vary widely between sites if they are:

- Saline reservoirs or depleted hydrocarbon fields
- Close to population centres
- Rural onshore
- Deep or shallow water offshore

Critically, the economics of CO_2 storage is driven by the fundamental geologic characteristic of the site under consideration, and emphasizes:

- Containment (safety/security of storage);
- Injectivity (rate at which CO_2 can be injected into the reservoir)
- Capacity (volume of CO_2 that can be stored).

One of the main observations of current CCS-related work is that the issue of capture and compression has received a great deal of attention in the CCS value chain. However, the finding and appraisal of CO_2 storage sites is the critical path technology in the CCS value chain, and can potentially be the key to proceed or not in early projects.

As far as depleted oil and gas reservoirs are concerned, the primary attraction is that they are usually well understood. They potentially offer early commercial viable storage. However, like all sites, they have their own challenges. Depleted oil and gas reservoirs may have both active and abandoned wells that could potentially act as leakage pathways to the surface. Detailed well integrity studies and risk assessment are required on a field-by-field basis, as with geology, no generalisation is possible. Furthermore, the space available in depleted fields remains limited (compared to aquifers of a similar area) due to the presence of residual, un-produced hydrocarbons and likely pressure limitations caused by the field setting and complex depletion history. The primary advantage, as stated before, comes from the amount of upfront characterisation work that has been done on these formations during the asset's life. This reduces a project "finding" costs quite considerably.

CCS economics gap

The primary economic gaps to the implementation of CCS can be summarized by the following important points:

- Insufficient financial incentive to implement CCS
- High capital and operating costs and minimal experience with integrated operation on a large scale to reduce these costs
- Availability of infrastructure to implement the technology
- Limited geologic information for CO_2 injection and its long-term safe storage

A more effective financial incentive for the adoption of CCS among GCC nations is its potential application in enhanced oil recovery (EOR) and enhanced gas recovery (EGR). Currently, many of the countries in the GCC increase the productivity of mature oil and gas fields by pumping in natural gas to increase well pressure. Given the projected spike in electricity demand in the region, and the corresponding increase in the use of natural gas supplies for power generation, the use of gas for oil recovery may become economically unfeasible. By pumping CO_2 into declining oil wells in place of natural gas, the countries of the GCC can free up valuable volumes of hydrocarbons. The gas saved can then be used either for domestic power generation or for export, earning additional income. It is important to recognize that EOR/EGR is not long term CCS. Given the status of CCS described in the previous sections, what are the specific challenges and perspectives in the GCC?

CARBON MANAGEMENT CHALLENGES AND PERSPECTIVES IN THE GCC

Status of carbon capture and geological storage sites in the GCC region

So far no public announcement has been made on an identified geological site in the GCC region for CO_2 storage for a demonstration or commercial scale facility. Furthermore, no significant investment has been made to develop CO_2 capture technologies from gas or oil fueled power plants. The plausible reasons for this lack of progress in CCS in the GCC region stems from the fact that the majority of power plants are fueled by natural gas, considered as a clean fuel and having considerably less carbon emissions than coal. In addition, carbon capture studies elsewhere have shown that economics are more favorable for coal than for natural gas as more CO_2 is emitted from the former than from the latter. This is seen as a serious setback and negative incentive. Hence, if carbon capture has no incentive for development and investment, it is highly unlikely that carbon storage demonstration units would even be considered. However, as was pointed out in the introduction section of this paper, there is a genuine intention in the GCC region to promote sustainability and environmental protection. This was for example articulated in the Qatar National Development Strategy 2011–2016. However, the pace of future CCS deployment in the GCC region may be hindered by insufficient understanding of sequestration resource potential and infrastructure. Just like elsewhere in the world, the GCC states currently have no policies or legal frameworks to regulate future CCS operations. This makes it difficult to "price" CO_2 in the market place.

Real challenges in the GCC region

The GCC permanent characteristics cited in the introduction indicate that these countries will need to continue to consume considerable amounts of energy to maintain the standard of living currently enjoyed, regardless of the source of energy. In the short term, it is likely that these sources will continue to be oil and natural gas. Hence it is quite understandable to accept the feeling of discomfort at prospects that injected CO_2 plumes in underground saline formations may displace brine into strata containing resources like hydrocarbons or potable water. Furthermore the known rock acidification and fracturing practices to enhance production only add to the risks associated with CO_2 leakage in the future, especially for carbonate formation known to prevail in the GCC region.

On the societal side, the GCC nations currently enjoy one of the highest and most lavish standard of living in the world with all the environmental consequences that ensue. For instances, in some GCC states citizens do not pay for the electrical power or water consumed, thus eliminating any incentive to reduce waste in these precious resources. It is well known that water consumption in the GCC is amongst the highest in the world despite water being produced in energy intensive desalination plants. The notion of global climate change does not seem to be a major concern in the GCC as most people think that in an arid region, the climate cannot get any worse. Other aspects of climate change consequences are hardly discussed or even understood in general terms.

Carbon management opportunities in the GCC

The GCC region has accumulated considerable oil and gas exploration and processing experience in the past four decades that can be put into useful practice in CCS development. For instance, post-combustion carbon capture is very similar to natural gas sweetening and acid gas removal, and may be an area where GCC states can make impressive efforts in cost reduction. In addition, several GCC nations including the United Arab Emirates, Saudi Arabia and Qatar have pledged substantial financial support for research on sustainability and environmental protection.

Energy efficiency, renewable sources and lifestyle

The GCC countries enjoy one of the world's most abundant solar resources. Estimates of the solar potential in the GCC put the region's annual average global radiation available to photovoltaic cells at about 6 kWh/m^2/day. Estimates of the direct normal irradiance (DNI, available to solar concentrating technology) are around 4.5 kWh/ m^2/day [6]. These figures indicate that a land area of approximately 1,000 km^2, representing about 0.2 percent of the GCC may be covered with photovoltaic cells at 20 percent efficiency, could produce 438 TWh every year which is more than the 400 TWh typically consumed by the region [6]. Nations of the GCC have either initiated, or committed to, investments in solar projects, with solar photovoltaic (PV) and concentrated solar power (CSP) being the main technologies of choice. Other potential solar-related applications applicable to the region include solar derived bioenergy and solar-generated hydrogen.

There is a need to sustain campaigns for energy and water saving in the GCC as the consumption of these ranks amongst the highest in the world. Whilst PV solar energy may not be immediately useful for large oil and gas industries, it certainly has an outstanding potential for homes, especially for lighting and small electrical appliances. In remote housing compounds, solar energy (both PV and CSP) may prove to be not only economic in the long term, but actually essential. The massive expansion of oil and gas industries in the GCC was also accompanied by a substantial release of low grade heat into the environment. There is a need to evaluate both quantities and useful applications of such waste heat, especially in water desalination.

Carbon conversion opportunities

Carbon conversion is gaining more and more attention as an alternative to underground storage where this is not feasible in the short or medium term or at all. Given that the CO_2 molecule is quite stable, it is anticipated that a limited but effective number of processes to convert CO_2 into a useful or harmless form be considered. The literature already identified biofixation [7], catalytic conversion [8] and low temperature mineralization [9] as promising ways to usefully convert CO_2 into a valuable product or into a harmless solid form. Given that the GCC countries enjoy sunshine for most of the days in the year, there are opportunities to exploit this free energy source to convert captured CO_2 into hydrocarbons through microalgae growth. The process engineering experience accumulated in the past three decades in the GCC's gas processing industries can also be put into action for the development of selective catalysts to activate and convert CO_2 into hydrocarbons. This new industry can be fully integrated with existing petrochemical industries to enhance energy efficiency.

CONCLUSIONS

The final solution to the carbon conundrum seems to be out of reach in the short term mainly because of the lack of policies and legal framework. A great deal of knowledge has been gained from demonstration CCS facilities in some countries. However, cost, risk management and liability prevent full CCS deployment. In addition, there are doubts about the global storage capacities to absorb all potential captured CO_2 from power plants worldwide. In the GCC states, no geological sites have been identified for demonstration or commercial CO_2 storage. Some of the reasons for this lack of initiative include the cost of CO_2 capture that currently favors coal as fuel compared to natural gas, and the reluctance to experiment in operational oil/gas fields that are mainly well away from depletion. There are indeed genuine risks that need evaluating. At some point in the future, the GCC nations will need to rely on their capacity to address the carbon conundrum given their specific characteristics. The following recommendations may be put forward to assist in gaining experience ahead of future CCS deployment or application of alternative carbon management schemes in the GCC:

CCS related

- Geological potential for sequestration
- Capture technologies
- Site characterization
- Monitoring and verification
- Risks and risk management
- Remediation and mitigation
- Economic consideration
- Regulatory and statutory issues

Alternative carbon management related

- Energy efficiency gains in process plants
- Utilization of low grade waste heat
- Carbon conversion into useful products
- Low temperature mineralization of carbon
- Solar energy as concentrated and photovoltaic
- Citizen education on minimizing energy and water consumption

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